University of Southern Queensland

DEMOCRATIZING & ENHANCING EXOPLANET RESEARCH WITH THE UNISTELLAR CITIZEN SCIENCE NETWORK & ASTRONOMY MODELING INSTRUCTION

A Thesis submitted by

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ABSTRACT

This thesis explores the potential in democratizing and augmenting exoplanet research via citizen science by utilizing a global network of portable image-intensified computerized telescopes, and inquiry-based astronomy instruction. A central objective is to establish that citizen scientists, using exoplanet transit photometry with compact, connected telescopes, can bolster professional astronomy's reliance on a limited number of large professional telescopes for exoplanet follow-up, discovery, and characterization. This research also investigates the efficiency of the Modeling Instruction Astronomy pedagogy, underscoring that teachers, even without specialized training, can effectively engage in astrophysics research (e.g., exoplanets) and enrich the educational experience for their students. Pivotal insights from this thesis include publishable scientific results from the Unistellar Exoplanet Campaign, with >1,000 exoplanet observations from 163 citizen scientists across 21 countries and a 43.2% transit detection success rate. This work refined the orbit of Transiting Exoplanet Survey Satellite (TESS) planet candidates and improved mid-transit times (e.g., TOI 2031.01), highlighting the value of a globally distributed citizen science network in providing extended transit photometry across multiple time zones. In a corresponding education study, integrating stellar and exoplanet data into the Global Hands-on Universe (G-HOU) framework and using the Modeling Instruction pedagogy enhanced both teacher and student astronomical understanding, self-efficacy, and engagement. Following a workshop, teachers mostly without prior astronomy experience incorporated a depth of astrophysical content into their high school curricula that often surpassed what's found in many university-level introductory astronomy courses. Finally, this thesis confirms the discovery of the TESS single-transit dense warm sub-Saturn, TIC 139270665 b, identified with the help of citizen scientists and confirmed with the Doppler method and transit photometry. The Unistellar citizen science network provided vital photometric data, with high school students significantly contributing to this exoplanet through an "AstroReMixEd" (Astrophysics Research Mixed with Education) effort. The discovery of this unique sub-Saturn also offers a promising avenue for refining our understanding of planetary formation and evolution models. While the core of this thesis emphasizes advancement in exoplanet research, it concurrently highlights the significance of integrating professional astrophysics exoplanet endeavors with pioneering educational strategies.

CERTIFICATION OF THESIS

I Daniel O'Conner Peluso declare that the PhD Thesis entitled *Democratizing and Enhancing Exoplanet Research with the Unistellar Citizen Science Network & Astronomy Modeling Instruction* is not more than 100,000 words in length including quotes and exclusive of tables, figures, appendices, bibliography, references, and footnotes.

This Thesis is the work of Daniel O'Conner Peluso except where otherwise acknowledged, with the majority of the contribution to the papers presented as a Thesis by Publication undertaken by the student. The work is original and has not previously been submitted for any other award, except where acknowledged.

Date: 12 February 2024

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STATEMENT OF CONTRIBUTION

This section contains details regarding the contributions by the various authors for each of the papers presented within this thesis by publication.

Paper 1, Chapter 3, Peluso et al. (2023):

Peluso, D. O. , Esposito, T. M., Marchis, F., Dalba, P. A., Sgro, L., Megowan-Romanowicz, C., . . . Scientists, Unistellar Citizen. (2023). The Unistellar Exoplanet Campaign: Citizen Science Results and Inherent Education Opportunities. *Publications of the Astronomical Society of the Pacific, 135*(1043), 015001. doi:10.1088/1538-3873/acaa58

Author	Percent Contribution	Tasks Performed
Daniel O. Peluso	75%	Conception of project and ideas, data acquisition, creation of citizen scientist observation tracking system, analysis of data, investigation and amalgamation of data and analysis of over 1,000 exoplanet citizen scientist observations, data interpretation, creation of plots and tables, and wrote all drafts of paper.
Thomas M. Esposito Franck Marchis Paul A. Dalba Lauren Sgro Colleen Megowan-Romanowicz Carl Pennypacker Bradley Carter Duncan Wright Arin M. Avsar Amaury Perrocheau *163 Unistellar Citizen Scientists	25%	Supervision of paper and mentoring, assistance with navigating and utilizing the Unistellar data pipeline, assistance with analysis codes, suggested edits to manuscript, co-analysis of global network of citizen science data, and assistance with some plots from the data pipeline.

*See Appendix A for full citizen scientist list

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Author	Percent Contribution	Tasks Performed
Daniel O. Peluso	85%	Conception of project and ideas, led and wrote documents for the Institutional Review Board (IRB) submission, development and revision of curricular materials for workshop, development and deployment of survey instruments, co-leading and planning of workshop, led participant interviews and analyzed collected data from interviews, quantitative and qualitative data collection and analysis, statistical tests, created all plots and tables in paper, wrote all drafts of paper.
Colleen Megowan-Romanowicz Carl Pennypacker Franck Marchis	15%	Supervision of paper and mentoring, assistance in developing and revising workshop Modeling Instruction curriculum materials, supervising the creation of a new workshop with the American Modeling Teachers Association (AMTA), co-leading and planning of workshop, provided Unistellar eVscopes for research participant, and suggested edits to manuscript.

Paper 3, Chapter 5, Peluso et al. (2024):

Peluso, D.O., Dalba, P. A., Wright, D., Esposito, T. M., Sgro, L. A., Weaver, I. C.,.., Citizen Scientists, Unistellar. (2024), *Confirming the Warm and Dense Sub-Saturn TIC 139270665 b with the Automated Planet Finder and the Unistellar Citizen Science Network*, was accepted for publication on 6 February 2024 (manuscript AAS50575R1).

Author	Percent Contribution	Tasks Performed
Daniel O. Peluso	75%	Conception of project and ideas, data acquisition, planning and managing citizen scientist observations, creation and analysis of MCMC analysis code, creation of code for the analysis of various light curves and statistical tests on over 270 hours of photometric data, analysis of transit and radial velocity data, data interpretation, creation of plots and tables, and wrote all drafts of paper.
Paul A. Dalba Duncan Wright Thomas M. Esposito Lauren A. Sgro Ian C. Weaver Franck Marchis Diana Dragomir Steven Villanueva Jr. Benjamin Fulton Howard Isaacson Thomas Lee Jacobs Daryll M. LaCourse Robert Gagliano Martti H. Kristiansen Mark Omohundro Hans M. Schwengeler Ivan A. Terentev Andrew Vanderburg *43 Unistellar Citizen Scientists	25%	Supervision of paper and mentoring, assistance with the Unistellar data pipeline, suggested edits to manuscript, and assistance with radial velocity analysis and with some of the campaign plots from the Unistellar data pipeline for the paper's appendix.

*See Appendix A for full citizen scientist list

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Disclaimer:

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CHAPTER 1: INTRODUCTION

"Exploration is in our nature.
We began as wanderers, and we are wanderers still.
We have lingered long enough on the shores of the cosmic ocean.
We are ready at last to set sail for the stars."
-Carl Sagan, Cosmos (1980)

The desire to explore and understand the cosmos is deeply rooted in our evolutionary history. Our inherent fascination with the stars not only underscores our destiny as cosmic explorers but also signifies the importance of embedding this exploration in our educational systems and professional research fields. With the emergence of new technology, e.g., personal digital smart telescopes and innovative education strategies, the wonders and excitement of astronomy research need not be exclusive to academics alone. These advancements hold the potential to democratize astronomical exploration and research, making it universally accessible and possibly ushering in a renewed awakening of our cosmic perspective. This thesis delves into how combining professional and citizen scientist observations can enhance exoplanet research, the outcomes of an exoplanet and astrophysics data intensive workshop for out-of-field astronomy teachers, and the discovery and confirmation of a warm and unusually dense sub-Saturn exoplanet. Combining astronomical efforts from professionals, citizen scientists, and educators and students may set the groundwork for a more inclusive and ambitious future in democratized astrophysics research and education (i.e., *AstroReMixEd*—astrophysics research mixed with education).

1.1 Cosmic Curiosity Set into Motion

All of the Earth and its life is intertwined with the evolution of the cosmos. Not only do we share atoms made in the Big Bang and subsequent supernovae over the life of our galaxy, but on-going cosmic events also continue to impact us. We are dependent on our nearest star for all our planet's life. Humanity's evolution received a boost after a cosmic impact from an asteroid 66 million years ago. The mass extinction event on Earth from this impact, which resulted in the extinction of dinosaurs and death of most creatures more than one meter in length, is the way of the cosmos. Even so, cosmic cataclysms such as these seem to be important for life. For us, the extinction event helped to carve out an evolutionary niche for our species to evolve. Other dramatic cosmic events may have also shaped the course of our evolutionary history. Our ancestors, once arboreal quadrupedal primates, may have transitioned to the savannas in Africa to evolve into bipedal hominids after escalating wildfires sparked by increased lightning that possibly resulted from the effects of a nearby supernovae roughly 2.6 million years ago (Melott & Thomas, 2019). After becoming “wise apes”, or Homo sapiens (Fara, 2004), we began to wonder about our place in the universe. This thinking led to the development of astronomy, which is one of the oldest forms of inquiry about nature and is often considered along with medicine to be the first “science” (Hamacher et al., 2022; North, 2008; Pannekoek, 1989; Rees, 2009; Salimpour & Fitzgerald, 2022). Our human ancestors have relied on astronomical knowledge and its predictive nature for survival and cultures around the world have implemented astronomy into the very architectures of their societies (North, 2008; Pannekoek, 1989). Cosmic curiosity is strong, and its origins run deep in our evolutionary history.

1.2 Exoplanets: From Antiquity to Modern Times

Planets around other stars, i.e., exoplanets, although only first confirmed within the last 31 years, have been conceived as possibilities since ancient times. As early as 2300 years ago, Greek philosophers such as Epicurus suggested an infinite number of worlds in the universe ("Extrasolar planets: the Holy Grail of astronomers," 2007). Later, from the time of the Copernican revolution through subsequent centuries, the concept of the plurality of worlds gained traction. Notable figures such as Giordano Bruno, Christiaan Huygens, Bernard Le Bouvier de Fontenelle, and Immanuel Kant wrote about the potential existence of planets around other stars and the possibility of extraterrestrial life in the cosmos ("Extrasolar planets: the Holy Grail of astronomers," 2007; "A Short History of Panspermia from Antiquity Through the Mid-1970s," 2022). These thought experiments of the plurality of worlds eventually led way to the first exoplanets being discovered and confirmed with modern instruments in the 1990s (Mayor & Queloz, 1995; Wolszczan & Frail, 1992).

In our modern world, exoplanets are now being discovered at an amazing rate (see Figure 1) and we can say with statistical confidence that on average that there is at least one exoplanet per star in our Milky Way galaxy (Cassan et al., 2012). Venturing further from our galactic nest, we are now discovering extragalactic exoplanets (Dai & Guerras, 2018; Perottoni et al., 2021) and developing new tools to expand the search (Painter et al., 2023). If we invoke the Copernican Principle, it is highly likely that our accelerating expanding universe abounds with exoplanets. Further, since the raw ingredients for life are ubiquitous across the cosmos (Ehrenfreund & Charnley, 2000;

Ligterink et al., 2021; Scharf & Cronin, 2016), it is reasonable to consider that at least simple life may be commonplace throughout the universe. This notion would be further solidified if we were ever to discover definitive evidence of life originating independently elsewhere in our solar system or beyond (McKay, 2007).

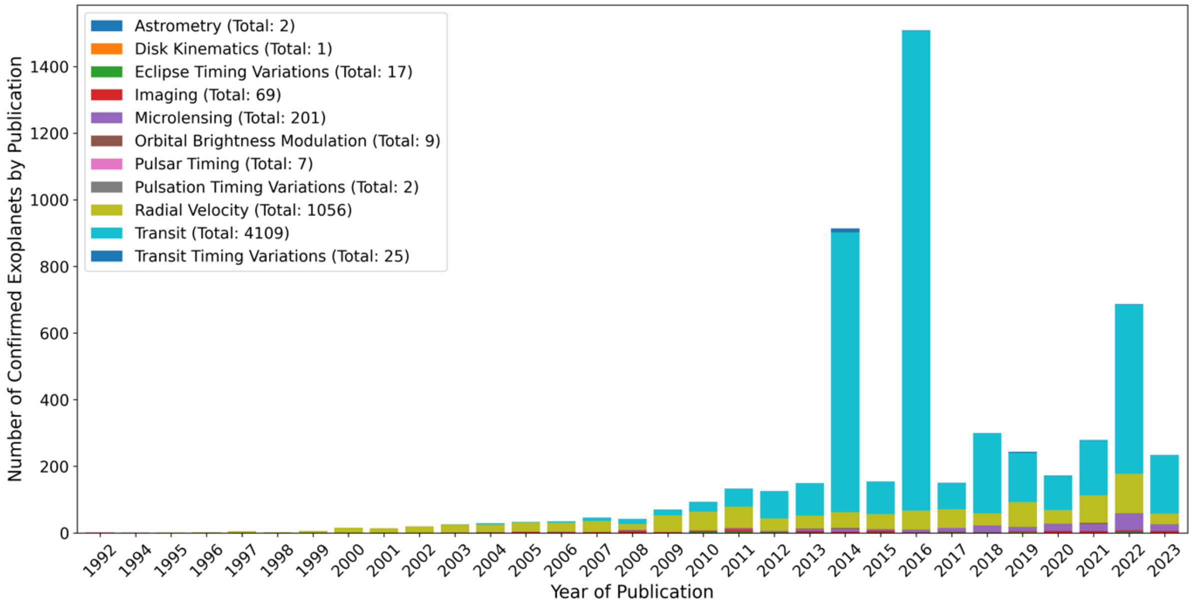

Figure 1. Growth of confirmed exoplanets with an associated publication over time. The figure showcases a total of 5489 confirmed exoplanets, each differentiated by detection technique as represented by the distinct colors in the legend. Data was sourced from the NASA Exoplanet Archive as of 2 September 2023.

1.3 The Need for a Democratized Science

In the context of this thesis, the term "democratization" refers to the inclusive and participatory involvement of diverse individuals, including professionals, citizen scientists, educators, and students, in astronomy research and education. It emphasizes breaking down traditional barriers and to make the pursuit of astrophysics universally accessible and fostering collaboration across a broad spectrum of peoples to transcend distinctions based on gender, ethnicity, or socio-economic status.

As thrilling as our advancement and understanding of the universe and discovery of other worlds is, modern civilization faces many obstacles. The dream of reaching beyond our planet, once an inspiring force that galvanized an entire generation during the Space Race (Wissehr et al., 2011), now competes with the immediate allure and instant gratification of smartphones and the ephemeral nature of social media. The technological ability to connect instantly with each other combined with our growing cosmic perspective should inspire and bring us closer together, however, we seem to be growing apart in an unhealthy fashion. Studies now show the unhealthy effects of smartphone technology on our youth (Twenge & Campbell, 2018) and how they may actually compromise our ability to smile and connect with each other (Kushlev et al., 2019). Beyond any scientific field's goals, it is imperative now more than ever, to rekindle the spark of curiosity and wonder in humanity's youth and find ways to help us to reconnect. In addition, interest in careers in astronomy and other STEM (science, technology, engineering, and mathematics) fields may be waning (Akram et al., 2017; Falk et al., 2016; Osborne et al., 2003; Tröbst et al., 2016) in some developed countries along with the youth's proficiency in pursuing them.

The rapid technological advancements and deepened cosmic understanding over the past century, juxtaposed against the backdrop of our current scientific, societal, personal, and environmental challenges, opens a unique avenue, which may offer solutions to both realms. Originating with a core objective of advancing astrophysics through exoplanet research and enhancing astronomy education, the implications of this thesis work may extend beyond its immediate findings. While this thesis research itself does not directly address societal challenges, it does illuminate how astronomical research can be democratic and experienced not just by professionals and citizen astronomers, but also by teachers and students in the classroom. If astronomy is a unifying force for humanity, then perhaps additional work to involve more of humanity in astronomy learning and activities could lay a foundational basis for more positive social changes in our future. If so, maybe we could one day evolve past being merely "wise apes" and into terra sapiens of a "wise Earth" where we truly embrace global sapience over intelligence (Grinspoon, 2016).

1.4 Thesis Summary and Outline

In this thesis, I report the success of the Unistellar Exoplanet Campaign (i.e., UE), which utilized over 1,000 exoplanet observations from 163 citizen astronomers from 21 countries for exoplanet follow-up. Additionally, I detail how the Astronomy Modeling Instruction with Exoplanets education initiative served as a proof of concept to show how out-of-field teachers and public-school students can improve self-efficacy, confidence, engagement, and pedagogy, as well as perform astrophysics and participate in exoplanet observations and analysis. The final research report in the thesis is of the discovery and confirmation of the Transiting Exoplanet Survey Satellite (TESS) single-transit warm and dense sub-Saturn, TIC[1] 139270665 b, which utilized follow-up radial velocity and photometric observations from professional observatories

[1] TESS Input Catalog. The TIC is used to help identify the best targets for two-minute cadence photometry by the TESS instrument.

and the Unistellar citizen science network. Notably, the TIC 139270665 b photometry incorporated observations from 16 high school students.

Chapter 2 offers a literature review that focuses on my primary research areas. These include exoplanet discovery and follow-up and the pivotal role played by citizen science astronomers, as well as the innovative contributions from emerging telescope technologies, specifically the Unistellar citizen science network. Furthermore, Chapter 2 reviews strategies and research for enhancing astronomy and science education using inquiry-based Modeling Instruction classroom experiences that also have potential in advancing contemporary exoplanet research. Chapter 3 presents my inaugural publication in the Publications of the Astronomical Society of the Pacific (PASP), titled "The Unistellar Exoplanet Campaign: Citizen Science Results and Inherent Education Opportunities." Following this, Chapter 4 presents my initiatives in the domain of astronomy and exoplanet education, showcased in the manuscript, "Astronomy Modeling Instruction with Exoplanets: Motivating Science Teaching and Learning in the 21st Century," which is presently under peer-review with the Journal of Science Teacher Education (JSTE). Then, in Chapter 5, my final paper is presented, which is also presently under peer-review, but with the Astronomical Journal (AJ), named "Confirming the Warm and Dense Sub-Saturn TIC 139270665 b with the Automated Planet Finder and the Unistellar Citizen Science Network and AstroReMixEd." Lastly, in Chapter 6, I include a short discussion and summary of this work, and conclusions.

1.5 Research Questions

The preceding can lead to a number of research questions that explore the potential of a network of citizen science telescopes that can benefit modern astronomical research while engaging more people, especially students, in science. In what ways and to what extent is a citizen science exoplanet network (i.e., Unistellar) valuable to the field of exoplanet science, especially for follow-up and confirming long-period exoplanets? Further, in what ways and to what extent can educators and students inexperienced in astronomy improve learning outcomes and engagement through Modeling Instruction Astronomy workshops and pedagogy infused with exoplanet observations and data? Additionally, what insights can researchers gain, or what new questions for future work emerge, regarding our theories on planetary formation and evolution with the discovery and characterization of longer-period exoplanets?

CHAPTER 2: LITERATURE REVIEW

"As our circle of knowledge expands,
so does the circumference of darkness
surrounding it."
-Albert Einstein

2.1 Exoplanet Discovery History and a Current Census

The reach of our human curiosity and discovery combined with our advancements in science and technology has allowed us to uncover one of the most profound realities of our universe—the existence of worlds around other stars, or exoplanets (Seager, 2010). It is truly amazing to think about the confirmed existence of other places in our galaxy and beyond that offer clues to our planetary existence and evolution, but also to consider the potentiality of other worlds like our own possibly with life. The discovery of two exoplanets orbiting a pulsar (Wolszczan & Frail, 1992) and then a Jupiter-sized planet orbiting close to a main-sequence star, i.e., the "hot Jupiter" 51 Peg b (Mayor & Queloz, 1995), helped to launch the field of exoplanets in the 1990s. Subsequent ground and space-based surveys have identified over 5,489 confirmed (see Figure 1, 2) and another 7,404 awaiting confirmation (Institute, 2023)[2]. The field of planet hunting science has exploded and is one of the most active areas of astronomy in the world (Heng & Winn, 2015). However, with hundreds of billions of stars in our galaxy to search, we have likely only uncovered a tiny fraction, optimistically around two to three millionths, of these worlds.

It is important to note that exoplanet discovery has historically been influenced by our observational biases, i.e., larger more massive planets with shorter orbital periods have been easier to detect (Dawson & Johnson, 2018). Initially, the most common discoveries were "hot Jupiters"—massive gas giants closely orbiting their stars—given their ease of detection. However, as the field has matured, the diversity of discovered exoplanets has expanded. Figure 2 showcases the current roster of most confirmed exoplanets. Notably, the majority of these have orbital periods under 100 days. If one adopts a broader definition of terrestrial planets, which encompasses even mega-Earth sizes and masses, it is apparent from the NASA Exoplanet Archive that the tally of exoplanets discovered to date is roughly split evenly between terrestrial and gas worlds. At a time in the not-too-distant past, most discovered exoplanets were gas worlds and with much shorter periods. Even though the diversity of discovered

[2] NASA Exoplanet Archive (Akeson et al. 2013): https://exoplanetarchive.ipac.caltech.edu/ | Accessed on 7 September 2023

exoplanets has evolved, we still have not yet found a planetary system analogous to our own with inner terrestrial rocky worlds and outer gas giants. Further, our planetary formation and evolution models are challenged and refined by the finding of hot and warm Jovian and sub-Saturn or Neptune sized worlds (Dawson & Johnson, 2018; Fortney et al., 2021). Thus, as the field of exoplanetary science grows and brings about new discoveries and expands the census of planets and planetary systems, it can bring forth fresh questions to investigate.

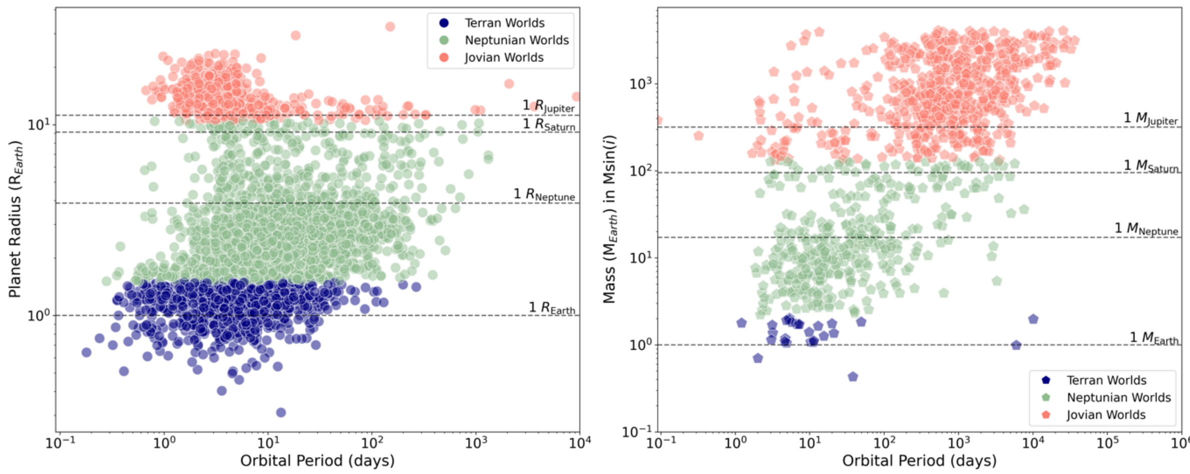

Figure 2. Left panel: Exoplanets by orbital period (days) and radius (R_{Earth}). Right panel: Exoplanets by orbital period and mass (M_{Earth} in Msin(i)). The left panel has all planets that have a transit detection, whereas the right panel is all planets that only have a radial velocity detection. Data was sourced from the NASA Exoplanet Archive[2]. Terran, Neptunian, and Jovian World planet ranges are based off of the work of Chen and Kipping (2017). Total exoplanets plotted across both plots is 5405, which is less than the current total confirmed value since planets with masses >13 $M_{Jupiter}$ (brown dwarfs) and less common detection techniques were excluded.

Since stars are much brighter and larger than the planets that orbit them, and they are very far away from Earth, detecting exoplanets is very challenging. Some of the most successful techniques for detecting an exoplanet are: radial velocity (RV), transit photometry, gravitational microlensing, and direct imaging (Perryman, 2018; Seager, 2010). Thus far, the transit method has been the most successful (Heng & Winn, 2015) and accounts for ~75% of all currently confirmed exoplanets with the RV method in second place with roughly 19% discovered (Institute, 2023). While the transit method has proven highly effective in determining a planet’s size, and RV techniques are adept at discerning a planet’s mass, their combined application considerably enhances exoplanet characterization beyond the capabilities of either method used in isolation. This integrated approach offers insights into additional planetary characteristics, foremost among them being its bulk density (Charbonneau et al., 2000; Perryman, 2018; Seager, 2010). The following will summarize the most common detection techniques, which are also used in this thesis work, i.e., the RV and transit methods.

2.2 Radial Velocity Detection Method

The RV technique for discovering exoplanets was the first successful method in detecting an exoplanet around a Sun-like star. The first confirmed exoplanet around a Sun-like star is usually quoted as 51 Pegasi b, which used high-precision spectroscopy (Mayor & Queloz, 1995). However, some have argued Gamma Cephei Ab, discovered in 1988 (Campbell et al., 1988), but confirmed in 2002 was the first (Hatzes et al., 2003). Since all objects in a planetary system, including the star, will orbit around the system's center of mass, it is possible to detect the motion of the star's orbit around this barycentre, and this could indicate the presence of an exoplanet. This technique is only successful in detecting exoplanets when the orbital inclination of the planetary system is angled at the observer in such a way that the system has some line-of-sight component so that the star's forward and backward motion from the gravitational tug of planets orbiting around the star produces a Doppler shift. Measuring this requires the observer to determine the periodic velocity shift from analyzing the wavelength shift in the star's spectral lines. This velocity (v_{rv}) can be determined with the following equation:

$$v_{rv} = K[\cos(\omega + \nu) + e\cos(\omega)]$$

where K is the semi-amplitude, ω is the argument of pericentre, e is the orbital eccentricity, and ν is the true orbit anomaly. The shape of the RV curve will depend on e and ω (see Figure 3). Incorporating Kepler's 3rd law of planetary motion, K can be determined by the following:

$$K = \left(\frac{2\pi G}{P}\right)^{\frac{1}{3}} \frac{M_p \sin i}{\left(M_* + M_p\right)^{\frac{2}{3}}} \frac{1}{\sqrt{1 - e^2}}$$

where G is universal gravitational constant, P is the orbital period, M_p is the mass of the planet, M_* is the stellar mass, i is the inclination angle of the planet's orbit, and e the orbital eccentricity. It is important to note here that the expression, $M_p \sin i$, only allows researchers to determine the planet's minimum mass since i is unknown. This showcases the importance for combining RV and transit detection techniques to provide researchers with optimal scientific results—a transit will only occur when i is very nearly 90° and, therefore, $\sin(i)$ being very close to being equal to 1 (Henry et al., 2000) will give a much more accurate estimate of the planet's mass.

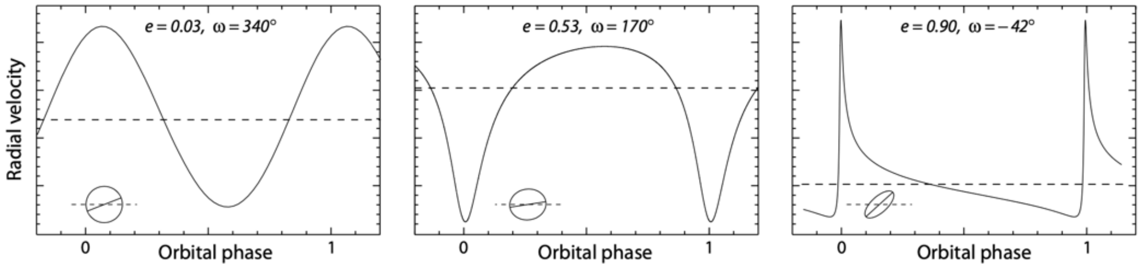

Figure 3. Example radial velocity curves for stars, which shows the dependency on e and ω. The horizontal dashes show systemic velocity and ellipses show geometric positions (Perryman, 2018).

2.3 Transit Photometry Detection Method

One of the most successful methods of detecting exoplanets has been the transit method, which finds extrasolar planets from finding a decrease in brightness from the host star as the planet passes (transits) in front of the star (Heng & Winn, 2015). The search for exoplanets via the transit method was likely first proposed by Struve (1952), but was not successful until many decades later. The use of the transit method was motivated and actualized by its ability to measure the planets size and give researchers a more precise measurement of a planet's mass since a confirmed transit improves the orbital inclination uncertainties from RV observations (Charbonneau et al., 2000). In 1999, two independent teams observed the periodic dip in stellar flux of HD 209458 every 3.5 days to confirm the first exoplanet discovered by transit photometry (Charbonneau et al., 2000; Henry et al., 2000). Figure 4 illustrates the transit light curve for the exoplanet, HD 209458 b. The change in flux, which was roughly 1.5% for HD 209458 b, can be used to determine the planets size, if the star's size is known (see equation below Figure 4, where R_p is the planet radius, R_* the stellar radius, and F is stellar flux).

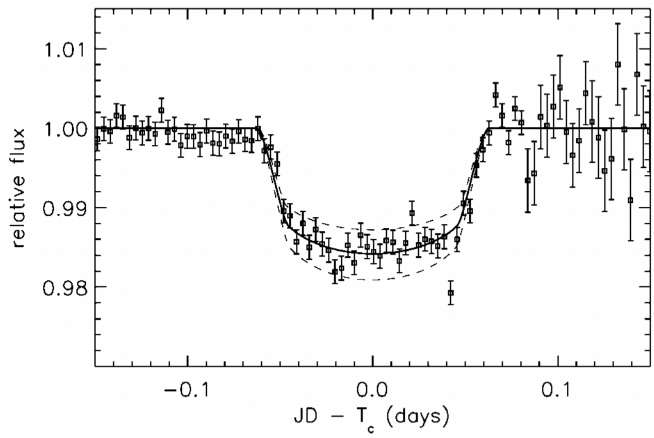

Figure 4. Transit light curve of first exoplanet detected via the transit method, HD 209458 b, showing measured flux versus time. The increased noise on the right of the figure is from increasing atmospheric air mass during observation. From Charbonneau et al. (2000).

$$\left(\frac{R_p}{R_*}\right)^2 = \frac{\Delta F}{F}$$

By observing the transit of HD 209458 b, the RV mass could be better defined and therefore, using the planet size obtained from the transit, Charbonneau et al. (2000) were able to determine HD 209458 b's average density, surface gravity, estimated planet temperature, and the orbital inclination of the planet through fitting of modeled data (Charbonneau et al., 2000). Knowing the planet's density is extremely important so that its characteristics can be estimated (e.g., gas giant or rocky terrestrial world). The orbital inclination angles for HD 209458 b were determined using known integral forms (Sackett, 1999) and applying them in models with upper and lower stellar radius and mass values (Charbonneau et al., 2000). The orbital period of the exoplanet can be obtained from transit photometry if multiple transits of the same depth are observed. Transit data from HD 209458 b gave measurements of its orbital period consistent with its previous RV measurements (P = 3.5 days), but were noted to be less precise than the earlier obtained RV data (Charbonneau et al., 2000).

2.4 Space-based Exoplanet Surveys

Exoplanet discovery was accelerated with the launch of space-based surveys dedicated to exoplanet discovery. Space missions can collect more precise photometric measurements and seem capable of collecting more data than ground-based surveys. One of the most successful exoplanet search missions has been NASA's Kepler space telescope (Borucki et al., 2010; Lissauer et al., 2014), which launched in 2009. Kepler utilized the transit method to discover exoplanets and subsequently caused the number of confirmed exoplanets to skyrocket (Batalha et al., 2013; Borucki et al., 2011; Lissauer et al., 2014; Mullally et al., 2015). Kepler was an exoplanet survey satellite, and although it had a specific objective to find the frequency of Earth-like planets orbiting in the habitable zone of sun-like stars (Heng & Winn, 2015; Lissauer et al., 2014; Lund et al., 2016), its broad objective was to look at many stars at once so that it could discover a very large number of planets in the process (Lissauer et al., 2014). Looking at many stars is important since the probability of detecting a transit across any random star at a random time is very low since an exoplanet must pass in front of its star in almost perfect geometrical alignment with Earth observers (Heng & Winn, 2015; Perryman, 2018). Large space surveys, like Kepler, are thus important to the field of exoplanet science since they can overcome this, and other obstacles faced by ground-based observatories (Heng & Winn, 2015). Unfortunately, for Kepler, some of its reaction stability wheels failed in 2013. Nonetheless, through the ingenuity of NASA engineers, Kepler was repurposed into the "K2" mission, extending its operational life for an additional five years (Howell et al., 2014).

After the Kepler and K2 retirement in 2018, NASA's TESS took the baton (Kempton et al., 2018; Ricker et al., 2014; Witze, 2018). Initially planned for a two-year primary mission, TESS has since moved into its extended mission phase, continuing the comprehensive search for exoplanets in our cosmic neighborhood by conducting the first all-sky survey for exoplanets around bright and nearby stars (Ricker et al., 2014). The TESS mission remains an important workhorse for exoplanet research as it represents an ongoing survey of planets orbiting a range of relatively bright stars amenable to follow-up studies. Its predecessor, Kepler, mainly stared at the same small patch of sky (in Cygnus) during its primary mission covering a field of view (FOV) of roughly 115 square degrees (Heng & Winn, 2015), whereas TESS is mapping most of the sky (~85%) surrounding Earth (Heng & Winn, 2015) and an area 350 times larger than that of Kepler's primary mission (Cartier, 2018). Additionally, TESS has been looking at stars closer and 10 to 100 times brighter than stars surveyed by Kepler, which allows easier follow-ups by ground-based observatories and telescopes (Ricker et al., 2014). Another goal of the TESS mission has been to provide scientists with exoplanet targets for future atmospheric characterization (Kempton et al., 2018) such as with the recently launched James Webb Space Telescope (JWST).

Several other exoplanet survey satellites have launched or are in the pipeline for launch, such as the Characterizing Exoplanet Satellite (CHEOPS), Planetary Transits and Oscillations of Stars (PLATO) (Heng & Winn, 2015), and the Atmospheric Remote-sensing Infrared Exoplanet Large-survey (ARIEL) (Kempton et al., 2018). Since any given star is unlikely to host transiting planets oriented in the correct geometry with Earth, space surveys like these can increase the odds of planet discovery with their ability to observe hundreds of thousands of stars (Borucki et al., 2010; Heng & Winn, 2015; Ricker et al., 2014).

Planetary targets with constrained densities (e.g., rocky “Earth-like” or “super-Earth” planets or highly dense gas giants), will be prioritized for future space missions that plan to perform a spectral analysis on their atmospheres in order to characterize the planet more fully and even attempt to search for life by the detection of biosignatures (Des Marais et al., 2002; Seager et al., 2013). Although not exclusively an exoplanet survey mission, JWST is just now beginning to play an important role in exoplanet characterization and discovery (Gardner et al., 2023) through its capabilities in atmospheric analysis, direct imaging, and transit photometry (Beichman et al., 2014; Gardner et al., 2006; Greene et al., 2016). JWST has already collected spectra from several interesting exoplanets and teams are identifying TESS Objects of Interest (TOIs) for JWST follow up (Hord et al., 2023).

2.4.1 Professional Ground-based Exoplanet Surveys

In addition to space-based surveys, it is important to note that there have been several ground-based surveys that have and continue to make valuable contributions to the field. Notable ground-based surveys include the Kilodegree Extremely Little Telescope (KELT) (Burger, 2023), the Las Cumbres Observatory (LCO) (Observatory, 2023), the MicroObservatory Robotic Telescope Network (Institution, 2023), the Hungarian-made Automated Telescope Network (HATNet) (University, 2023), Wide Angle Search for Planets (WASP) (Group, 2023), the Qatar Exoplanet Survey (Foundation, 2023), and the Transatlantic Exoplanet Survey (TrES) (O’Donovan, 2016).

2.5 Long-Period Planets and Single-Transit TESS Candidates

While short-period exoplanets dominate our current detection statistics, the elusive long-period planets and single-transit TESS candidates present unique challenges and opportunities for exoplanetary research. Our primary detection methods, transit photometry and RV, are both much more sensitive to short-period, large mass, or large sized exoplanets[3]. Short-period exoplanets are generally defined to have periods (P) less than 10 days (d), and long-period planets greater than 10 d (Perryman, 2018). Further, some researchers also make more detailed classifications for orbital period ranges for exoplanets with P < 10 d as "hot" planets (e.g., hot Jupiters) (Dawson & Johnson, 2018), and 10 d < P < 100 d as "warm" planets (e.g., warm Jupiters, Saturns, or giants) (Dong et al., 2014). However, it is important to note that some researchers may define slightly different ranges for these regimes. We can also differentiate between planet size or mass; however, it should be emphasized that when classifying an exoplanet researchers should consider both mass and size when possible since a planet's density can infer important characteristics about the planet's structure and history (Dawson & Johnson, 2018; Fortney et al., 2021; Perryman, 2018).

Although methods vary by researchers, when differentiating by mass and size we may do so in three broad categories: Jovian, sub-Jovian, and super-Earth or smaller rocky terrestrial worlds. The quantitative distinction between these classes is somewhat arbitrary and varies slightly by researchers, but we'll use the work of Beaugé and Nesvorný (2013) to set one example of a baseline reference. Beaugé and Nesvorný (2013) classifies exoplanets as follows:

By mass (M):

- Jovians: $\geq 1.0\ M_J$
- Neptunes or sub-Jovians: $0.03\ M_J \leq M < 1.0\ M_J$
- Super-Earths: $M < 0.03\ M_J$

By size (R):

- Jovians: $R \geq 11\ R_\oplus$
- Neptunes or sub-Jovians: $3\ R_\oplus \leq R < 11\ R_\oplus$
- Super-Earths: $R < 3\ R_\oplus$

Hot Jupiters, marked by early discoveries like 51 Pegasus b and HD 209458 b, unveiled the surprising reality of planetary systems with gas giants in close-in orbits. This discovery challenged our prior convictions about our solar system's typicality. Just as Einstein observed that the expansion of our knowledge will magnify the boundary of the unknown, our growing understanding of exoplanets, catalyzed by hot Jupiters,

[3] Some researchers refer to this as exoplanet detection bias.

compelled researchers to re-evaluate and adapt our models of planetary formation and system evolution.

Even though thousands of exoplanets have been discovered, it is still unknown if there exists an analog of the Solar system, and if how our Solar system has evolved is rare or common (Nielsen et al., 2019; Weiss et al., 2018). Gas giant exoplanets (Jovians and sub-Jovians) whether having a short or long period, offer researchers great value in helping to understand planetary formation, migration, and evolutionary history (Dawson & Johnson, 2018; Fortney et al., 2021) and may inform our model for evolutionary history of our own Solar system. E.g., it has been hypothesized that dynamical interactions between our planets and Jupiter and Saturn likely shaped our system's final orbital architecture (Batygin & Laughlin, 2015; Morbidelli & Crida, 2007; Tsiganis et al., 2005). Gas giant planets also likely contributed to the deliverance of volatiles, affected asteroid/comet impact rates, and the development of life on Earth (Horner et al., 2010; Morbidelli et al., 2000; Zahnle & Sleep, 2006). Planetary migration has also largely shaped the evolution of our Solar system, which has been especially evident with the study of the formation of Jovian and Neptunian trojans (Gomes et al., 2004; Lykawka et al., 2009; Morbidelli et al., 2005).

Long-period exoplanets, such as warm giants, are interesting for exoplanet researchers not only because their intermediate distances are unparalleled to our own Solar system, but because they also offer clues for solving the mysteries surrounding our planetary formation and evolution models. Warm giants may be less common than hot Jupiters, not only because of detection bias, but also since they may require special disk conditions for migration timescales (Dawson & Johnson, 2018). Warm giants also beg researchers to further question their planetary system models since their occurrence rates, eccentricities, and other properties challenge the models based on the more well-known hot Jupiters and their formation and orbital evolution theories Dawson & Johnson, 2018). For example, why did warm giants not migrate closer and become hot Jupiters or remain in orbits farther out? Additionally, their lower equilibrium temperatures of <1,000 K (Fortney et al., 2021) may help researchers better characterize their internal structure since their atmospheres are likely not as inflated as their hot Jupiter counterparts (Fortney & Nettelmann, 2010). These worlds may also be interesting candidates for the search for life for future exoplanet missions capable of detecting exoplanet satellites since there is potential for icy moons to have habitable conditions from tidal conditions, such as what we may have with our own examples with Europa and Enceladus (Scharf, 2006).

Long-period exoplanets are more challenging to detect photometrically because of a lower geometric transit probability and a higher chance of having incomplete photometry for phase folding (Perryman, 2018). For exoplanets analogous to Solar system planets orbiting at several AUs with very long periods *(P > 2 years*), the challenges are heightened even further because of limitations with current exoplanet detection methods and the needed requirement for campaigns with intensive dedicated observations focused on following up candidates well after their initial detection. Their exploration requires precise predictions of future transits, which is a challenge for extended or extra-long-period targets (Dalba & Muirhead, 2016). This challenge exists even for our wide field surveys, such as with TESS, however it is still possible and worth wild to attempt their discovery and confirmation.

Due to TESS's 27-day observational window, many of its long-period exoplanets exhibit only a single observed transit event (e.g., a TESS or TOI single-transit candidate). This limitation means that their orbital periods are largely estimated based on the transit duration alone. Although this approach offers some insights, the accuracy of the estimation is clouded by undetermined orbital eccentricities (Foreman-Mackey et al., 2016; Yee & Gaudi, 2008). Even so, researchers predict that TESS light curves from single transit events may reveal hundreds of potentially long-period exoplanets (Cooke et al., 2018; Villanueva et al., 2019). Additionally, by harnessing RV data, researchers can better anticipate subsequent transits of these single-transit TOIs, as RVs offer insights into the orbital period (Lendl et al., 2019). Further, investigators can employ Bayesian statistical techniques, including Markov Chain Monte Carlo (MCMC) simulations and fitting procedures, which enables the extraction of maximum likelihood values for planetary parameters based on combined RV and single-transit event data (Dawson et al., 2014; Eisner et al., 2020; Foreman-Mackey et al., 2013; Wang, 2023).

Ultra-long-period exoplanets (with periods >100 d) present formidable challenges for study. For TESS candidates, only three ultra-long-period exoplanets have been confirmed (Institute, 2023): TIC 172900988 b (Kostov et al., 2021), TOI-4562 b (Heitzmann et al., 2023), and notably for having largest period, the 2.8 M_J TESS single-transit, TOI-2180 b, with a 261-day orbital period (Dalba et al., 2022). In contrast, warm giants—often characterized by orbital periods between 10 d and 100 d—offer a more accessible and compelling subject of research. Not only are they more feasible for study, but as previously highlighted, warm giants hold significant importance for the advancement of the field. Even so, their extended orbital periods still underscore the intricacies and challenges inherent in their detection (Bakos et al., 2004; Bakos et al., 2013; Pollacco et al., 2006). While the TESS program holds promise for broadening our understanding with its wide-field surveys, the bulk of its findings have gravitated towards shorter period systems (Ricker et al., 2014; Barclay et al., 2018). Single-transit exoplanets, in particular, with their unknown or low probability of next appearance, require more intensive follow-up due to their transit times and orbital periods having little to no confidence levels (Villanueva et al., 2019; Díaz et al., 2020; Hobson et al., 2022).

In the realm of giant exoplanets, sub-Saturns present another layer of complexity and curiosity. These celestial bodies, which can be classified to be between 4.0 and 8.0 $R_\oplus$ in size, are considered rarities (Petigura et al., 2017a; Brady et al., 2018; Addison et al., 2020). Theories around their formation suggest that these sub-Saturns might not have undergone the same runaway accretion of gas seen in more massive planets like Jupiter (Lee & Chiang, 2015; Lee et al., 2018). As researchers aim to shed more light on these mysteries, the global citizen science community stands poised to make a difference, especially given their geographically diverse presence, which may complement professional telescope observations (Cooke et al., 2018). Chapter 5 of this thesis presents the discovery and confirmation of the dense warm sub-Saturn, TIC 139270665 b, which employed professional and citizen science operated instruments to aid in its follow-up. TIC 139270665 b's campaign also highlights the potential of including young students in such work. Further literature and details related to this campaign and impact of citizen science are detailed later in this chapter and in respective chapters later in this thesis.

2.6 The Need for Follow-up Campaigns

Upon initial detection in exoplanet searches, a potential exoplanet is labeled a 'candidate' (Croll, 2012). Subsequent observations are crucial to not only confirm its existence but also to exclude false positives such as eclipsing binaries or transits of low-mass stars (Cameron, 2012; Collins et al., 2018; Heng & Winn, 2015; Lissauer et al., 2014). Confirmation of an exoplanet can be obtained by additional statistically significant observations while utilizing the same, and when possible, different detection methods or statistical arguments to confirm a signal as a planet and not of the false positive nature (Perryman, 2018). Ground-based follow-ups for these candidate exoplanets are crucial complements to the large and costly aforementioned space-based surveys (Bouchy et al., 2008; Morton, 2012). Professional astronomers frequently rely on them as they are cost-effective, convenient (Heng & Winn, 2015), and allow continued observation of targets even after space telescopes have been decommissioned (Santerne et al., 2014). Even so, space-based surveys find many more exoplanet candidates than can be realistically confirmed by follow-up observation campaigns in existence on the ground (Bouchy et al., 2008; Morton, 2012) and the amount of data is too much for professionals alone to handle (Henden, 2011; Kempton et al., 2018; Mousis et al., 2014). For example, TOIs, such as the unconfirmed TOIs reported in Guerrero et al. (2021), are significantly higher than the confirmed TESS exoplanets currently (2023) found in the Exoplanet Archive[2].

With the challenges associated with following up the vast number of current and future planet candidates, it becomes increasingly evident that professional astronomers need not shoulder all the burden. Therefore, it is becoming imperative for the field to embrace collaborative and innovative approaches, and potentially harnessing the collective power and passion of the broader community. This could augment current infrastructure, enhance our understanding of these interesting planetary worlds, help with follow-up needs, and provide additional benefits to society beyond exoplanet discovery alone.

2.7 Citizen Science in Astronomy

Citizen science involves the engagement of typically non-professional volunteers in scientific research. These individuals dedicate their time and resources to gather or analyze data, often utilizing user-friendly tools or online platforms, with the overarching aim of furthering scientific objectives (Bonney et al., 2009). The line between professional and citizen science astronomy, also known as amateur astronomy, is considered by some to be a relatively recent distinction. Historically, many early astronomers pursued other careers, whereas full-time, salaried positions in astronomy have only become widely available over the last century (Henden, 2011). Today, the role of citizen science astronomers working with professional astronomers has been shown to be a very successful venture warranting of future collaborations (Burdanov et al., 2018; Croll, 2012; Mousis et al., 2014). There are many discoveries and useful observations that the citizen astronomer community has contributed to, such as discovery and characterization of asteroids and comets, Solar system planet monitoring, planetary impacts, variable stars, meteor showers, supernovae and gamma-ray bursts, and exoplanets (Marshall et al., 2015). In addition to these contributions, there are several advantages that the citizen science community holds over the professional one.

Since professional ground-based observatories are costly and often have many scientists across the world competing for time to observe, citizen astronomers have an important niche to fill where and when the professionals cannot (Marshall et al., 2015). Additionally, citizen astronomers may have a global distribution and with their own equipment can observe more frequently, be more flexible with their time, and collect data for a much longer period of time (Marshall et al., 2015). Citizen astronomers are interested in helping the professional community because of their passion for the field, but mostly for their desire to contribute to science (Marshall et al., 2015). Additionally, citizen astronomers are often incentivized by being included as co-authors on professionally published articles (Conti, 2016; Henden, 2011).

2.8 Exoplanet Citizen Science

The first confirmed transiting exoplanet, HD 209458 b, although observed by professional astronomers, utilized equipment accessible to most astronomy hobbyists today and demonstrated that small telescopes could participate in this work. When Tim Brown and Dave Charbonneau were preparing to observe HD 209458 b, they calculated from previous RV data that the planet should produce a dip in flux from its host star at around 1% and that this dip could be easily measured by a small telescope (Sincell, 1999). Their observation of this historic transit was done with a 4-inch telescope with a charge-coupled device (CCD) that Brown built in his garage (Sincell, 1999). The previously mentioned ground-based surveys, such as HATNet, WASP, KELT, MicroObservatory, and Qatar have also demonstrated that small telescopes are capable of exoplanet transit photometry.

Since Brown and Charbonneau's historic observation, the professional community has helped to facilitate the collaboration with citizen scientists by working to help organize data analysis opportunities, follow-up candidates, or additional targets for the community to participate in observing (Collins et al., 2018; Fischer et al., 2012). In 2014, one of the best sets of photometric data of a new transiting exoplanet, HD 80606 b, came not from a professional, but from an amateur astronomer using a modestly sized 30-cm telescope in the suburbs of London, England (Mousis et al., 2014). Close to twenty citizen astronomers helped to improve the transit ephemeris of exoplanet, KOI-1257.01, when the *Kepler* space telescope failed from mechanical problems in 2013 (Santerne et al., 2014). Incredibly, exoplanets can also be discovered through an effect of Einstein's theory of general relativity, called gravitational microlensing (Gaudi, 2012) and several citizen astronomers have made significant contributions to the discovery of exoplanets via this technique, which has resulted in first and co-authored publications (Mousis et al., 2014). In addition to citizen scientists observing exoplanets with small telescopes, there have also been successful online data analysis campaigns to engage the general public, such as Zooniverse's Planet Hunters[4] (Simpson, Page, & De Roure, 2014), which successfully identified two new *Kepler* planet candidates from citizen scientist analyzed light curves (Fischer et al., 2012). With Zooniverse's Planet Hunters, citizen scientists were also able to successfully identify 90 new planet candidates and 73 TESS single-transits through rigorous candidate vetting with their online program (Eisner, Barragán, Lintott, et al., 2020). This led to the discovery and confirmation of long period exoplanets that the TESS pipeline often overlooks, such as with the 84-day orbit of the Planet Hunters confirmed planet, TOI 813 b (Eisner, Barragán, Aigrain, et al., 2020).

The democratization of digital imaging, technology, the proliferation of the Internet, and the increased accessibility and affordability of CCD detectors and robotic telescopes has allowed citizen science astronomy efforts to rapidly increase (Gomez & Fitzgerald, 2017; Mousis et al., 2014). In 2014, David Schneider demonstrated this by showing that anyone could build an exoplanet detecting instrument with a do-it-yourself (DIY) setup tracking device and a USD $93 digital single-lens reflex (DSLR) camera from eBay (Schneider, 2014). However, the multifaceted tasks of assembling a tracking system, mastering astrophotography, making informed choices about instruments, cameras, and software, and constructing a telescope primed for exoplanet data collection pose significant challenges to many citizen astronomers. These complexities are amplified for educators, students, or the general public with an interest in astronomy. Figure 5 highlights the DIY instrument alongside a few other examples of advanced telescope setups used by citizen astronomers for exoplanet observations. Assembling these devices demands both technical know-how and time,

[4] https://www.zooniverse.org/projects/nora-dot-eisner/planet-hunters-tess | Accessed on 7 September 2023.

often involving intricate components like electronics, cables, and external computers. Such technical barriers, unfortunately, may have dissuaded numerous astronomy enthusiasts, educators, and students, thereby limiting the potential number of exoplanet transit observations, despite the technology and growing interest in astronomical citizen science in the contemporary era.

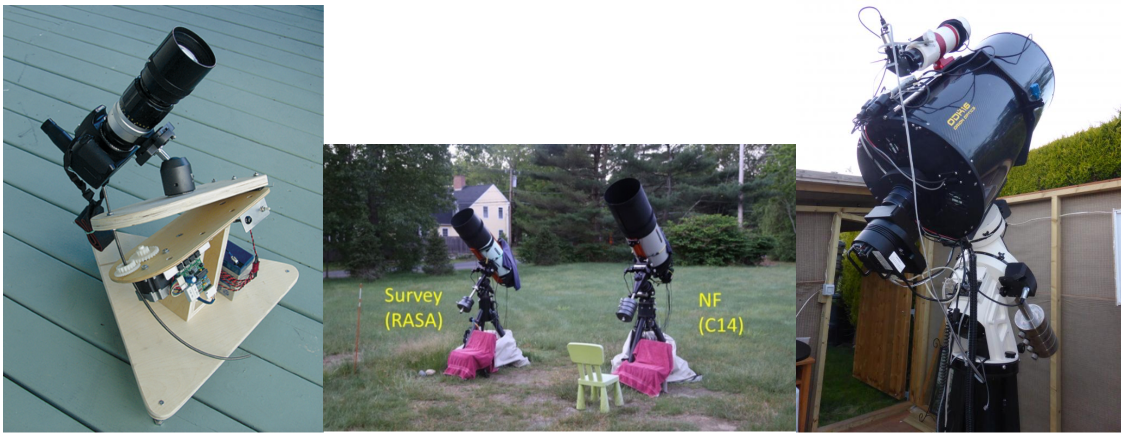

Figure 5. Left: David Schneider's DIY DSLR exoplanet observer (Schneider, 2014). Middle: Example of a professional-amateur (pro-am) setup for exoplanet observations in Sky and Telescope[5]. Right: Another example of a citizen astronomer setup from the British Astronomical Association[6]. The technical setup of these instruments is likely not accessible to most astronomy hobbyists, educators, students, or the general public.

2.9 New Exoplanet Citizen Science Observing Initiatives

As the field of astronomy continues to evolve to include citizen astronomers, several new exoplanet citizen science initiatives have emerged. Among these initiatives, NASA's Jet Propulsion Laboratory (JPL) has launched Exoplanet Watch (EW)[7], a project aiming to enhance the accuracy of professional telescope observations by refining the predicted timing of exoplanet transits (Zellem et al., 2020). Similarly, ExoClock[8] supports the European Space Agency's (ESA) Atmospheric Remote-sensing Infrared Exoplanet Large-survey (ARIEL) mission by refining transit timings using data from citizen astronomers worldwide (Kokori Tsiaras, et al., 2022; Kokori, Tsiaras, et al., 2022). EW encourages a network of small telescopes to engage in follow-up observations of TESS TOIs, not only to validate their existence but also to refine their ephemerides. Through their continued monitoring, it's also possible to unearth the presence of other unknown planets in the system by observing subtle shifts or variations in the timing of their transits, known as transit-timing variations (TTVs).

[5] https://skyandtelescope.org/astronomy-news/first-discoveries-pro-am-exoplanet-survey/ | Accessed on 7 September 2023.
[6] https://britastro.org/2020/exoplanet-transit-imaging-and-analysis | Accessed on 7 September 2023.
[7] https://exoplanets.nasa.gov/exoplanet-watch/about-exoplanet-watch/ | Accessed on 7 September 2023.
[8] https://www.exoclock.space/ | Accessed 7 September 2023.

Recent work by EW has shown that the transit time of an exoplanet (such as a TESS candidate) can become uncertain as a function of time since its last observation, and that small citizen scientist operated telescopes can keep these transit times fresh (see Figure 6). EW encourages citizen astronomers to observe exoplanet transits, reduce and analyze their results, and upload data to the American Association of Variable Star Observers (AAVSO) Exoplanet Database[9] to share with the professional community and help them to achieve scientific goals. EW currently has ~2,000 members on their Slack channel, 2,570 light curves of 355 different exoplanets in their results database, and 24 peer-reviewed EW-related exoplanet publications listed on their website (NASA, 2023). ExoClock has three peer-reviewed exoplanet publications listed, but over 6500 reported exoplanet observations from their citizen astronomer observers[10]. The EW and ExoClock initiatives represent significant advancements in citizen science. However, the hands-on act of observing an exoplanet with an in-situ telescope presents formidable technical hurdles. While remote robotic telescopes like Harvard's MicroObservatory's DIY Planet Search[11] or LCO offer solutions, the on-site observational challenges of in-situ telescopes remain a steep learning curve for most citizen astronomers, educators, students, and the general public.

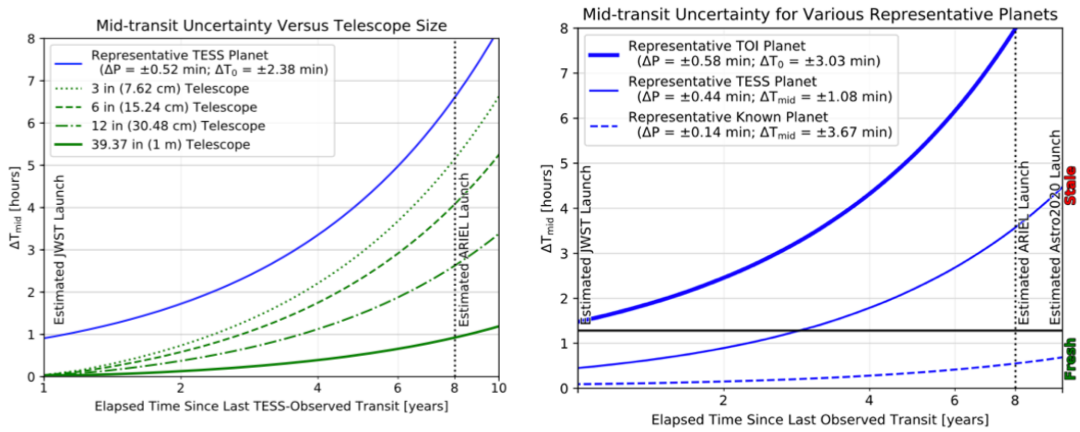

Figure 6. Left: shows how a single transit observation of a representative TESS planet by a 3-inch (7.62 cm) diameter telescope can greatly reduce its 1-year-old mid-transit time uncertainty from 48.05 minutes to just 0.86 minutes. Right: The graph depicts how the accuracy of mid-transit timing for representative TESS and known planets diminishes over time, emphasizing the need for periodic observations, especially after ~3 years, to maintain precision for subsequent large telescope studies (Zellem et al., 2020).

[9] https://www.aavso.org/apps/exosite/ | Accessed on 7 September 2023.
[10] https://www.exoclock.space/database/observations | Accessed 7 September 2023.
[11] https://waps.cfa.harvard.edu/microobservatory/diy/index.php | Accessed 7 September 2023.

2.10 The Unistellar Citizen Science Telescope Network

On 21 May 2019, NASA announced that Unistellar[12], a French-headquartered startup, with offices in San Francisco, California, was among 25 companies selected as semifinalists for NASA iTech[13], a competition of the Space Technology Mission Directorate. Unistellar is reinventing popular astronomy through the development of the Enhanced Vision Telescope (eVscope), a compact mass-market consumer device. The goal of Unistellar is to democratize astronomy by making observational astronomy more enjoyable, accessible, and easier to do than it is today, as well as develop a strong, and new growing interest and participation in astronomical research and citizen science (Marchis et al., 2020).

In July 2017, two years before the NASA iTech began, the SETI Institute and Unistellar initiated a partnership to develop scientific applications for an eVscope citizen science network for asteroid occultations, orbiting comets, and transiting exoplanets. The goal is for the network to allow any owner of an eVscope to receive notifications via the smartphone app on transient events visible in the sky. Scientists can request observations through the network and if the owner of an eVscope initiates campaign mode on the app and accepts the request, the telescope will automatically point to the correct field of view and collect data as the citizen astronomer observes the event in the eyepiece or app. Observational data is collected on the SETI Institute and Unistellar shared cloud-based server, where it is then processed and analyzed by citizen observers and/or professional astronomers (Marchis et al., 2020). See Figure 7 and caption for a schematic of this process. According to Unistellar in early 2020, the network was projected to grow to 10,000 telescopes across the world by mid-2022. They have since exceeded this projection.

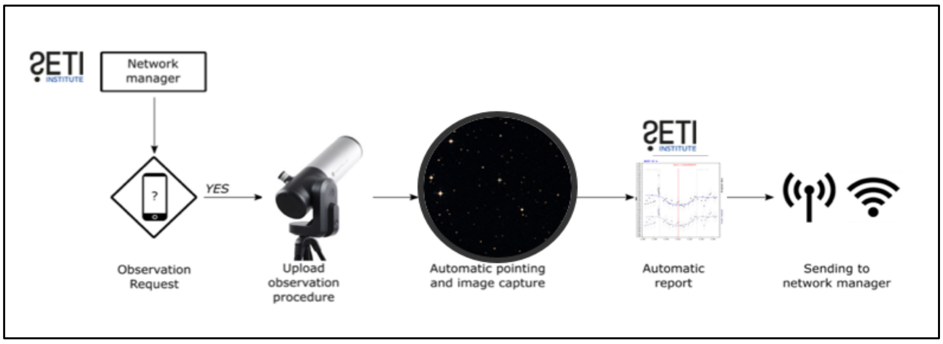

Figure 7. Unistellar "Campaign Mode" schematic. In this example, WASP-43 (V=10.2), was located with eVscope autonomous field detection (AFD), and then the transit of exoplanet, WASP-43b, was detected and a light curve

[12] https://www.unistellar.com/ | Accessed 7 September 2023.
[13] https://www.nasa.gov/directorates/spacetech/itech/nasa-itech-semifinalists-propose-unique-solutions-for-space | Accessed 7 September 2023.

processed (Marchis et al., 2019). A report is then sent to the SETI/Unistellar network. The ultimate long-term goal is to have this entire process fully automated for the end-user so that the telescope and software will automatically produce a light curve and the user can upload their results directly to the American Association of Variable Star Observers (AAVSO), other scientific databases, or use in publications or learning.

Unistellar began delivering eVscopes in 2019 and today over 10,000 are in the hands of citizen astronomers in over 61 countries around the world (see Figure 8). The first eVscope is a 4.5" (11.4 cm) aperture telescope designed to work in urban and countryside environments. It is equipped with a Sony complementary metal-oxide-semiconductor (CMOS) low-light detector IMX224 and is controlled with the Unistellar smartphone app while an on-board computer stacks and processes frames to produce an improved image that is projected in real time through both the eyepiece and app. The improved image is processed through the user initiated "Enhanced Vision" mode within the eVscope app. Enhanced Vision uses a fast-stacking algorithm to continuously combine captured images, correcting for small movements, rotations, and light pollution, resulting in a clearer image displayed in real-time through the eyepiece and app. This proprietary technology replicates the light-collection ability of larger telescopes, offering detailed views of previously unreachable night-sky objects to citizen astronomers (Marchis et al., 2020). Since the first eVscope in 2019, three new models[14] have since released, the eQuinox, eQuinox 2, and eVscope 2.

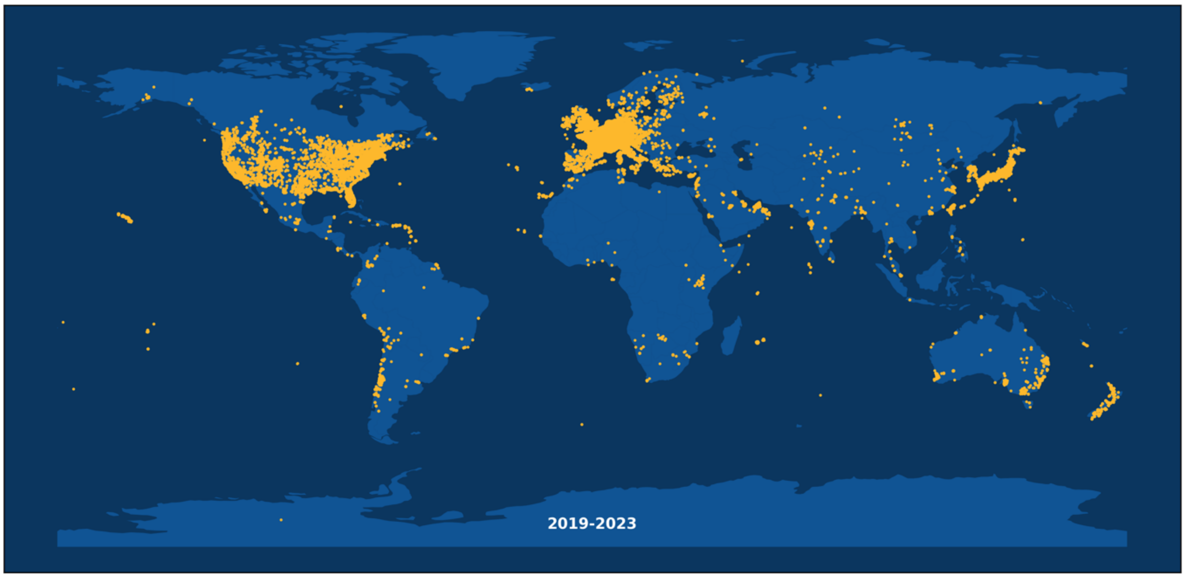

Figure 8. Global distribution of the Unistellar eVscope citizen science network. Each dot marks where Unistellar's "Enhanced Vision" was activated, which gives good indication of the spread of the network since its inception in 2019. Image courtesy of Lauren Sgro, Unistellar.

[14] Camera specifications vary by eVscope model. eVscope/eQuinox 1: SONY IMX224 sensor, field-of-view (FOV) of 37′ X 28′, pixel scale of 1.72″ pixel^{-1}. eVscope/eQuinox 2: SONY IMX347 sensor, FOV of 45′ X 34′, pixel scale of 1.33″ pixel^{-1}.

Differential photometry is also possible by retrieving stacked FITs (Flexible Image Transport System) files from the eVscope. Early testing of the eVscope demonstrated the ability to observe Pluto from light-polluted urban downtown environments (Vmag=14.5) (Marchis et al., 2020), however, more recent reporting states a limiting magnitude of 18.2 in light polluted cities[15].

Unistellar eVscopes are equipped with Autonomous Field Detection (AFD), an algorithm that uses an internal map of ten million stars to accurately pinpoint the telescope at a target; and has key features not yet offered by classical telescopes (see Figure 9). Since the network began in 2019, at least six peer-reviewed publications (Dalba et al., 2022; Pearson et al., 2022; Peluso et al., 2023; Perrocheau et al., 2022; Wang et al., 2022; Zellem et al., 2020) related to exoplanet research have released. More details on the Unistellar exoplanet network, technical specifications, target selection, image processing, and analysis are included in my first-author publication in chapter three (i.e., *The Unistellar Exoplanet Campaign*), which is the inaugural network paper for the Unistellar exoplanet citizen science campaign. Chapter five of this thesis also contains additional details and will likely be the next addition to the peer-reviewed publications that have utilized this network for exoplanet follow-up.

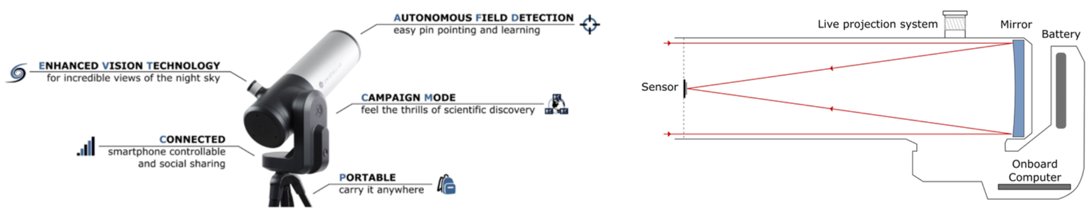

Figure 9. Five key features highlighted [left] and eVscope design [right] (Marchis et al., 2020).

2.11 Examples of Exoplanet Science in the Classroom

Although there are some examples of exoplanet research and education in schools, it is still in its early days. A notable example is Harvard College and Whipple Observatory's MicroObservatory's DIY Planet Search[11], which allows students worldwide to remotely access and observe predicted exoplanet transits and explore data using their online exoplanet lab for teachers and students (Gomez & Fitzgerald, 2017). Multi-hemisphere ground-based survey, KELT, instituted a follow-up network (FUN) named KELT-FUN, which has also facilitated the involvement of students, as well as the citizen astronomer community to help with follow-up false-positive

[15] https://help.unistellar.com/hc/en-us/articles/360012555733-100-times-more-powerful-than-a-standard-telescope-Really- | Accessed 7 September 2023.

identification for their own exoplanet candidates as well as TESS TOIs (Collins et al., 2018; Conti, 2016; Pepper et al., 2018). Another remotely accessible telescope network used for exoplanets in education is LCO, which allowed exoplanet observations from students (Sarva et al., 2020). In 2011, LCO also launched Agent Exoplanet[16], a browser-based tool to train citizen scientists on how to create and analyze exoplanet light curves in a collaborative way (Brown et al., 2013) without the need to perform any coding. Other notable initiatives include the Panoptic Astronomical Networked Observatories for a Public Transiting Exoplanets Survey (PANOPTES)[17] and Sonoma State University's Gamma-ray Optical Robotic Telescope (GORT)[18], though there are likely additional ones as well.

The Zooniverse Planet Hunters citizen science initiative also made its way into some classrooms (Borden et al., 2012; Costello et al., 2012; Simon et al., 2022). Other initiatives, such as the previously mentioned EW (Zellem et al., 2019; Zellem et al., 2020) and ExoClock (Kokori Tsiaras, et al., 2022; Kokori, Tsiaras, et al., 2022) also have included educators and students in exoplanet research and observations.

2.12 Challenges to Current Exoplanets in Education Initiatives

As exciting as many of the aforementioned exoplanet education initiatives are, there are some limitations and challenges. The main drawbacks are that educators and students are not fully "owning" the process for many remotely controlled telescopes and there can also be limitations in observation time, geographic observatory locations, and ability for custom target selection. For example, studies indicate that a sense of "ownership" over the research process plays a vital role in participant motivation and competence (Gould et al., 2006; Marshall et al., 2015). Additionally, several of the aforementioned exoplanet education programs have ended, which often happens when a project grant concludes. According to a 2021 update on their website[19], LCO retired Agent Explorer claiming its reasons due to junk data, old technology, and it being an end of an experiment.

2.13 The Need for Improved Science Education

Students today are entering a world that demands a skillset in science and technology to fulfill the jobs of tomorrow and drive innovation for its future economic success and prosperity (Lavi et al., 2021; National Academy of Sciences, 2007). In a

[16] https://agentexoplanet.lco.global/ | Accessed 10 September 2023.
[17] https://www.projectpanoptes.org/ | Accessed 7 September 2023.
[18] https://phys-astro.sonoma.edu/resources/facilities/gort | Accessed 7 September 2023.
[19] https://lco.global/news/agent-exoplanet-comes-to-an-end/ | Accessed 7 September 2023.

report to President Barack Obama in 2010, his council of advisors on science and technology stated that the success of the United States in the 21st century would depend on the population's abilities in science, technology, engineering, and mathematics (STEM), and that this success directly correlated with the achievement of STEM education in the country (Technology, 2010). Several studies show that US's K-12 performance in STEM education, as well as the number of citizens pursuing STEM careers after high school, is very near the bottom of the international rankings for industrialized nations (National Academy of Sciences, 2007; Technology, 2010). Other studies have shown that US students across all socioeconomic levels score lower in literacy, numeracy, and problem-solving skills than in most countries of the world (Gaze, 2015).

More recent national report cards show little has changed since earlier reports for K-12 science performance in the US (U.S. Department of Education et al., 2019). In contrast, the 2022 National Science Board reported that although the US ranked 7th of 37 for Organisation for Economic Co-operation and Development (OECD) countries, it ranked 25th of 37 for OECD countries in mathematics (Rotermund & Burke, 2021), which seems to further illustrate the Gaze (2015) study that US mathematical reasoning is suffering the most.

In Australia, students score just below average in STEM along with the United States as compared with the rest of the world, according to the 2018 Programme for International Student Assessment (PISA) (Schleicher, 2019). However, the 2016 World Economic Forum listed Australia as leading the region in gaining technology related skills, but there is apparently a 'brain drain' of some of their top students migrating to other countries (Timms et al., 2018). Additionally, only a minority of students in higher education are pursuing STEM fields in Australia, much like in the United States. In a study of all full-time Australian higher education students, the majority of students were studying Management and Commerce (26.5%) or Society and Culture (18.6%), whereas only ~7% of students were studying either Natural and Physical Sciences or Engineering related fields (Marginson et al., 2013).

The US National Research Council (NRC) realized the importance of reforming science education and teaching the scientific process when it drafted its Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas (Council, 2012), which lays the ground for the increasingly adopted, Next Generation Science Standards (NGSS) (Council, 2015). With NGSS, students are encouraged to be involved with developing questions, modeling, critical thinking, and project-based inquiry closely paralleling that of a professional scientist conducting research (Council, 2012, 2015). Having a new framework and research-based initiative to reform science education is only part of the solution; there also needs to be new pedagogies adopted by science teachers and professional development to prepare them how to implement and change their practices (Windschitl et al., 2008).

Alongside nationwide, state, and teacher reforms to STEM education, ensuring student engagement and fostering their intrinsic motivation in the classroom is crucial (Middleton, 1995; Middleton et al., 2003) for the genuine success of any new educational initiative. Research indicates that student motivation and engagement are significantly enhanced when they participate in projects with societal benefits, real-world applications, and authentic, meaningful value (Bell, 2010; Blumenfeld et al., 1991; Fortus et al., 2005). Project-based learning (PBL) such as this not only engages students by allowing them to drive their own learning through inquiry (Bell, 2010), but it also aligns seamlessly with the evolving needs of STEM education, particularly the emphasis on the claim, evidence, reasoning (CER) model (Krajcik & Shin, 2014). This model is especially pertinent for science educators and school administrations in the context of the NRC NGSS.

2.14 Modeling Instruction Pedagogy

Modeling Instruction is an inquiry-based science pedagogy developed by high school physics teacher, Malcolm Wells, and physicist, David Hestenes in the 1980s and 90s (Wells et al., 1995). It aligns with the NRC NGSS initiative and has been supported by the National Science Foundation (NSF) for over 19 years. The Modeling Instruction pedagogy involves students in the process of actually “doing science” through the building, testing, and deployment of conceptual scientific models through data-driven investigations (Megowan-Romanowicz, 2016). Very little lecturing is done in a “modeling” classroom (Megowan-Romanowicz, 2016) since it is a constructivist approach where students are building their own knowledge. Instead, students are “learning by doing” (Dewey, 1916) through engaging collaborative investigations to collect data and uncover a scientific model through public discourse and peer review (Hestenes, 2013; Jackson et al., 2008), much like how a scientist operates.

Students in a Modeling classroom work in groups around a physical or digital whiteboard to develop and apply their models, then in a Socratic-style “board meeting” students learn how to refine their models, and then repeat this cycle (see Figure 10)

Modeling Instruction has been found to significantly improve student scores in reading, writing, mathematics, and higher-order thinking (Hestenes, 2013), and science teachers who go through modeling workshops are more confident in teaching their subjects, even if they do not have a background in that subject (Haag & Megowan, 2015).

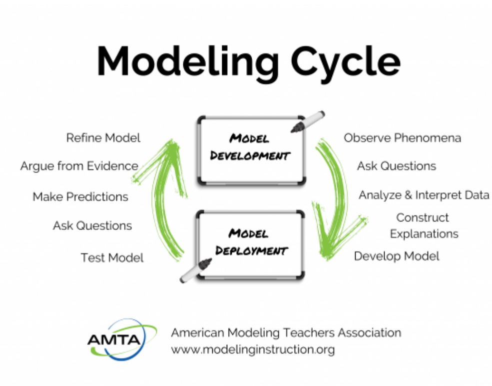

Figure 10. Left: The modeling cycle performed in a Modeling Instruction classroom (image courtesy of the American Modeling Teachers Association). Right: Educators in a professional development workshop engaging in the methodologies and interactive strategies of a Modeling classroom (Image courtesy of Arizona State University).

2.15 G-HOU and Modeling Instruction Astronomy

The Hands-On Universe project (HOU or Global Hands-On Universe, G-HOU), has been successfully involving teachers and their students around the world in astronomy investigations by connecting them with robotic telescopes to collect real astronomical data for authentic research projects (Doran et al., 2012) for decades[20]. One HOU teacher helped acquire data at the Isaac Newton Telescope (Canary Islands) that was essential for the discoveries that led to the Nobel Prize in Physics in 2011 (Carpenter et al., 2018). Further, studies have shown that G-HOU activities can result in significant improvements in student mathematical reasoning (Perazzo et al., 2015). A recent collaboration between Modeling Instruction experts and G-HOU has been established to merge G-HOU's vision and resources with the successful Modeling pedagogy (Carpenter et al., 2018). The first emergence of this partnership occurred in July 2019 at the University of Louisville for the first ever Modeling Instruction Astronomy[21] workshop for teachers, coordinated by the American Modeling Teachers Association (AMTA)[22].

[20] http://handsonuniverse.org/ | Accessed on 7 September 2023.

[21] https://www.eweblife.com/prm/AMTA/calendar/event?event=2022 | Accessed on 7 September 2023.

[22] https://www.modelinginstruction.org/ | Accessed on 7 September 2023.

Chapter 4 of this thesis will detail how a reformed version of the original Astronomy Modeling workshop, titled Astronomy Modeling Instruction with Exoplanets, was realized and used as an intervention in an astronomy education research study with both teachers and students.

2.16 Literature Summary

Since the first humans hypothesized about their possible existence, to the first confirmed detection in the 1990s, exoplanet discovery and characterization has grown into one of the most active areas of astronomy today. By combining transit photometry and RV data, researchers can gain a robust characterization of an exoplanet. Even so, with many thousands of exoplanet candidates being discovered by space-based exoplanet surveys, there is a significant need for help from ground-based observatories to follow-up, confirm, and maintain important parameters of these worlds. Additionally, observation biases limits detection of interesting longer-period exoplanets and the extent of professional research telescopes available is limited in number, available observation time, and location. With new telescope technology, such as with Unistellar eVscopes, comes a potential solution to aid professional exoplanet research and engage the public through novel citizen science initiatives on the ground. Also on the ground, exists an opportunity to combine research-based pedagogical approaches (e.g., Modeling Instruction) with accessible remote and in-situ telescopes (e.g., LCO, MicroObservatory, Unistellar) for exoplanet observations by educators and students.

CHAPTER 3: THE UNISTELLAR EXOPLANET CAMPAIGN

"We are all apprentices in a craft where
no one ever becomes a master."
-Ernest Hemingway, The Wild Years (1962)

3.1 Introduction

The following manuscript paper by Peluso et al. (2023), *The Unistellar Exoplanet Campaign: Citizen Science Results and Inherent Education Opportunities* was published in the *Publications of the Astronomical Society of the Pacific,* in 2023, Volume 135, Number 1043, 015001, and doi:10.1088/1538-3873/acaa58.

The paper summarizes the SETI Institute and Unistellar's citizen science initiative, called the Unistellar Exoplanet Campaign, which we launched in 2020 with 163 citizen scientists across 21 countries and showcases how a global citizen science network can provide high-quality light curves for exoplanet research and lay the groundwork for innovative education initiatives by involving educators and students.

3.2 Published Paper

Publications of the Astronomical Society of the Pacific, 135:015001 (18pp), 2023 January https://doi.org/10.1088/1538-3873/acaa58

The Unistellar Exoplanet Campaign: Citizen Science Results and Inherent Education Opportunities

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Abstract

This paper presents early results from and prospects for exoplanet science using a citizen science private/public partnership observer network managed by the SETI Institute in collaboration with Unistellar. The network launched in 2020 January and includes 163 citizen scientist observers across 21 countries. These observers can access a citizen science mentoring service developed by the SETI Institute and are also equipped with Unistellar Enhanced Vision Telescopes. Unistellar technology and the campaign's associated photometric reduction pipeline enable each telescope to readily obtain and communicate light curves to observers with signal-to-noise ratio suitable for publication in research journals. Citizen astronomers of the Unistellar Exoplant (UE) Campaign routinely measure transit depths of $\gtrsim 1\%$ and contribute their results to the exoplanet research community. The match of the detection system, targets, and scientific and educational goals is robust. Results to date include 281 transit detections out of 651 processed observations. In addition to this campaign's capability to contribute to the professional field of exoplanet research, UE endeavors to drive improved science, technology, engineering, and mathematics education outcomes by engaging students and teachers as participants in science investigations, that is, learning science by doing science.

Unified Astronomy Thesaurus concepts: Astronomy education (2165); Amateur astronomers (34); Exoplanets (498); Transit photometry (1709)

Online material: machine-readable table

1. Introduction

The demand for follow-up observations of transiting exoplanets is larger than ever. The NASA Exoplanet Archive[12] (Akeson et al. 2013) currently reports 3892 confirmed transiting planets and 3937 project candidates yet to be confirmed by ground-based observations by the Transiting Exoplanet Survey Satellite (TESS) mission (Ricker et al. 2014). Some estimate that over 10,000 exoplanets are predicted for discovery by TESS (Barclay et al. 2018), and there are still over 3000 candidates (NASA Exoplanet Archive) needing follow-up from Kepler and Kepler Space Telescope "Second Light" (K2). Follow-up observations are important for unconfirmed exoplanets to determine if candidates are false positives, such as caused by eclipsing binaries, or transits of low-mass stars (Cameron 2012; Lissauer et al. 2014; Heng & Winn 2015; Collins et al. 2018).

For confirmed planets, regular reobservations by ground-based systems are necessary to keep their orbital ephemerides updated, because small uncertainties in periods and past transit epochs can compound over each orbit and cause predictions of

[11] See Appendix for full list of citizen scientist names.
[12] https://exoplanetarchive.ipac.caltech.edu/ (accessed 2022 September 10).

future transit times to have uncertainties up to several hours (Kokori et al. 2022a, 2022b; Zellem et al. 2020). Transit time uncertainties complicate the planning of new observations to do in-depth characterization of the planets and lead to wasted time for large telescopes already in high demand (e.g., 8–10 m telescopes, Hubble Space Telescope, James Webb Space Telescope (JWST), and future 30 m class telescopes).

The need for robust ground-based exoplanet photometric follow-up campaigns combined with the ever-growing catalog of candidate exoplanets creates challenges for the current infrastructure of conventional observing facilities for follow-up observations (Morton 2012). To conduct important photometric follow-ups of candidate exoplanets, ground-based telescopes are advantageous because they are both more economical and convenient than space-based telescopes (Heng & Winn 2015), and they can look at targets of interest when there are problems with their space-based counterparts (Santerne et al. 2014).

While there is not enough time available on large ($\geqslant$1 m), professional-grade telescopes to conduct the photometric follow-up observations needed for exoplanet studies, citizen scientists using smaller telescopes are fully capable of collecting these data. Since the first confirmed transiting exoplanet, HD 209458b, was discovered in 1999 (Charbonneau et al. 2000), the democratization of digital imaging, technology, the Internet, widespread affordability of charge-coupled device and complementary metal-oxide semiconductor (CMOS) detector sensors, and availability of robotic telescopes has caused citizen science astronomy efforts to increase rapidly (Mousis et al. 2014; Gomez & Fitzgerald 2017). Although HD 209458b was observed by professional astronomers, they utilized equipment accessible to most astronomy hobbyists; they used a $\sim$10 cm telescope with a camera that Tim Brown built in his garage (Sincell 1999). This represents some of the first evidence to show that small telescopes can contribute to this work.

Since this discovery, several professional telescope networks have shown that small telescopes with "off-the-shelf" parts are capable of exoplanet transit science, such as the Hungarian-made Automated Telescope Network[13] (Bakos et al. 2004; Hartman et al. 2004), Wide Angle Search for Planets (WASP)[14] (Pollacco et al. 2006), Kilodegree Extremely Little Telescope (KELT)[15] (Pepper et al. 2007), Las Cumbres Observatory (LCO)[16] (Brown et al. 2013; Nair et al. 2020), Harvard and Smithsonian MicroObservatory Robotic Telescope Network[17] (Fowler et al. 2021), and Qatar Exoplanet Survey[18] (Alsubai et al. 2011, 2013). Although not specifically built for exoplanets, Dragonfly Telephoto Array[19] (van Dokkum et al. 2014) has also made quality contributions to science of similar caliber.

For exoplanet science, citizen scientists can collaborate with professionals in their searches (e.g., Henden 2011; Fischer et al. 2012; Kokori et al. 2022a, 2022b; Mousis et al. 2014; Baluev et al. 2015; Marshall et al. 2015; Zellem et al. 2019, 2020). These authors reviewed the contributions of citizen science in the study of exoplanets, and this paper intends to build on their seminal work and others. There are several citizen science programs that have provided meaningful results to the Kepler, K2, and TESS exoplanet missions. Programs, such as Zooniverse's Planet Hunters (Eisner et al. 2020), which is a popular online exoplanet data analysis campaign available to the general public (Schwamb et al. 2013; Wang et al. 2013; Simpson et al. 2014), have reported over 34,957 volunteers and 27,937 exoplanet classifications.[20] Planet Hunters successfully identified two new Kepler exoplanet candidates from citizen scientist-analyzed light curves (Fischer et al. 2012). Other programs, such as Exoplanet Explorers[21] (Christiansen et al. 2018), the KELT Follow-Up Network (Collins et al. 2018), NASA's Exoplanet Watch[22] (Zellem et al. 2020), and ExoClock[23] (Kokori et al. 2022a, 2022b), have also made valuable contributions to the field of exoplanet science. Some have even included students in the work (Collins et al. 2018; Edwards et al. 2020). Observations by LCO (Sarva et al. 2020) and the MicroObservatory's Harvard DIY Planet Hunters[24] projects (Fowler 2019; Mizrachi et al. 2021) have also generated photometric results contributing to the mentioned initiatives (e.g., Exoplanet Watch) and have involved students.

A network allowing junior observers to actively participate in the exciting field of exoplanet science may make an impact in science education by teaching with science that is current, inspiring, and fun (e.g., Global Hands-On Universe (GHOU) showed students preferred astronomy over other sciences and became interested in science, technology, engineering, and mathematics (STEM) careers[25]). The young generation of today is entering a world that demands a skill set in science and technology to fulfill the jobs of tomorrow and drive innovation for its future economic success and prosperity (National Academy of Sciences, National Academy of Engineering, & Institute of Medicine 2007; Lavi et al. 2021). However, in many developed countries (e.g., USA and Australia), students score just below average in STEM as compared with the rest of the world, according to the 2018 Programme for International

[13] https://hatnet.org/operations.html
[14] https://www.superwasp.org/about/
[15] https://keltsurvey.org/
[16] https://lco.global/
[17] https://mo-www.cfa.harvard.edu/MicroObservatory/
[18] https://www.qatarexoplanet.org/
[19] https://www.dragonflytelescope.org/
[20] https://www.zooniverse.org/projects/nora-dot-eisner/planet-hunters-tess
[21] www.exoplanetexplorers.org
[22] https://exoplanets.nasa.gov/exoplanet-watch/about-exoplanet-watch/overview/
[23] https://www.exoclock.space/
[24] https://waps.cfa.harvard.edu/microobservatory/diy/index.php
[25] https://handsonuniverse.org/tryme/?page_id=2707–

Student Assessment (Schleicher 2019). Common knowledge among public school teachers (Bartlett et al. 2018; Oliveira 2019) is that concepts related to astronomy, space, and the search for extraterrestrial life excite students; therefore, exoplanet science may serve as a "jumping board" into science for many students who may otherwise not show interest. Additionally, many studies show that learning science by doing it and project-based learning initiatives (e.g., exoplanet observations) are more effective and motivating for students (Blumenfeld et al. 1991; Fortus et al. 2005; Jackson et al. 2008; Bell 2010; Jenkins 2011; Green & Medina-Jerez 2012; Hestenes 2013).

The potential for citizen scientist contribution to exoplanet science is high and has exciting implications for STEM education. However, the ability for nonprofessional astronomers to observe and contribute their own collected data for exoplanet research or education has been largely out of reach due to high costs and high levels of technical expertise required to run, build, or operate observing equipment, as well as limited access and ability for observing customization with remotely available robotic telescope networks.

Unistellar Exoplanet (UE) Campaign, which provides professional mentoring and curated targets, can make meaningful contributions to exoplanet research (e.g., photometric data for monitoring transit times and confirming traditional and long-period exoplanets) while also engaging nonprofessionals and students in this exciting work. This paper reports early results and future prospects for UE from 2020 January through 2022 August. We begin by clarifying the science and education goals (Section 2), then we detail UE's network and its observation methods (Section 3). Next, we outline the methods for image processing and photometry (Section 4), report the overall campaign results from 1018 exoplanet transit observations, and highlight three significant transit light curves (Section 5). Finally, we discuss plans for TESS long-duration planet confirmations and STEM education initiatives (Section 6).

2. Science and Education Goals of the Unistellar Network's Exoplanet Campaign

2.1. Meeting the Demand for Follow-up and Monitoring

One possible solution to the infrastructure challenges for more generalized exoplanet follow-up confirmation and monitoring is to engage citizen scientists. Large exoplanet survey missions require the assistance of ground-based follow-ups, specifically from the amateur astronomy citizen science community, because it is logistically impossible for the professional community alone to handle the volume of incoming data (Henden 2011; Mousis et al. 2014; Kempton et al. 2018). In addition to follow-up transit observations, UE plans to search for new transits by observing the large collection of planets that have currently only been observed through radial velocity (RV) and are unknown to also have a transit (Kane et al. 2011).

If current trends in the exoplanet field persist, the rate that candidate planets are identified will increase, and even more help from follow-up ground-based observations will be needed. One of the primary goals of UE is to help fill these gaps and be part of that help from elsewhere through a general monitoring and follow-up of candidate, known, and RV exoplanets from its large global network of citizen astronomers.

2.2. Short-period Planet Ephemeris Maintenance for Future Planet Characterization by Large Telescopes

Dedicated citizen astronomers with backyard telescopes have been working to help confirm exoplanet candidates by ruling out false positives for years (e.g., the American Association of Variable Star Observers' (AAVSO) exoplanet division). Inspired by the growth, interest, and ability of citizen astronomers to contribute to exoplanet science, NASA instituted its Exoplanet Watch group (Zellem et al. 2020) to train and coordinate citizen astronomers for ephemeris maintenance: to keep transit times fresh for space-based observing missions, such as for TESS, JWST, and for future missions, such as space telescopes dedicated to the direct imaging of exoplanets as recommended in the Decadal Survey on Astronomy and Astrophysics 2020 (National Academies of Sciences, Engineering, Medicine 2021). ExoClock (Kokori et al. 2022a, 2022b) is a similar initiative but more focused on supporting the European Space Agency's upcoming Atmospheric Remote-sensing Infrared Exoplanet Large-survey mission.

The UE science team will not only work to contribute to ephemeris maintenance initiatives (Ikwut-Ukwa et al. 2020; Zellem et al. 2020; Battley et al. 2021; Kokori et al. 2022a, 2022b) with the observations from its citizen astronomers, but it will work with the network to help confirm exoplanet candidates by ruling out false positives and contribute photometric data to public archives, such as the AAVSO Exoplanet Database.

2.3. Long-period Planet Confirmation and Period Constraints

By taking advantage of UE's global distribution of telescopes, the science team initiated a program to observe and characterize long-period Jupiter-mass exoplanets ($P > 100$ days) in 2020. Those long-period planets, such as HD 80606b (e.g., Naef et al. 2001; Moutou et al. 2009; Winn et al. 2009), are interesting because they may be a proto-hot Jupiter, i.e., in its early phase of becoming a hot Jupiter ($P < 10$ days) (see Wu & Murray 2003; Fabrycky & Tremaine 2007; Socrates et al. 2012; Dalba et al. 2021). Alternatively, they could be stabilizing in a wide orbit after migrating through their systems like Jupiter did (Goldreich & Tremaine 1980;

Wu & Murray 2003; Baruteau et al. 2013; Dalba et al. 2021). Using its broad geographic coverage to observe long-period exoplanets like these, the UE science team has planned to focus some of its work on studying these types of systems. Results from a multi-time-zone UE observation of HD 80606b are in press (Pearson et al. 2022) and summarized in Section 5.3.4.

The network is also designed to focus on the detection and measurement of the timing for follow-up transits of exoplanet candidates that have only had a single or double transit detected by TESS, so-called solo transits and duo transits, respectively. More details on how UE will observe these long-period exoplanets are provided in Section 6.1.

2.4. STEM Education, Outreach, and Democratization of Science

The UE community includes a growing number of teachers, students, and instructors from K–12 schools, colleges, and informal education centers (e.g., science museums). The simplicity and accessibility of Unistellar telescopes make them more accessible to the general public. The diversity of UE gives it the potential to not only improve STEM education and outreach but also make strides toward the democratization of science and astronomy at large (as evidenced by this paper's author list). The education and science democratization goals for the UE campaign will be discussed in a future paper (D. O. Peluso et al. 2022, in preparation) but are included here as it is one of UE's major goals.

3. Observational Methods

3.1. Unistellar Enhanced Vision Telescopes

In early 2019, the SETI Institute partnered with the Enhanced Vision Telescope (eVscope) manufacturer, Unistellar, to commence the creation of the Unistellar Citizen Science network.[26] This network currently consists of >10,000 Unistellar telescopes in over 61 countries (Figure 1).

Since its inception, Unistellar has developed three different digital telescope models: eVscope 1, eVscope 2, and eQuinox. Similar in size to Brown's ~10 cm telescope (Sincell 1999), all three eVscopes are 11.4 cm Newtonian-style telescopes (focal length = 450 mm; magnification of 50×) with a very-low-noise high-quantum-efficiency CMOS digital image sensor at the focus. The eVscope is controlled by an operator who is physically close and uses a smartphone or tablet using the Unistellar app linked by Wi-Fi to the Unistellar telescope onboard computer. The eVscope was developed specifically for use by amateur observers who live in light-polluted urban and countryside environments (Marchis et al. 2020).

The portability of eVscopes makes them well suited for citizen scientists traveling for location-specific observing events. The eVscope's equipped Sony CMOS low-light detector sensor (IMX224 for the eVscope and eQuinox and IMX347 for eVscope 2) at its prime focus combined with Unistellar's Enhanced Vision technology (a proprietary algorithm that stacks images and reduces noise and light pollution) allows users to observe faint objects even in light-polluted urban skies (Marchis et al. 2020). The eVscope and eQuinox detector provides a $27' \times 37'$ field of view (FOV) and plate scale of $1.72'' \text{pixel}^{-1}$. The eVscope 2 detector provides a $34' \times 47'$ FOV and plate scale of $1.33'' \text{pixel}^{-1}$.

3.2. Observer Network

With 10,000+ eVscopes, Unistellar's Citizen Science telescope network holds the potential to be the largest coordinated network of telescopes in the world. More importantly, this network is mostly operated by citizen scientists. Unistellar focuses its network on additional scientific programs, like occulting asteroids, planetary defense, comets, transients, and transiting exoplanets. Unistellar has over 500[27] eVscope owners that are registered to participate in exoplanet campaigns.

The broad geographical distribution of UE allows for almost continuous coverage of the night sky, enabling long-duration observations of an exoplanet target beyond the span of a single night or of that target's visibility from a single location. For short-period exoplanet ephemeris maintenance, UE allows coverage for observing the >250 short-period ($P < 20$ days) TESS Objects of Interest (TOI) candidates (from ExoFOP-TESS) and many of the confirmed exoplanets on the NASA Exoplanet Archive. For long-period exoplanet confirmations, UE can obtain multi-time-zone observations.

The uniform optics and cameras of each eVscope simplify the combination of data from multiple telescopes. This allows for greater precision when combining observer data because photometric and transit timing precision in principle improves, proportional to the square root of the number of simultaneous flux measurements obtained (i.e., as $N_{\text{obs}}^{1/2}$).

UE also allows the effect of localized weather to be mitigated by providing redundant stations throughout its global network. Additionally, because citizen scientists conduct those observations, the small science team of SETI Institute astronomers does not need to spend every night observing or competing for observing time, which frees them to coordinate science goals and analyze network results.

UE has many strengths, but it also has limitations. Although capable of detecting large, Jupiter-sized exoplanets, the

[26] https://www.seti.org/press-release/seti-institute-signs-mou-unistellar-develop-and-enhance-citizen-science-network

[27] As of 2022 September 10, there are 552 members in UE's dedicated Slack communication channel.

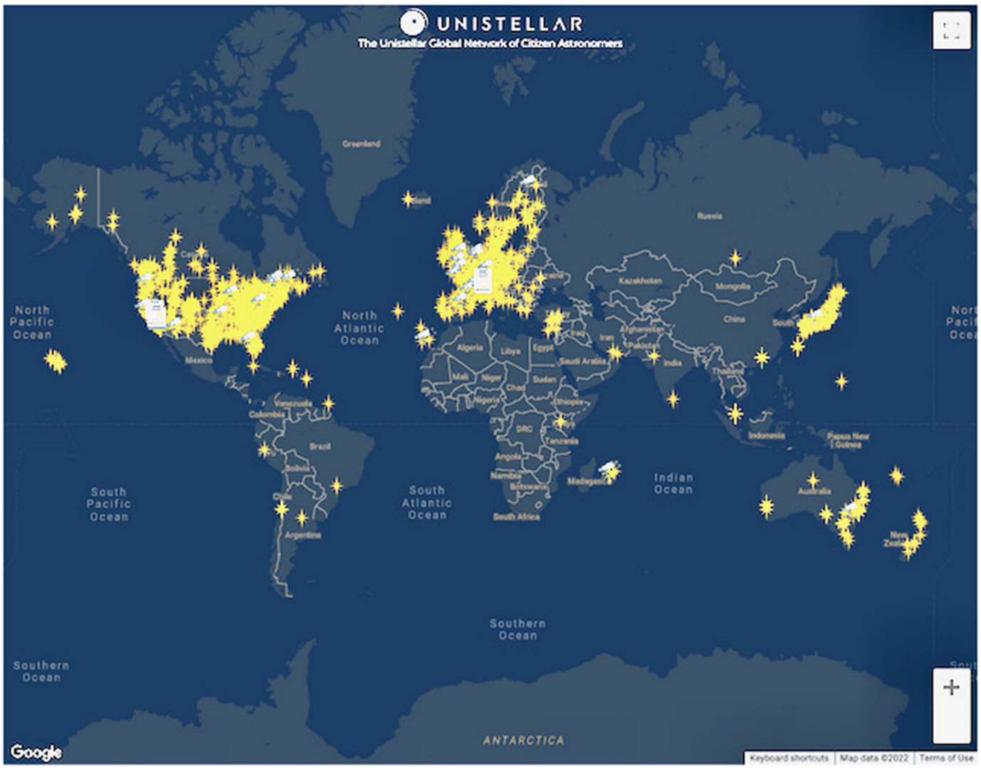


Figure 1. Unistellar Citizen Science network. Yellow dots represent Unistellar eVscope users. Credit: Unistellar.

Unistellar telescopes have a relatively small aperture and therefore have constraints in light-gathering power, hence sensitivity, challenging its ability to detect smaller-sized exoplanets. Because UE observers are mainly located in urban and suburban areas, they often may not have the best sky conditions for astronomical observations. Additionally, even though our UE citizen astronomers are very capable, as compared to professional observational astronomers, there may be some margin of error.

After observing an event, should they wish, Unistellar eVscope owners may request their FITS files from observations from the science team. As outlined in more detail in Section 3.4, observers must upload their data to the science team's cloud-based servers for processing before they can then be sent to an observer who requests to receive data.

3.3. Transit Target Selection

For exoplanet target selection, the UE science team primarily makes use of the Swarthmore College Exoplanet Transit online database[28] (Jensen 2013) but also references NASA's Exoplanet Archive. Several members of the science team have also joined the NASA TESS Follow-up Observing Program (TFOP) Working Group Sub Group (SG), SG1, and they have provided the network with special targets while also adhering to TESS TFOP SG1 guidelines. When possible, the science team prioritizes targets for UE that could help provide meaningful data for the TESS science team by designating either special SG1 targets or publicly known TOI. The UE science team also selects well-known non-TESS specific transiting

[28] https://astro.swarthmore.edu/transits/transits.cgi

exoplanets from the NASA Exoplanet Archive to test instrument capabilities and for observer practice and education.

At first, targets were mainly selected for North American and European citizen scientists because those regions hosted the majority of eVscope owners, but as the network grew targets for observers located around the world were selected. To date, there are nine geographic regions for which exoplanet targets are selected and broadcasted to eVscope users: Europe, South America, North America, Middle East, South Asia, East Asia, Africa, Japan, and Oceania.

Initial testing of the eVscope by Unistellar indicated that the instrument could observe target stars with a transiting exoplanet around 12th visual magnitude (*V*mag) and transit depth >1% (Marchis et al. 2019), so similar targets were selected for the network in the early stages of testing. However, since the preliminary tests in early 2019, the science team has developed a range of criteria for selecting standard transit targets (e.g., TOI) for detection by single eVscopes. This comes from the team's testing of eVscope sensitivity and information gathered from observations to date.

These include:

1. Host star $V = 5.0$–13.5 mag. Target star signal-to-noise ratio (S/N) $\sim$ 10 for $V = 13.5$ and >100 for $V = 7.5$ in single images with a typical integration time of 3.97 s and gain of 30 dB (0.0719 e-/ADU for eVscope 1; 0.0340 e-/ADU for eVscope 2).
2. Transit depth $\gtrsim$1.0%.
3. Transit duration $\lesssim$6 hr to stay within the eVscope image storage limits and battery life limitations and to avoid twilight hours (unless multiple eVscopes are being used to stitch together observations >6 hr).
4. Target is observable for $\gtrsim$30 minutes before/after the transit start/end time (with the sky darker than 12° twilight) to measure an out-of-transit photometric baseline for light-curve normalization.
5. Target elevation does not exceed 85° during the planned observation (to keep telescope tracking stable).

Typically, a suitably high S/N reference star for performing differential photometry will be in the FOV, but the science team may adjust exposure settings or the FOV centering for edge cases near *V* upper and lower limits. For long-period planets with durations >6 hr and planets with highly uncertain periods that have large windows of observation or planets with depths <1.0%, the science team attempts to obtain observations from multiple eVscopes. Staggering the observations in time allows for a larger observation window, and combining photometry from multiple telescopes over the same period improves the total precision and sensitivity (see Section 5).

3.4. Network Communication and Observing Strategies

The UE science team experimented with a variety of tactics to encourage eVscope citizen scientists to observe exoplanet transits with their instruments. The first official communication began in 2020 January with a series of blogs posted on the SETI Institute blog website, Cosmic Diary. These were shared by both the Unistellar and SETI Institute social media channels. These blog posts sparked the beginning of UE, but communication later evolved into updated monthly posts on the Unistellar website Citizen Science page and through a dedicated Unistellar Citizen Science Slack channel (see slack.com/about). Although the bulk of communication is now done through Unistellar's website and Slack channel, the science team continues to write blogs and posts on social media for important campaigns or to highlight success from the Citizen Science network.

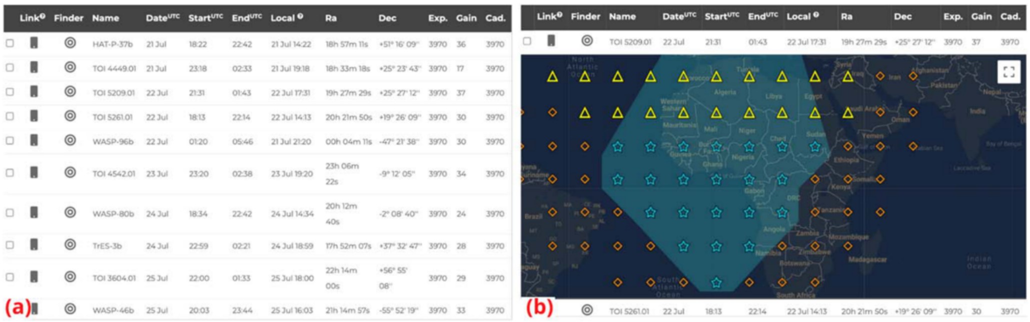
Any Unistellar eVscope user can join the Unistellar Citizen Science channel. As of 2022 August, the Unistellar Slack channel had 1350 members. There are 26 sub-channels on the Unistellar Slack channel for various citizen science missions, such as comet tracking and observation, planetary defense, asteroid occultations, various satellite-tracking missions (such as the JWST orbit) (Lambert et al. 2022), and exoplanet transits and data reduction help. There are also additional private education channels for educators and students, where they are encouraged and trained for exoplanet observations as well as where developed educational materials are shared.

In late 2020, the science team created the exoplanet communication channel, #exo_transit, on the official Unistellar Slack Citizen Science workspace, and in 2021 March the science team implemented an exoplanet education page directly on the Unistellar website[29] for UE's citizen scientists. The exoplanet page includes guides on exoplanet science, a "how to" guide for observing exoplanets with the eVscope, an interactive global target selection menu that allows users to find targets by geographic region (see Figure 2), and recent results from the network.

The network's exoplanet transit observing protocol is generally the same regardless of the target. Approximately 1 hr before the transit ingress is predicted to begin, the observer sets up the eVscope in a location with a clear view of the target star. Over 5–10 minutes, the observer turns on the eVscope, connects it wirelessly with the app on a smartphone or tablet, activates the orientation of the telescope (based on a proprietary fast plate solving algorithm), and then checks the telescope's collimation and focus by observing a bright star and adjusting them as needed. Figure 3 illustrates the various menus that observers may use in setup and use.

After the initial setup and alignment, citizen astronomers then slew to the target by using a URL-like "deep link" that

[29] https://unistellaroptics.com/citizen-science/exoplanets/



Link	Finder	Name	Date UTC	Start UTC	End UTC	Local	Ra	Dec	Exp.	Gain	Cad.
		HAT-P-37b	21 Jul	18:22	22:42	21 Jul 14:22	18h 57m 11s	+51° 16′ 09″	3970	36	3970
		TOI 4449.01	21 Jul	23:18	02:33	21 Jul 19:18	18h 33m 18s	+25° 23′ 43″	3970	17	3970
		TOI 5209.01	22 Jul	21:31	01:43	22 Jul 17:31	19h 27m 29s	+25° 27′ 12″	3970	37	3970
		TOI 5261.01	22 Jul	18:13	22:14	22 Jul 14:13	20h 21m 50s	+19° 26′ 09″	3970	30	3970
		WASP-96b	22 Jul	01:20	05:46	21 Jul 21:20	00h 04m 11s	-47° 21′ 38″	3970	30	3970
		TOI 4542.01	23 Jul	23:20	02:38	23 Jul 19:20	23h 06m 22s	-9° 12′ 05″	3970	34	3970
		WASP-80b	24 Jul	18:34	22:42	24 Jul 14:34	20h 12m 40s	-2° 08′ 40″	3970	24	3970
		TrES-3b	24 Jul	22:59	02:21	24 Jul 18:59	17h 52m 07s	+37° 32′ 47″	3970	28	3970
		TOI 3604.01	25 Jul	22:00	01:33	25 Jul 18:00	22h 14m 00s	+56° 55′ 08″	3970	29	3970
		WASP-46b	25 Jul	20:03	23:44	25 Jul 16:03	21h 14m 57s	-55° 52′ 19″	3970	33	3970

Figure 2. Screen captures from the Unistellar Exoplanet Citizen Science website. In addition to learning about how exoplanet science works and the directions on how to use an eVscope for exoplanet detection, users can select curated exoplanet targets from a drop-down menu by selecting one of nine global geographic regions. The phone icon on the left of each row represents the "deep link" that users can easily click on to autofill the observation information for an exoplanet target. (a) An example of transit predictions for Africa and (b) a Google KML map showing visibility of transit observations for the region (different colors/shapes represent visibility, e.g., blue stars represent full visibility, orange diamonds represent partial visibility, and yellow triangles indicate that the target is visible but may be difficult for the telescope to track at high altitude in the sky).

Figure 3. Screen captures of the V.1 of the Unistellar app. (a) Main controls and image viewing, (b) target selection, (c) citizen science mode, (d) saved images, and (e) user settings menu.

automatically populates all of the observation settings into the smartphone app: celestial coordinates (i.e., R.A. and decl.), exposure time, gain, duration, and a new "cadence" setting (to allow for pauses between exposures). Alternatively, observers may manually enter the target's R.A. and decl. and other settings for more custom use. The science team has created an "exposure calculator" that is made available to exoplanet observers on Unistellar's Slack channel and calibrated to reference observations, and that determines eVscope exposure settings a priori based on target V magnitude and expected sky brightness.

Observers take "dark" frames for calibration immediately after the science sequence using the same exposure settings and gain settings as the science images. After finishing their exoplanet observation, they use the app to connect their eVscope to a local Wi-Fi network and upload their recorded data to the Unistellar cloud servers for data reduction, processing, and analysis by the science team. An average

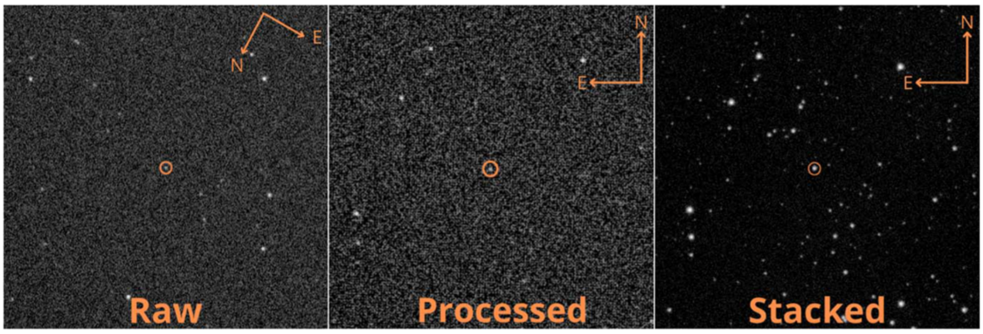


Figure 4. The observation was done in a Bortle 7 sky in a small city near Caen, France with a relatively high air mass between 2.4 and 1.9. The raw FITS file had an exposure of 3.970 s and gain of 0.0640 e−/ADU (31 dB). The processed image was dark subtracted, and the stacked image is of 30 frames with 119.1 s integration time. The raw and single processed frames correspond to the first image in the stack. Each image is on a log brightness scale with minimum set to mean background level.

exoplanet observation of ∼4 hr includes ∼3600 images (∼9–22 GB depending on the eVscope model) and can take ∼2–5 hr to upload depending on network bandwidth. To notify the science team that data have been uploaded, the observers submit an observation report on the Unistellar website to provide the target name, date and time, observer name, location, the eVscope serial number (to easily find the uploaded data for processing), weather conditions, etc. Next, the observers are notified on the status of their observation and are provided with a light curve, if successful.

4. Image Processing and Photometry

Raw data collected from an eVscope during an observation are stored in the instrument's onboard computer and then uploaded by citizen astronomers into the Unistellar cloud storage. Science data that the science team requests for analysis are converted in the community standard FITS file format and transferred to the SETI Institute cloud servers for processing. The necessary steps to go from raw data to modeled exoplanet light curve are encapsulated in the science team's Python-based SETI Institute Data Reduction Pipeline (SETI DRP).

The SETI DRP is used for calibrating raw frames (e.g., with dark subtraction, bad pixel correction, etc.) and deriving their astrometric solution (i.e., plate solving). This process typically involves 2500–4500 images for an exoplanet observation of 3–5 hr. Individual images are combined (by average in groups of 15–30) into 100–200 stacked images that increase the S/N of detected stars to improve the precision of measurements. Figure 4 shows an example of a raw, processed, and stacked image collected from a UE citizen scientist eVscope during a routine observation of Qatar-1b in 2022 April ($V = 12.7$).

Stacking images is useful because of the eVscope 1/eQuinox Sony IMX224 and the eVscope 2 IMX347 CMOS image sensors, which have a Bayer matrix design, where adjacent pixels have different spectral responses (peaking at red, green, or blue wavelengths), so source flux measurements are dependent on the star's detector-frame coordinates. Averaging several images, in which the star is centered on different pixels, averages over spectral responses and reduces scatter in the derived flux measurements. Work is also underway to test if extracted monochrome fluxes contain less scatter. Positive aspects of the CMOS detector include readout noise of less than 1 e−, which is generally insignificant compared to the source's Poisson noise term, and a quantum efficiency of ∼75% that enhances low-light sensitivity.

The science team uses three independent methods for performing aperture photometry to reliably extract stellar fluxes and create light curves, which includes the EXOTIC transit photometry package developed by JPL's Exoplanet Watch (Zellem et al. 2020). These light curves show the ratio of the target star's flux to a reference star's flux over time. The team also runs two independent modeling algorithms (one least-squares minimization and one Markov Chain Monte Carlo from EXOTIC) that incorporate stellar limb darkening and other essential star–planet system parameters to robustly identify transit detections and measure their properties. Results are logged and outputted in formats ready for upload to the TFOP and AAVSO NASA Exoplanet Watch databases.

Poor data quality can limit the eVscope's sensitivity. Common issues include defocus (from user error or thermal variation), blurring (e.g., due to wind shake), and extinction by clouds. The science team has found that moderate defocus and blurring do not significantly worsen photometric precision; in fact, a slight defocus can improve precision, as spreading the

Table 1
List and Total Sum of the Various Types of Statistically Significant Transit Detections

Successful Detection Types	Total
Full transit detected	179
Full transit detected [combined data]	49
Partial transit detected	53
Total transit detections	281

Note. "Full transit detected [combined data]" results mean the data set contributed to a successful detection only when combined with other data sets, as individually they were not statistically significant.

stellar point-spread function across more pixels averages out pixel response (commonly practiced for point-source photometry) (Winn 2010). Cloud extinction is mitigated by the science team's differential photometry method but does increase photometric scatter, and high extinction could prevent the team from measuring a light curve at all.

Science-grade light curves can be processed within 1–2 hr using four 2.5 GHz arm64 processors on our cloud-based servers and returned to the observers. After manual inspection of the results by the science team, additional processing can be performed if needed, and the results can then be sent to the appropriate databases.

5. Exoplanet Transit Results

5.1. Overall Network Transit Results

Since the beginning of UE (2020 January), our team has kept track of all citizen science exoplanet observations with a collaborative spreadsheet that combines observation reports submitted online with status updates and notes from the science team. We have logged 1018 observations to date with 163 unique citizen scientist exoplanet observers (after subtracting seven observers from our internal science team). Then, 651 observations have been processed, with 281 having a significant detection (a 43.2% transit detection success rate). Table 1 lists the numbers of different detection types that have resulted in a statistically significant transit detection. Table 2 provides a list of all 1018 exoplanet observations to date, including all currently known entries for detection status pulled from our SETI DRP. Figure 5 shows the total observations of UE for each month.

5.2. Publication of Data

Photometric exoplanet data from UE with high S/N detections, constraints on mid-transit times, part of a jointly created light curve, or with a statistically significant non-detection are published by uploading them to the AAVSO Exoplanet Database with the AAVSO Observer Code "UNIS." Currently, there are 71 transit data sets uploaded to this database from eVscopes. An example of a Unistellar Network exoplanet data set uploaded to AAVSO is shown in Figure 6.

In addition to submission to AAVSO, the science team has also submitted one TFOP to the SG1 internal science team for inclusion in their internal databases. More TFOP submissions are planned.

5.3. Highlighted UE Campaign Transits

5.3.1. Coordinated Intercontinental Transit Detection: TOI 2031.01

On 2020 November 18, two Unistellar citizen scientists collaborated on UE's first transatlantic exoplanet observation, demonstrating the scientific value of coordinated observations across a geographically distributed network. Their observation of TESS planet candidate TOI 2031.01 was a combined effort of ∼6 hr with the two observers separated by over 6700 km. The first observer, Bruno Guillet, who was in northern France, observed for 192 minutes from pre-transit through ingress and ended at approximately mid-transit. The second observer, Justus Randolph, who was in southeastern USA, collected ∼30 minutes of pre-transit data but paused before ingress began (first contact point) due to user error. He then continued observing from ∼25 minutes after ingress ended (second contact) and stopped approximately 1 hr after egress ended (fourth contact). Both used an eVscope 1 telescope, had clear skies, and were located in suburban areas with moderate light pollution.

Individually, both data sets showed significant transit signals with depths of ∼1.3%, but they only weakly constrained the mid-transit time because each lacked data at either ingress or egress. The best-fit model to Guillet's data returned an $O-C$ of -37 ± 13 minutes, where O is the observed T_0 measured from our data and C is the predicted mid-transit time calculated from the ExoFOP ephemeris (a negative $O-C$ means the observed T_0 was earlier than the prediction). The quoted uncertainty is the 68% (∼1σ) confidence interval and is dominated by our uncertainty on observed T_0. That relatively large uncertainty primarily stems from allowing the transit duration to vary in our model fit; with either ingress or egress missing from a light curve, the duration can increase or decrease in the model fit with impunity, and thus pull T_0 earlier or later. Indeed, the best-fit duration from Guillet's data alone is 157 ± 45 minutes, substantially shorter than the 235.5 minutes predicted. Randolph's data constrained $O-C$ to be 8.3 ± 5.7 minutes, with the small amount of data from early in the transit leading to a smaller T_0 uncertainty. While we could fix the transit duration in our model fitting to alleviate the effect of missing ingress or egress data, that would require an additional assumption that the predicted duration is accurate, which is not always a safe assumption for recently discovered planet candidates that have few transits detected. Even so, doing so

Table 2
Truncated Version of the Full Master Spreadsheet for All 1018 Exoplanet Observations from UE to Date

Target	Observer Name (First Initial(s), Last Name)	Observer Country	Observation Start Date (UTC+0) (YYYY-MM-DD)	Apparent Magnitude (*V*mag)	Estimated Depth (ppt)	Detection Status
HAT-P-32b	E. Friday	USA	2020-02-02	11.2	22.2	Inconclusive
HAT-P-32b	A. Nott	Canada	2020-02-02	11.2	22.2	Inconclusive
HAT-P-32b	C. Crim	USA	2020-02-02	11.2	22.2	Inconclusive
TOI 1720.01	P. Tikkanen	Finland	2020-03-08	11.3	14.1	Inconclusive
WASP-85Ab	M. J. Smallen	USA	2020-04-11	10.7	20.1	Inconclusive
WASP-43b	F. Davies	USA	2020-04-13	12.4	31.6	Inconclusive
WASP-183b	F. Davies	USA	2020-04-16	12.8	22.6	Full transit detected
HAT-P-12b	J. de Lambilly	Switzerland	2020-04-22	12.8	19.8	Inconclusive
Qatar-1b	J. de Lambilly	Switzerland	2020-04-23	12.7	21.4	Full transit detected
Qatar-2b	F. Davies	USA	2020-04-30	13.3	30.3	Full transit detected
Qatar-2b	F. Davies	USA	2020-05-04	13.3	27.5	Full transit detected
TOI 1779.01	J. de Lambilly	Switzerland	2020-05-06	15.4	102.9	Full transit detected
HAT-P-18b	R. Fienberg	USA	2020-05-14	12.8	20.4	Full transit detected

(This table is available in its entirety in machine-readable form.)

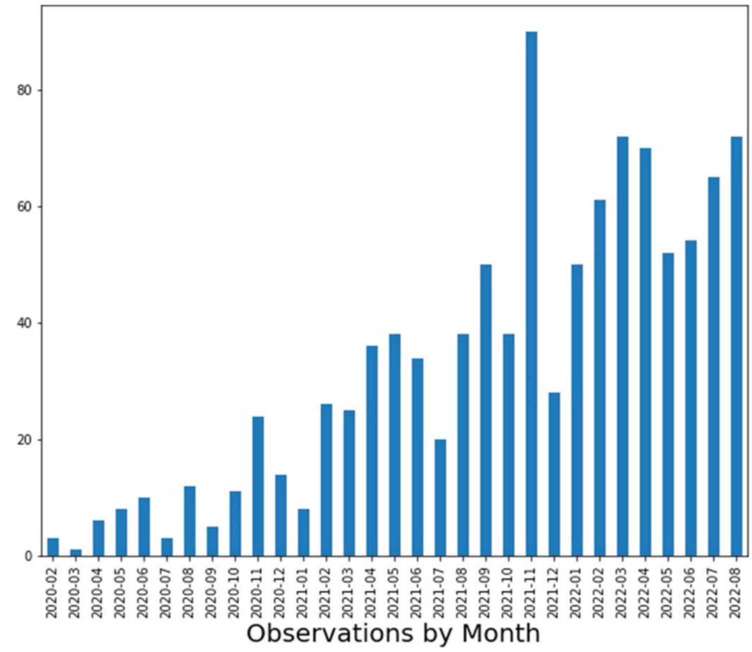


Figure 5. Distribution of all exoplanet observations of UE by observation date (YYYY-MM).

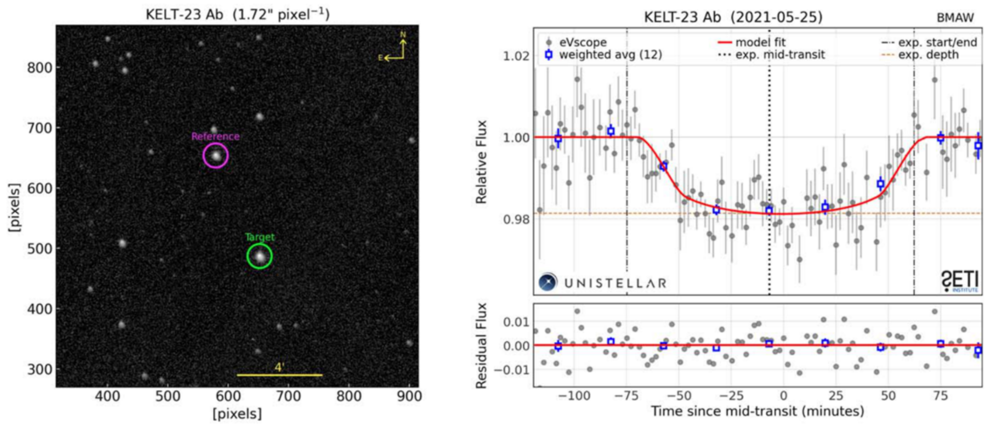


Figure 6. Example of data uploaded to AAVSO Exoplanet Database. Pertinent FITS header information is also included in these uploads. FOV for KELT-23 Ab (left). Light curve for KELT-23 Ab (right).

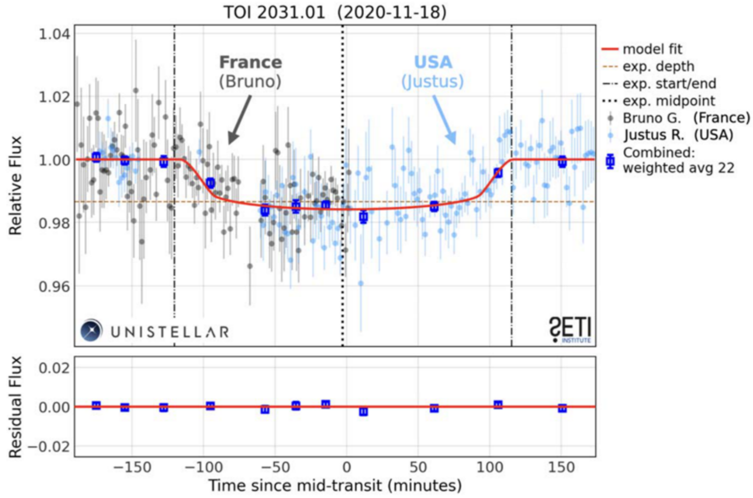


Figure 7. Transit light curve of TOI 2031.01 combines eVscope data taken by two citizen scientists located over 6700 km apart. Broken lines are the predicted transit times (black) and depth (orange).

in this case only reduces the T_0 uncertainty to 5.5 and 4.1 minutes for Guillet's and Rudolph's data set, respectively.

The combined light curve (Figure 7), including both data sets, contains both ingress and egress, so it constrains T_0 much more tightly with a value of 2459171.6116 ± 0.0013 BJD_{TDB} and $O - C = 2.7 \pm 1.9$ minutes. This is substantially more precise and more accurate if we take the TESS-based prediction to be the planet's true mid-transit time. The measured best-fit depth of $1.34\% \pm 0.15\%$ agrees with the predicted value of 1.33%, and the standard deviation of the residuals of 0.85% indicates a high confidence detection. Our measured transit duration of 232 ± 11 minutes also agrees with the predicted value (236 minutes). This successful observation was not only significant for showing the network's strategic and photometric capability for this type of observation, but it also demonstrated how engaged the citizen community can be in their motivation and ability to contribute to novel observation ideas and planning.

5.3.2. TESS Planet Candidate Orbit Refinement: TOI 3799.01

Two UE campaign citizen scientists observed TESS planet candidate TOI 3799.01 on 2022 January 26 and revealed an inaccurately reported orbital period for the planet. Their combined light curve showed the beginning of a transit with a $3.82\% \pm 0.36\%$ depth and an ingress that started 154.3 ± 4.1 minutes later than predicted based on the TESS ephemeris (Figure 8). This measurement was plausible given the TESS science team's estimated $\sigma \sim 1.3$ hr uncertainty in the transit time. In terms of observation date, this was the first ground-based detection of the candidate's transit, based on publicly available data. A TFOP member unaffiliated with Unistellar independently measured a similarly late ingress for a transit on 2022 March 8, which led the TFOP team to reexamine the TESS 2 minutes cadence data and revise the candidate's orbital period by 1 minute as a result (from 8.20523 ± 0.00061 days to 8.20596 ± 0.00039). This period has since been refined further based on new epochs of TESS data. Our subsequent report shortly afterward of the January timing was consistent and supported that new period.

Coincidentally, we engaged the Unistellar Network to observe the 2022 March 8 transit to confirm the late transit time we had identified from the January data. At that point, no revisions had been made to the ephemeris. Five Unistellar citizen scientists and two astronomers from the science team reobserved TOI 3799.01 for this event, collecting data over a $\sim$6.3 hr window that was expected to include the entire transit. The resulting combined light curve is shown in Figure 9. This re-detection of TOI 3799.01 showed a late transit consistent with the January timing. When we later compared it to the transit time predictions based on the TFOP-revised ephemeris (also shown in Figure 9), we calculated an $O - C$ of 5.5 ± 3.8 minutes, thus confirming the new orbital period. We plan to reobserve this target again in the future to continue monitoring the transit times, confirm the period over a longer

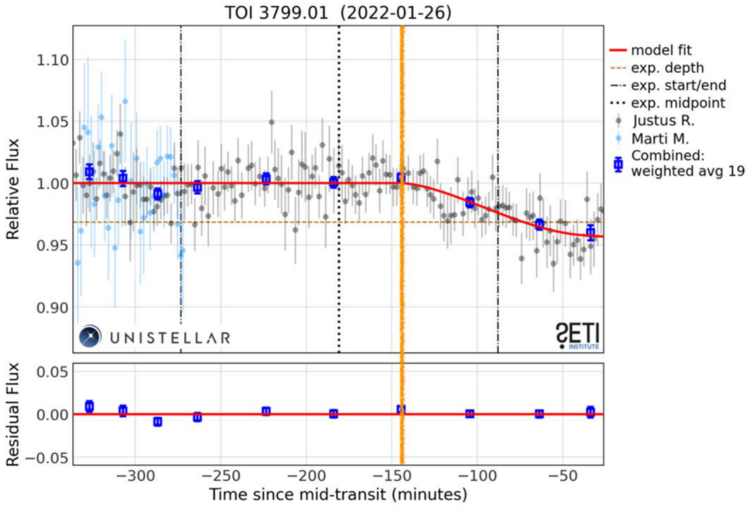


Figure 8. Ingress of TOI 3799.01 by two UE campaign citizen scientists in 2022 January showing a transit start time ~154 minutes later than the predicted TESS data. The bold orange stylized line highlights the beginning of the ingress captured from this observation.

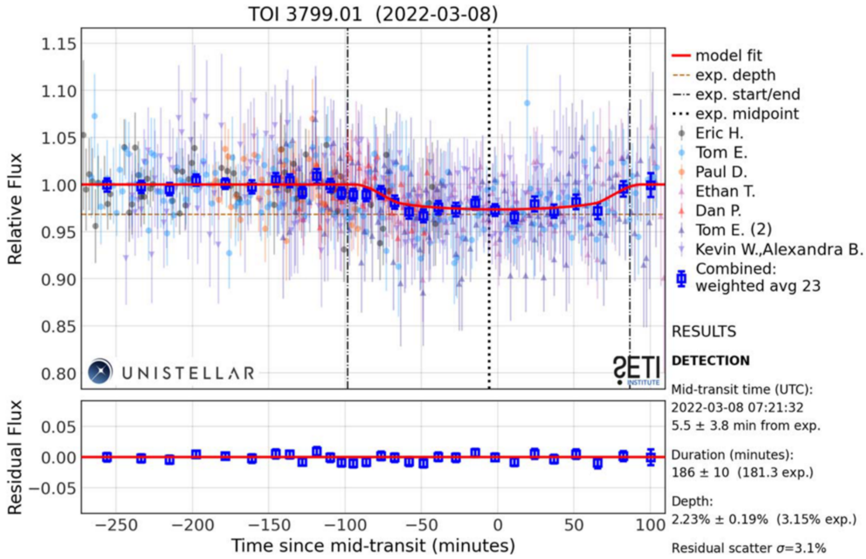


Figure 9. Transit of TOI 3799.01 by seven eVscopes (five citizen scientists and two science team astronomers) on 2022 March 8. This follow-up measurement confirmed our initial timing from 2022 January and the revised ephemeris computed from the TESS data.

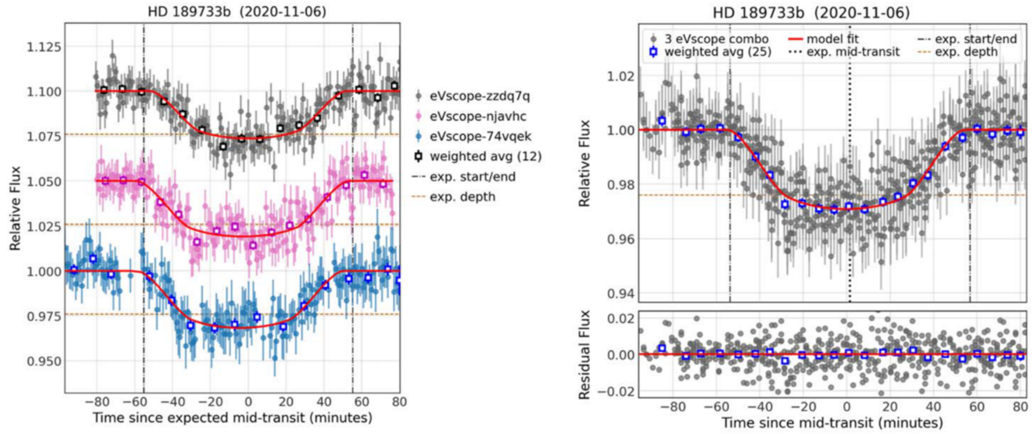


Figure 10. Photometric transit observations of HD 189733b by three Unistellar eVscopes in Europe (left). The alphanumeric strings after each "eVscope-" are the identifiers for each eVscope used. Photometric transit observation of HD 189733b with the data from three combined eVscope observations (right). The blue squares represent the weighted average of the gray points (combined data of normalized flux). Error bars are at 1σ uncertainty with ~68% confidence intervals. The uncertainty of this combined data of timing measurement is roughly 1.8 times smaller than the smallest uncertainty from an individual eVscope.

time baseline, and possibly search for transit-timing variation (TTV) signals.

5.3.3. Gee Whiz Astronomy Education Inspires First Significant Combined Data Set: HD 189733b

Members of the American Modeling Teachers Association (AMTA) and GHOU formed the Gee Whiz Astronomy Exoplanet Hunters Club for teachers, middle and high school students, and scientists from five continents in early 2020. The group utilizes GHOU's mission of connecting students with real astronomical data and instruments, as well as AMTA's inquiry-based Modeling Instruction (Wells et al. 1995; Jackson et al. 2008; Hestenes 2013; Megowan-Romanowicz 2016) learning practices. While collaborating with Gee Whiz, it was learned that they were planning to observe HD 189733b using the LCO network. With the goal to compare and combine data and make a learning experience out of the venture, the science team decided to ask UE campaign citizen scientists to make a simultaneous observation of the target.

Inspired by the Gee Whiz education team's request, five European UE citizen scientists attempted an observation of HD 189733b on 2020 November 6. Three of five UE campaign observers were successful (left panel, Figure 10). For a more precise measurement of the transit time than using individual measurements alone, we combined the three measurements (right panel, Figure 10). This combined data set marked the first successful combination of multiple eVscope exoplanet observations to improve results and S/N—all inspired by middle and high school students.

Although UE was successful in detecting the transit, the Gee Whiz team was not able to obtain their requested LCO observation due to a scheduling conflict on the LCO network. Even so, the Gee Whiz students were inspired by the UE results and used them to hone their exoplanet observing and data analysis skills. Ultimately, we used the data from this observation to create a data-driven exoplanet education laboratory activity, which is available to the public on the SETI Institute website.[30] Our team has current and future initiatives for UE and education, which will be detailed in future publications (D. O. Peluso et al. 2022, in preparation).

5.3.4. Various Dedicated Campaigns

In 2021 November, the network collected observations from the long-period exoplanet ($P = 2.9$ yr), Kepler-167e. The science team collected 43 observations from 31 different observers located around the world in nine countries (Finland, Spain, USA, Japan, Singapore, France, UK, Germany, and Canada). This could be the second longest transit ever observed from the ground or space. The transit was predicted to last for 16 hr but took 32 hr for the network's citizen astronomers to observe the entire event. Of the 43 observations, only 27 were used for the light curve by Perrocheau et al. (2022) because of

[30] https://www.seti.org/unistellar-seti-institute-education

various observation factors (such as poor viewing conditions or weather).

The science team has also been including teachers and students in exoplanet observations for inquiry- and project-based learning initiatives. Three educators within one of their initiatives, the Unistellar College Astronomy Network (UCAN), collected data for the Kepler-167e observation. An astronomy education publication is currently in preparation to detail UCAN and other UE campaign education initiatives (D. O. Peluso et al. 2022, in preparation).

In 2021 December, the science team asked UE campaign citizen scientists to observe the transit of HD 80606b, which is a long-period exoplanet ($P = 111$ days), known for its highly eccentric orbit (Winn et al. 2009). The 12 hr transit of this exoplanet was captured by eight eVscope citizen astronomers spread across Europe and North America over the course of 27.5 hr. Data from these observations are currently in press (Pearson et al. 2022) and will help for the scheduling of a JWST Cycle 1 transit spectroscopy observation to characterize the planet's atmosphere (PI: T. Kataria, GO proposal 2008).

One of the network's citizen scientists, Kevin Voeller, who is also a high school science teacher, contributed his eVscope data to the observation of WASP-148b. The eVscope timing data were useful beyond planet confirmation and timing measurements in that it may help determine the actual time of transit during simultaneous Rossiter–McLaughlin measurements as done by a professional science team (Wang et al. 2022). Kevin was also the first citizen scientist from UE to have his data published in a paper and be listed as a co-author.

In 2022 July, UE had its first non-detection of TOI 1812.01 from 15 of its network's observers. This non-detection was important because it ruled out a 71 days orbital period for this planet. Future follow-ups of this planet and publications are planned and are in preparation.

6. Future Work

6.1. Long-duration TOI

For long-period planets, the network is focusing on long-duration TOI for the detection and measurement of the timing of second transits for solo-transit TESS planet candidates. The team will also aim to eliminate orbital period degeneracies for TESS duo-transit planet candidates. In addition to contributing to professional exoplanet research, this supported work will also enhance the science team's goals of democratizing exoplanet science by including a population that will diversify the pool of citizen scientists by bringing people from different backgrounds, nationalities, and genders around the world.

6.2. Unknown RV Transits, New Planets, and Ambitious Applications

The RV method of exoplanet detection (Pepe et al. 2004; Howard et al. 2010) is not biased toward short-period exoplanets like the transit method, and therefore finds more long-period exoplanet candidates. With hundreds of RV exoplanets discovered, it is estimated that ∼25 (Dalba et al. 2019) will also have an observable transit from Earth. By taking advantage of its global network capable of detecting both short- and long-period exoplanets, UE will seek to observe all possible RV exoplanets that may also have a transit.

The Hipparcos mission showed exoplanet astronomers that by examining the photometric time series from such missions that new exoplanet transits could be found (Robichon & Arenou 2000; Hébrard & Lecavelier des Etangs 2006). Some estimates considering Gaia data show the potential for detecting hundreds of new exoplanets (Dzigan & Zucker 2012), and recent photometric data searches have already been proven successful in finding the first "Gaia exoplanets" (Panahi et al. 2022). UE may also follow up to search for transits from potential Gaia planets and other possibilities from other data sets, such as K2. Other future work to find new planets will aim to measure TTVs in concert with TFOP and the Exoplanet Watch Group.

Some more ambitious applications of UE include detecting rings and exomoons of gas giant planets and searching for microlensing events for exoplanets. By combining citizen scientists' observations, it may be possible to achieve high-enough precision to detect exomoons or ring systems (Kipping et al. 2012, 2013; Heising et al. 2015; Kenworthy & Mamajek 2015). The most ambitious application would be detecting new exoplanets or exomoons from gravitational microlensing events (Seager & Dotson 2010; Gaudi 2012). However, although the detection of such events is technically possible with smaller telescopes (Christie 2006), it is unlikely eVscope data would see an event in the near future because of its small FOV.

6.3. Education Initiatives and Research

Our team has already made efforts to place eVscopes into K–12 schools and community colleges (e.g., the aforementioned UCAN in Section 5.3.4) and determine availability of eVscopes already placed in schools. Additionally, materials, curriculum, teacher training courses, and other education programs themed around exoplanets have been developed and deployed. Much of this work has been produced using AMTA's Modeling Instruction pedagogy and in coordination with GHOU.

Multiple astronomy education research studies are in preparation for future publication (Peluso et al., in preparation). One study will investigate the effect that an AMTA-sponsored data-driven teacher training course, Astronomy Modeling with Exoplanets, has on teacher and student competence and motivation. Some teachers and students in this course and study used UE for exoplanet observations and learning. Another education study examines whether a SETI Institute-supported UE campaign within an education setting (such as with UCAN) can increase teacher competence in observational astronomy and increase their inclusion of inquiry-based experiences (e.g., exoplanet observations) for their students.

Continued efforts are made to encourage UE participants, especially K–12 teachers and students, to lead and publish their work in citizen science academic journals (e.g., *JAAVSO: Journal of the American Association of Variable Star Observers*), scientific conferences and proceedings, and even in high-impact journals. The inclusion of the general public, teachers, and students in scientific publications (both co-authored and lead-authored) will not only support more effective STEM education but will also improve efforts to heighten the democratization of science and astronomy in more diverse communities worldwide.

7. Conclusions

The Unistellar Exoplanet Campaign has grown from just hundreds of 11.4 cm, portable, and easy-to-use telescopes and one detected exoplanet transit (from internal testing) in 2019 to over 10,000 worldwide telescopes and over 1000 exoplanet observations and 281 detections as of 2022 August. The scientific scope of our campaign includes exoplanet confirmations for missions, such as TESS, short-period ephemeris maintenance, long-period confirmation, multi-time-zone exoplanet observations, and more generalized exoplanet follow-up and monitoring to meet the demand.

The SETI Institute UE campaign science team plans to continue to contribute to the professional sector of exoplanet scientific research. However, the team also has aspirational goals in education and outreach. Largely through observations done by citizen scientists, educators, and students, our team hopes to inspire a love and appreciation of science, research, exploration, and astronomy to create a more democratized future of science for the planet.

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The authors thank all the teachers everywhere—your work is extremely important. The world needs you to keep inspiring people and lead people into tomorrow.

Appendix

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References

Alsubai, K. A., Parley, N. R., Bramich, D. M., et al. 2013, AcA, 63, 465
Alsubai, K. A., Parley, N. R., Bramich, D. M., et al. 2011, MNRAS, 417, 709
Bakos, G., Noyes, R. W., Kovács, G., et al. 2004, PASP, 116, 266
Baluev, R. V., Sokov, E. N., Shaidulin, V. S., et al. 2015, MNRAS, 450, 3101
Barclay, T., Pepper, J., & Quintana, E. V. 2018, ApJS, 239, 2
Bartlett, S., Fitzgerald, M. T., McKinnon, D. H., Danaia, L., & Lazendic-Galloway, J. 2018, JAESE, 5, 1
Baruteau, C., Crida, A., Paardekooper, S., et al. 2013, arXiv:1312.4293
Battley, M. P., Kunimoto, M., Armstrong, D. J., & Pollacco, D. 2021, MNRAS, 503, 4092
Bell, S. 2010, CHAJES, 83, 39
Blumenfeld, P. C., Soloway, E., Marx, R. W., et al. 1991, EdPJ, 26, 369
Brown, T. M., Baliber, N., Bianco, F. B., et al. 2013, PASP, 125, 1031
Cameron, A. C. 2012, Natur, 492, 48
Charbonneau, D., Brown, T. M., Latham, D. W., & Mayor, M. 2000, ApJ, 529, L45
Christiansen, J. L., Crossfield, I. J. M., Barentsen, G., et al. 2018, AJ, 155, 57
Christie, G. W. 2006, arXiv:astro-ph/0609599
Collins, K. A., Collins, K. I., Pepper, J., et al. 2018, AJ, 156, 1
Dalba, P. A., Kane, S. R., Barclay, T., et al. 2019, PASP, 131, 034401
Dalba, P. A., Kane, S. R., Li, Z., et al. 2021, AJ, 162, 154
Dzigan, Y., & Zucker, S. 2012, ApJ, 753, L1
Edwards, B., Changeat, Q., Yip, K. H., et al. 2020, MNRAS, 504, 5671
Eisner, N. L., Barragán, O., Lintott, C., et al. 2020, MNRAS, 501, 4669
Fabrycky, D., & Tremaine, S. 2007, ApJ, 669, 1298
Fischer, D. A., Schwamb, M. E., Schawinski, K., et al. 2012, MNRAS, 419, 2900
Fortus, D., Krajcik, J., Dershimer, R. C., Marx, R. W., & Mamlok-Naaman, R. 2005, IJSEd, 27, 855
Fowler, M. J. F. 2019, JBAA, 129, 174
Fowler, M. J. F., Sienkiewicz, F. F., Zellem, R. T., & Dussault, M. E. 2021, JBAA, 131, 359
Gaudi, B. S. 2012, ARA&A, 50, 411
Goldreich, P., & Tremaine, S. 1980, ApJ, 241, 425
Gomez, E. L., & Fitzgerald, M. T. 2017, AstRv, 13, 28
Green, C., & Medina-Jerez, W. 2012, ScTea, 79, 58
Hartman, J. D., Bakos, G., Stanek, K. Z., & Noyes, R. W. 2004, AJ, 128, 1761
Hébrard, G., & Lecavelier des Etangs 2006, A&A, 445, 341
Heising, M. Z., Marcy, G. W., & Schlichting, H. E. 2015, ApJ, 814, 81
Henden, A. A. 2011, Proc Intl Astro Union, 7, 255
Heng, K., & Winn, J. 2015, AmSci, 103, 196
Hestenes, D. 2013, EJMSE, 1, 13
Howard, A. W., Johnson, J. A., Marcy, G. W., et al. 2010, ApJ, 721, 1467
Ikwut-Ukwa, M., Rodriguez, J. E., Bieryla, A., et al. 2020, AJ, 160, 209
Jackson, J., Dukerich, L., & Hestenes, D. 2008, NSELA, 17, 10
Jenkins, L. L. 2011, CSSE, 6, 501
Jensen, E. 2013, Tapir: A web interface for transit/eclipse observability, Astrophysics Source Code Library, ascl:1306.007
Kane, S. R., Howard, A. W., Pilyavsky, G., et al. 2011, ApJ, 733, 28
Kempton, E. M., Bean, J. L., Louie, D. R., et al. 2018, PASP, 130, 1
Kenworthy, M. A., & Mamajek, E. E. 2015, ApJ, 800, 126
Kipping, D. M., Bakos, G. Á., Buchhave, L., Nesvorný, D., & Schmitt, A. 2012, ApJ, 750, 115
Kipping, D. M., Hartman, J., Buchhave, L. A., et al. 2013, ApJ, 770, 101
Kokori, A., Tsiaras, A., Edwards, B., et al. 2022a, ApJS, 258, 40
Kokori, A., Tsiaras, A., Edwards, B., et al. 2022b, ExA, 53, 547
Lambert, R., Marchis, F., Asencio, J., et al. 2022, Proc SPIE, 12182, 121822Z
Lavi, R., Tal, M., & Dori, Y. J. 2021, Stud. Educ. Evaluation, 70, 101002
Lissauer, J. J., Dawson, R. I., & Tremaine, S. 2014, Natur, 513, 336

Marchis, F., Arbouch, E., Bertin, E., et al. 2019, EPSC-DPS Joint Meeting, 2019, 13
Marchis, F., Malvache, A., Marfisi, L., Borot, A., & Arbouch, E. 2020, AcAau, 166, 23
Marshall, P. J., Lintott, C. J., & Fletcher, L. N. 2015, ARA&A, 53, 247
Megowan-Romanowicz, C. 2016, NSTA Reports, 28, http://static.NSTA.org/pdfs/NSTAreports/NSTAreports201607.pdf
Mizrachi, R., Ly, D., Bewersdorff, L., & Tock, K. 2021, JAVSO, 49, 186
Morton, T. D. 2012, ApJ, 761, 6
Mousis, O., Hueso, R., Beaulieu, J. P., et al. 2014, ExA, 38, 91
Moutou, C., Hébrard, G., Bouchy, F., et al. 2009, A&A, 498, L5
Naef, D., Latham, D., Mayor, M., et al. 2001, A&A, 375, L27
Nair, S., Koodli, K., Chalcraft, E., & Tock, K. 2020, JAVSO, 48, 265
National Academies of Sciences, Engineering, Medicine 2021, Decadal Survey on Astronomy and Astrophysics 2020 (Washington, DC: The National Academies Press)
National Academy of Sciences, National Academy of Engineering, and Institute of Medicine 2007, Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future (Washington, DC: The National Academies Press)
Oliveira, V. d. A. 2019, Proc. Int. Astro Union, 15, 439
Panahi, A., Zucker, S., Clementini, G., et al. 2022, A&A, 663, A101
Pearson, K. A., Beichman, C., Fulton, B. J., et al. 2022, AJ, 164, 178
Pepe, F., Mayor, M., Queloz, D., et al. 2004, A&A, 423, 385
Pepper, J., Pogge, R. W., DePoy, D. L., et al. 2007, PASP, 119, 923
Perrocheau, A., Esposito, T. M., Dalba, P. A., et al. 2022, ApJL, 940, L39
Pollacco, D. L., Skillen, I., Cameron, A. C., et al. 2006, PASP, 118, 1407
Ricker, G., Winn, J., Vanderspek, R., et al. 2014, JATIS, 1, 014003
Robichon, N., & Arenou, F. 2000, A&A, 355, 295
Santerne, A., Hébrard, G., Deleuil, M., et al. 2014, A&A, 571, A37
Sarva, J., Freed, R., Fitzgerald, M. T., & Salimpour, S. 2020, Atom, 1, 34
Schleicher, A. 2019, PISA 2018: Insights and Interpretations (OECD Publishing)
Schwamb, M. E., Orosz, J. A., Carter, J. A., et al. 2013, ApJ, 768, 127
Seager, S., & Dotson, R. 2010, Exoplanets (Tucson: Univ. Arizona Press)
Simpson, R., Page, K. R., & De Roure, D. 2014, in Proc. 23rd Int. Conf. World Wide Web, Zooniverse: observing the world's largest citizen science platform (New York: Assoc. for Computing Machinery), 1049
Sincell, M. 1999, Sci, 286, 1822
Socrates, A., Katz, B., Dong, S., & Tremaine, S. 2012, ApJ, 750, 106
van Dokkum, P. G., Abraham, R., & Merritt, A. 2014, ApJ, 782, L24
Wang, J., Fischer, D. A., Barclay, T., et al. 2013, ApJ, 776, 10
Wang, X.-Y., Rice, M., Wang, S., et al. 2022, ApJL, 926, L8
Wells, M., Hestenes, D., & Swackhamer, G. 1995, AmJPh, 63, 606
Winn, J. N. 2010, arXiv:1001.2010
Winn, J. N., Howard, A. W., Johnson, J. A., et al. 2009, ApJ, 703, 2091
Wu, Y., & Murray, N. 2003, ApJ, 589, 605
Zellem, R. T., Biferno, A., Ciardi, D. R., et al. 2019, arXiv:1903.07716
Zellem, R. T., Pearson, K. A., Blaser, E., et al. 2020, PASP, 132, 054401

3.3 Links and Implications

The Unistellar Exoplanet Campaign (UE) served as a foundational pillar of this thesis, showcasing the potential of a global citizen science network to contribute to both exoplanet research and education. Through UE, the citizen science network was able to make significant contributions to exoplanet research with their follow-up photometric data for ephemerides maintenance for exoplanets such as TOI 2031.01 and TOI 3799.01. Additionally, the collaborative efforts of 163 citizen scientists across 21 countries highlights the value of diversity and inclusivity in scientific endeavors and demonstrates the power of community-driven research. Furthermore, the integration of education and research, as exemplified by the "Gee Whiz Astronomy" inspired observation of HD 189733 b laid the groundwork for future AstroReMixEd initiatives, by opening new avenues for engaging students and teachers in meaningful astrophysics exploration and research.

CHAPTER 4: ASTRONOMY MODELING INSTRUCTION WITH EXOPLANETS

"The teacher who is indeed wise does not
bid you to enter the house of his wisdom
but rather leads you to the threshold of your mind."
-Kahlil Gibran

4.1 Introduction

The following manuscript paper by Peluso et al. (2023), *Astronomy Modeling Instruction with Exoplanets: Motivating Science Teaching and Learning in the 21st Century*, was submitted to the Journal of Science Teacher Education (JSTE) on 26 May 2023 with the submission ID of 232454474 and went into peer-review for publication on 1 June 2023.

This paper highlights the Astronomy Modeling Instruction with Exoplanets workshop's impact on enhancing high school teachers' and students' understanding and confidence, emphasizing teachers' adoption of Modeling Instruction and astrophysical data and analysis (including exoplanets), which enhanced student engagement and provided hands-on learning experiences more rigorous than certain college-level courses.

4.2 Submitted Paper

Full Title: Astronomy Modeling Instruction with Exoplanets: Motivating Science Teaching and Learning in the 21st Century

Shortened Version Title for Running Head:
A new approach to teaching high school astronomy

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Abstract: This study utilized a mixed method design to investigate the effects of an inquiry-based and data-driven astronomy course on high school teacher and student pedagogy, confidence, motivation, competence, and engagement. Participants were composed of two groups: 1) teachers in a workshop, and 2) the students of one of those teachers. Quantitative data revealed significant increases in both teachers' and students' astronomy concept knowledge, as well as improved teacher self-efficacy. Qualitative data further illustrated these results and added context about how teachers transformed their pedagogy by including Modeling Instruction (MI) and the use of astrophysical data and analysis techniques. Data-driven experiences resulted in improved student engagement and students reported enjoying working with real astrophysical data over "learning from a book". After completing a 15-week Astronomy Modeling with Exoplanets workshop, teachers with little or no prior background in astronomy or astrophysics were able to conduct astronomical observations, perform photometry on astronomical data sets, and include more astrophysics in their high school level courses than many college-level introductory astronomy courses.

Keywords: astronomy; astrophysics; astronomy education; exoplanets; Modeling instruction

Introduction

Astronomy has some of the greatest powers of any scientific field to both educate and induce awe and inspiration in our students (National Academies of Sciences, 2021). The 1960s space race, although driven by the cold war, built on human curiosity about the cosmos and helped galvanize the world's interest in STEM (science technology, engineering, and mathematics) driving STEM education to new heights (Wissehr et al., 2011). Today, it is projected that the US will lead the space industry (e.g. NASA, Space Force, Virgin Galactic, Blue Origin, SpaceX, etc.) and that jobs in this sector are growing fast and are already higher (55%) than a decade ago (Foundation, 2021). However, future US jobs in STEM, especially within the more specialized space industry sectors may go unfilled due to an insufficient supply of skilled US STEM professionals (Butow et al., 2020; Foundation, 2021; National Academy of Sciences, 2007). With students in developed countries, such as the US, scoring below average on standardized assessments in STEM disciplines (Schleicher, 2019) and studies reporting low student interest in science courses (Osborne & Collins, 2001; Schreiner & Sjøberg, 2004; Steidtmann et al., 2023) there is an obvious need for STEM education reform. Adding astronomy to the high school curriculum could help, since astronomy and space-related concepts function as a "Gateway Science" to motivate and excite student STEM interest (Bartlett et al., 2018; Oliveira, 2019; Salimpour et al., 2021).

While astronomy has the potential to be a catalyst to increase student interest in STEM and space careers and prepare a US workforce for its future economy, current opportunities in K-12 schools to exploit this appeal and invoke its intrinsic awe-inspiring nature in our students are scarce.

The Astronomy Modeling with Exoplanets (AME) Pilot Study

This paper describes results of a small mixed methods astronomy education pilot study involving both teachers and students. Our research is informed by the potential student excitement about advances in space science and astronomy and astrophysics and the current state of high school astronomy education.

Most high school astronomy teachers are out-of-field (i.e., did not major or minor in astronomy or astrophysics). We wanted to explore the extent to which teachers could master skills and techniques used by professional astronomers, i.e., working with research quality telescopes, self-collected or publicly available astronomical data and images, and conduct their own analyses. We measured their confidence in their ability to help students learn and use these skills in the context of a more engaging and rigorous astronomy or astrophysics course. We also wanted to learn what impact such a course would have on high school students.

Research Questions

(1) In what ways and to what extent does astronomy professional development for secondary science teachers grounded in Modeling Instruction (MI) pedagogy and utilizing the collection and analysis of astronomical image data:
   (a) transform their approach to teaching astronomy?
   (b) improve teacher confidence and competence in teaching astronomy?
   (c) affect student engagement?

(2) In what ways and to what extent do students in an astronomy course taught by one of these teachers:
   (a) increase understanding of astronomy concepts, skills, and knowledge?
   (b) affect interest, motivation, and engagement?

The Current State of K-12 Astronomy Education

Worldwide, only 17% of K-12 schools offer an astronomy course (Salimpour et al., 2021). The Committee of Ten, a group of educators convened by the National Education Association in 1892, decided that astronomy need not be a part of college admission requirements and therefore should not be a required element of the high school curriculum (Studies, 1894). Previously, it was a required course for virtually all secondary school students (Bishop, 1990; Bishop, 2003; Krumenaker, 2009; Sheppard & Robbins, 2002). This committee opted for the now familiar sequence of biology, chemistry, and then physics (B-C-P) for US high schools (Sheppard & Robbins, 2002). B-C-P resulted in not only the near disappearance of astronomy at the high school level, but also a decline in physics enrolment, since in many cases it became an elective option for students (Sheppard & Robbins, 2002). Despite the space race that began over 60 years ago, this trend has continued. In 2019, 40% of US high school graduates completed a physics course, while 97% completed biology, and 76% completed chemistry (Statistics, 2022). Regarding astronomy, there is little data about its current availability, but as of 2007 just 12% of US high schools reported offering an astronomy course and the number of sections offered was declining (Krumenaker, 2009).

Although astronomy is touched upon occasionally in other K-12 science classes, misconceptions (e.g., gravity in space, cause of seasons, lunar phases, scale, cosmic spatial reasoning and knowledge, and others) abound in teachers at all grade levels (Brunsell & Marcks, 2005) and are the most prevalent in elementary and middle school teachers (Brunsell & Marcks, 2005; Trumper, 2003). While high school physics classes have potential for including some astronomy, a recent national US survey of 506 physics teachers indicated that only about 14% of them teach any astronomy (Personal Communication, Megowan-Romanowicz, March 28, 2023). A 2007 study indicated that most high school astronomy teachers are not highly qualified to teach it (Krumenaker, 2009). While more recent studies about teachers' qualifications to teach high school astronomy are lacking, there is little reason to suppose that this has changed significantly. A recent study reports 84% of middle school and 68% of high school physical science teachers are teaching out-of-field (no major or minor in the field), while 91% of middle school and 80% of high school earth and space science teachers are teaching out-of-field (Taylor et al., 2020). Moreover, most community college astronomy teachers do not have a degree in astronomy and over 88% of students are taking astronomy from a teacher with no formal training in it (French, 2019).

The language of astronomy is mathematics, and the degree to which it is utilized in an astronomy course is considered a metric for its academic rigor level (Brogt, 2009; Brogt & Draeger, 2015). Little is known about the rigor of high school astronomy courses, however, in college level introductory astronomy courses for non-majors, the level of rigor is generally considered low for most offerings, (Brogt & Draeger, 2015; MacLeod et al., 2015).

Modeling Instruction Pedagogy for Astronomy Education

Modeling Instruction (MI), developed in the late 1980s by physicist David Hestenes and his graduate student Malcolm Wells, restructured the teaching of physics by systematically building, refining and applying the fundamental conceptual models that form the content core of the discipline (Hestenes, 1997; Wells et al., 1995). The development and dissemination of MI via Modeling Workshops for high school teachers, and its eventual replication for chemistry, biology, and physical science in middle school was supported for over 20 years by National Science Foundation (NSF) funding. When funding expired in 2005 the American Modeling Teachers Association (AMTA) made it their mission to support the Modeling teacher community (which now numbers over 15,000), offer Modeling Workshops, and develop and curate Modeling curriculum resources. Research has validated the effectiveness of Modeling Instruction pedagogy in middle and high school science education (Haag & Megowan-Romanowicz, 2021; Hestenes, 1997, 2006; Jackson et al., 2008), and has also demonstrated that it improves out-of-field teacher confidence and competence (Haag & Megowan, 2012, 2015; Hestenes et al., 2011; Jackson et al., 2008).

In 2018, AMTA joined with astronomy education researchers from the Global Hands-on Universe (GHOU) project to create an Astronomy Modeling Workshop (Carpenter et al., 2018). The expectation that students learn to "do science as scientists do," is the norm in MI classrooms, and is a fundamental part of science education reform (Council, 2012, 2013, 2015) This served as a guiding principle in the development of this workshop as it does in all Modeling Workshops.

Teacher Self-Efficacy

A teacher's belief in one's self, or self-efficacy, relates directly to their confidence level in their abilities to advance student learning (Bandura & Wessels, 1994). Teachers with low self-efficacy tend to give up more easily with struggling students, are less tolerable of student misconceptions (Nurlu, 2015), and their students will learn less as compared to teachers with a higher self-efficacy (Akbari & Allvar, 2010; Çakiroglu et al., 2005). These teachers are also more likely to have higher stress and poor job satisfaction (Klassen & Chiu, 2010).

In contrast, improving teacher self-efficacy can positively effect teacher motivation, confidence, and job satisfaction (Perera & John, 2020), as well as positively transform how they teach within the classroom (Bray-Clark & Bates, 2003; De Neve et al., 2015; Nurlu, 2015). A strong self-efficacy can also help a teacher overcome challenges and develop resilience (Lent et al., 2000), such as with a science teacher with poor skills in their teaching subject area (e.g., astronomy). However, even though some studies find it to be independent of one's skills in a discipline (Bandura, 1986), others find that self-efficacy can be negatively affected when a science teacher lacks adequate conceptual knowledge in the field in which they teach, and this can then affect their teaching approach and motivation (Riggs & Enochs, 1990). For intervention, the implementation of teacher professional development workshops (e.g., MI) have been shown to increase teacher motivation, self-efficacy, and confidence in effectively embracing new teaching strategies (Bray-Clark & Bates, 2003; Gray et al., 2017; Haag & Megowan, 2015; Haag & Megowan-Romanowicz, 2021).

Student Motivation

Students will engage in a learning experience if they have intrinsic motivation from perceiving the activity to being “fun” and giving them both arousal and control (Middleton, 1995; Middleton et al., 2003; Middleton et al., 1992). The potentiality of space and astronomy being a “Gateway Science” (Bartlett et al., 2018; Oliveira, 2019; Salimpour et al., 2021) may inspire such intrinsic motivations from students. Additionally, the MI learning environment allows for more goal driven activities in line with goal theory (Ames, 1992) and has a more conceptual nature (Thompson et al., 1994), which can lead to a higher-level of adoption of intrinsic student engagement.

Methods

We combined quantitative and qualitative data for a mixed methods study to capitalize on the ability to add greater detail and context to our research investigation (Creswell & Clark, 2017; Johnson et al., 2007; Tolan & Deutsch, 2015). The intervention used was an AME Workshop for high school teachers. Our original intent was to study only teachers, however, during the workshop, one teacher expressed interest in having his high school astronomy students participate in our research during the following semester. We seized on the opportunity to expand our research to include students. To collect relevant data for this work, the investigator used surveys and semi-structured interviews to help to answer our research questions.

The Intervention: AME Teacher Workshop

AME is a 15-week, 45-hour, distance learning Modeling Workshop offered through AMTA, with optional enrolment available at a regional university for 3 graduate credits. Teachers, all but one in the US, were invited to AME through AMTA, SETI Institute, and associated researcher contacts. AME was conducted via Zoom from January – May 2022. Prior to the COVID-19 pandemic, the majority of Modeling Workshops were in-person 3-week summer workshops. However, the pandemic caused a sharp rise in distance-learning Modeling workshops. Distance-learning was a silver lining for AME as it better fit teachers' budgets, schedules, and allowed more time for participants to plan and schedule astronomical observations—a challenge for the shorter 3-week format. Additionally, although many teacher workshops in science require teachers to be present in person to conduct laboratory investigations, AME is unique in that investigations can be completed on a laptop computer with internet browser.

One college and 23 high school teachers enrolled in the AME Workshop. None were astronomers and most were out-of-field teachers who had completed at least one other Modeling Workshop (mostly physics). AME met weekly over Zoom for 3 hours.

As is the norm in Modeling Workshops, classroom discourse was in both "student" and "teacher" mode. In student mode, teachers participated as their students would, working through activities in collaborative groups of 3 or 4. Once workshop leaders had set the stage for an activity, "student" groups were placed into Zoom breakout rooms where they used digital whiteboards (i.e., Google Jamboards) to represent their data, analysis and consensus model. After each activity, teachers removed their "student hats" to have teacher-to-teacher discussions of classroom management and the design of the learning environment. Fundamental conceptual models for the course were embodied in four units as outlined in Table 1.

Table 1. Names and descriptions of the fundamental models into which the AME learning experience was divided.

Unit	Name	Fundamental Models
1	How Do We Map & Measure Space from Earth's Perspective?	The celestial sphere, coordinate systems (e.g. right ascension and declination), cosmic distances and measurements.
2	How Do Objects Interact in Space?	Motion, forces, gravity, and Kepler's Laws.

3	How Do We Know About Objects and Events in Space?	Light: gathering, measuring, and its analysis.
4	How Do We Know the Evolution and Fate of the Universe and SETI?	Stellar evolution, cosmology, and SETI.

To infuse the original MI/GHOU resources with exoplanet science and associated data, we used exoplanet citizen science resources and platforms accessible to K-12 teachers and students. Identifying exoplanets via the transit method was our primary approach with AME. This method works by measuring changes in flux in images of an exoplanet's host star during a transit event, which results in a transit light curve that shows this change as a dip in brightness over time.

We utilized the NASA Universe of Learning and Harvard-Smithsonian Center for Astrophysics MicroObservatory DIY Planet Search, which allows students to request images remotely from robotic telescopes, and hosts a browser-based photometry tools package (Gomez & Fitzgerald, 2017; Gould et al., 2012). Teachers were also able to request images from the Las Cumbres Observatory (LCO) Global Telescope Network (Brown et al., 2013), which facilitates exoplanet observations for students (Sarva et al., 2020). A Unistellar and SETI Institute citizen science network was also made available to AME teachers through a prototype education image and data request program called Unistellar Observation Requests for Education (UOR for Ed.). The citizen scientists who belong to this network use portable Unistellar eVscopes, which can acquire images of deep space objects and image data from exoplanets (Marchis et al., 2020; Peluso et al., 2023). UOR for Ed. allowed teachers to submit a request for an image or scientific observation (e.g., exoplanets) for their class. Requests were filtered and shared with Unistellar citizen scientists, then images or data captured were shared with the teacher who made the request. In addition, we facilitated the donation of an eVscope to the AME Workshop teacher whose students we studied.

In addition to the DIY Planet Search photometry tool, teachers learned to use SalsaJ, an astronomical image software developed for GHOU (Doran et al., 2012; Mora, 2022; Rollinde, 2019), as well as a GHOU edited version of JS9 (Cominsky et al., 2021; Matilsky, 2020; Noel et al., 2020), a browser-based, but more limited version of SalsaJ. Most teachers opted to use JS9 since SalsaJ required users to download and install it onto their local machine, an issue for many teachers as there are bureaucratic barriers to installing software on student computers.

Teacher & Student Participants

Of the 24 teachers who took the AME Workshop, 14 consented to participate in the research. One taught college and high school level physical science in Canada; the other 13 taught high school science in the US. Table 2 outlines various demographics for the teacher participants.

Table 2. Participant demographics for 14 AME teacher workshop participants.

Demographic Variables		Percentage
Gender		
	female	36%
	male	64%
Highest level of educational achievement		
	bachelor's degree	14%
	master's degree	79%
	doctoral	7%
College major		
	physics or physics education	50%
	astronomy or astrophysics	22%
	chemistry education	14%
	plant pathology or environmental science	14%
Primary teaching assignment		
	physics	79%
	chemistry	7%
	earth and space science	7%
	astronomy	7%

Years taught		
	1-5	29%
	6-10	21%
	10-15	29%
	16-20	7%
	21-25	14%
School type		
	public	57%
	private	43%
School size		
	>1000 students	29%
	~500 students	36%
	<500 students	36%
School location		
	urban	36%
	suburban	43%
	rural	21%
Student population		
	>50% student population free and reduced lunch	29%

Nineteen high school students who attended a public high school in the Northeastern US consented to participate in the study: 9 male, 9 female, 1 non-binary. Over half (50%) of students at this school received free or reduced lunch.

Teacher & Student Surveys

All teachers and students were given pre- and post-course surveys. We examined this data for statistically significant differences in pre- and post-test results using a dependent samples t-test to identify the direction of this difference, with $\alpha = 0.05$. For Likert scale data to measure qualities such as self-efficacy, motivation, confidence, etc., we found median differences between pre and post results.

Teacher Surveys

Teacher Survey Measures & Procedure

A pre- and a post-course survey and one delayed post-course survey were administered to teachers who participated in the AME Workshop to measure the effects of the course on teacher motivation, content knowledge, confidence, changes in pedagogy, and teacher self-efficacy.

To measure changes in astronomy content knowledge, we used the Test of Astronomy STandards (TOAST) (Slater, 2014), which has proven to be a reliable and valid instrument by Cronbach alpha and classical test theory analyses (Slater, 2014). In addition, to assess teacher competence in areas of specific relevance to the AME Workshop, such as exoplanets and observational astronomy, we designed a short assessment titled the Observational Astronomy Test Standards (OATS) (see Appendix).

To measure changes in teacher motivation, confidence, pedagogy, and general self-efficacy we adapted the Science Teaching Efficacy Belief Instrument (STEBI) (Riggs & Enochs, 1990) by replacing the word "science" with the word "astronomy" wherever it occurred, and renamed it STEBI for Astronomy (STEBI-AST, see Appendix). Additionally, we converted the STEBI-AST Likert scale to a scale ranging from 1 (strongly disagree) to 5 (strongly agree). The original STEBI was in reverse order. In analysing STEBI-AST data, questions that were phrased in the negative (questions 3, 6, 8, 10, 13, 17, 19-22, 24-25) were recoded so that pre and post results would give a consistent picture of teachers' self-efficacy.

To gauge the persistence of effects post-course, we administered a short 6 question Likert scale follow up survey 10 months after the AME Workshop for teachers ended. The response scales for this follow-up survey ranged from 1 (strongly disagree) to 4 (strongly agree). The follow-up survey questions focused on changes in astronomy teaching confidence and motivation following their 2022 AME Workshop experience.

All participants in the workshop were invited to complete the surveys, however, only results of those who chose to participate in the research study and completed both the pre- and post-surveys are reported here. Surveys were administered online using AMTA's Secure Online Assessment Repository, except the follow up survey, which was given via a secure password protected Google form. All results were anonymous.

Student Surveys

Student Survey Measures & Procedure

For students, 1 pre- and post-course survey was used to measure changes in astronomy concept knowledge. We utilized the same TOAST (Slater, 2014) assessment as with the teachers. We did not administer OATS to students.

Students were invited to participate in the study by their astronomy teacher, Percy Munoz (pseudonym) during their AME inspired astronomy course (Aug. 2022 – Jan. 2022). Munoz had all students from his two sections of high school astronomy complete both surveys, but we only report results from those who returned consent and assent forms and who completed both the pre- and post-course surveys. Surveys were given by Mr. Munoz during his two classes. He replaced student names with anonymous identifiers before forwarding the data to the research team.

Nineteen students ($N = 19$) completed the consent and assent process.

Methodology & Analysis for Teacher & Student Interviews

Qualitative data from teachers and students were collected using semi-structured interviews. Semi-structured interviews are advantageous by allowing reciprocity with both the interviewer and participant (Galletta, 2013) and improvisation from the interviewer (Rubin & Rubin, 2005) for a more organic and stimulating conversation to help provide context for the interview subject. Separate interview protocols were created for both teachers and students to help focus discussions.

Teacher interviews focused on confidence, motivation, competence, various challenges associated with AME and its implementation, suggestions regarding future AME Workshops, and changes in pedagogy. The semi-structured format allowed for the emergence of other topics, such as past, current, or future students, and other topics in science or astronomy education.

In student interviews, participants were initially asked to summarize what they were learning in their astronomy course. Then, students' astronomy concept knowledge was probed as well as their motivation and interest in astronomy and other STEM disciplines and careers.

All 21 interviews were conducted by the same investigator via Zoom and recorded for later analysis. Audio recordings from the interviews were digitally transcribed to text format by video and audio editing software, Descript (Descript), which produced 276 pages of interview transcripts. Interviews were then read and coded to identify utterances related to categories suggested by research questions. Teacher and student names were replaced with pseudonyms to preserve anonymity. A rubric was designed to assign a point value to each coded utterance (Table 3). Total scores were then tallied for each category (Table 5 – Teachers, Table 7 – Students).

Table 2. Scoring rubric for teacher and student interview analysis.

Description	Approximate Length of Utterance	Point Value Assigned Per Utterance
Simple and short answer with little context or value.	words to full sentence	1
Moderately complex answer with moderate context or value.	full to few sentence(s)	2
Significantly complex answer with significant context or value.	several sentences or longer	3

Teacher & Student Interview Samples

A total of 5 teachers participated in three rounds of interviews. Interviews were conducted during the AME Workshop (N = 5), shortly after it ended (N = 4), and concluded with a final interview ~10 months after the AME workshop (N = 3). A total of 5 students participated in 2 rounds of semi-structured interviews. Student interviews occurred in the middle (N = 5) and conclusion (N = 4) of their astronomy/AME course.

Results

Teacher Survey Results

TOAST consisted of 27 questions and OATS had 10 questions. The combined scores for TOAST & OATS ranged from 22 to 37 in the pre-test and 27 and 37 for the post-test (only one respondent had a perfect score for each survey, and it was not the same respondent). For TOAST & OATS (N = 12), STEBI-AST (N = 10). The results of a paired t-test from the teachers' combined TOAST & OATS pre-test (M = 31.3, SD = 4.62) and post-test (M = 32.5, SD = 3.12) indicated that content and conceptual knowledge improved significantly, $t(12) = 2.20$, $p < 0.05$. In contrast, the results of a Wilcoxon-Mann-Whitney test yielded a $p > 0.05$, and thus a non-significant improvement, which is likely the result of the small sample size and somewhat non-normal distribution of scores.

Comparing the results from the teachers' separated TOAST and OATS results also produced significant results. Teacher TOAST pre-test (M = 23.08, SD = 3.06) and post-test (M = 23.75, SD = 2.56) revealed that content and conceptual knowledge improved significantly, $t(12) = 2.20$, $p < 0.001$ and results from the teacher's OATS pre-test (M = 8.25, SD = 1.86) and post-test (M = 8.75, SD = 0.87) likewise revealed that content and conceptual knowledge improved significantly, $t(12) = 2.20$, $p < 0.01$.

Teacher Survey Results: STEBI-AST

STEBI-AST results (Figure 1) showed little change from pre to post from an already fairly confident group of teachers. Questions 11, 20, and 25 showed a slight decrease, while questions 3, 5, 8, 10, 13, 16 ,17, and 19 had positive shifts. Question 5 (teacher confidence in astronomy pedagogy and competence) showed the greatest increase. Only question 11 (teaching philosophy) from post-course responses scored below a 3 and overall there were more items of increase (10) in self-efficacy than a decrease (3).

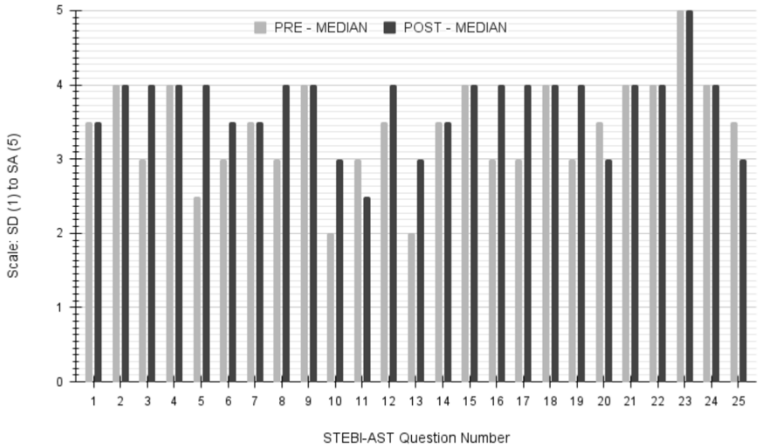

Figure 1 Caption: Bar chart comparing pre and post median results from teacher responses of the STEBI-AST. SD = strongly disagree and SA = strongly agree.

Teacher Survey Results: Follow Up Survey

Eleven teachers completed the follow-up survey (Table 4). Results from statements 1-4 show that most teachers report an increase in confidence and motivation to teach astronomy using Modeling pedagogy. The response for statement 3 from one participant for “strongly disagree” was clarified by the participant’s free response comment that he “was already strongly motivated” before the workshop, and by the same participant for statement 6 that his administration was making it challenging for him to do so. Statements 5 and 6 also show increased motivation, but towards including more astronomy in other classes and attempts to expand astronomy offerings.

Table 3. Results from the extended follow up survey ~10 months after the conclusion of the teacher AME workshop.

Statement	Percentage of Respondents			
	Strongly Disagree (1)	Disagree (2)	Agree (3)	Strongly Agree (4)
1. I am more confident in using Modeling Instruction in my science classes since taking the 2022 Astronomy Modeling with Exoplanets course.	0.0%	0.0%	27.3%	72.7%
2. I am more confident in my ability to teach astronomy.	0.0%	0.0%	27.3%	72.7%
3. I am more motivated to teach astronomy than I was prior to attending Astronomy Modeling with Exoplanets.	9.1%	0.0%	18.2%	72.7%
4. I am more motivated to teach astronomy using Modeling curriculum resources that include astrophysical data in student learning activities.	0.0%	0.0%	18.2%	81.8%
5. I am trying to include more astronomy concepts in my non-astronomy classes (e.g., physics, chemistry, earth and space science, etc.).	9.1%	18.2%	45.5%	27.3%
6. I am advocating for a new astronomy class at my school where none exists or trying to expand upon my school's current astronomy course(s) (e.g., more offerings, yearlong versus semester, etc.).	9.1%	18.2%	27.3%	45.5%

Student Survey Results: TOAST

The scores for the student TOAST ranged from 2 to 18 in the pre-test and 5 and 20 for the post-test. The results of a paired t-test from the students' TOAST pre-test ($M = 8.68$, $SD = 3.23$) and post-test ($M = 11.1$, $SD = 4.09$) revealed that content and conceptual knowledge improved significantly, $t(19) = 2.10$, $p < 0.001$. These greater gains in comparison with teacher results on TOAST are not unexpected as teachers had greater content knowledge at the start of the AME workshop than did students at the beginning of their astronomy course. However, and in contrast, the results of a Wilcoxon-Mann-Whitney test yielded a $p > 0.05$, and thus a non-significant improvement, which like our teacher data is likely the result of the small sample size and somewhat non-normal distribution of scores.

UOR for Ed. Use

The availability of UOR for Ed. resulted in 14 AME teachers requesting images of asteroids, stars, star clusters, nebulae, and galaxies. This yielded 115 images from nine participating Unistellar citizen scientists. We also polled 21 citizen scientists on their interest in undertaking an exoplanet observation for middle or high school teachers and 90% had interest. From 4 teacher requests, 2 exoplanet transit observations were attempted, which resulted in 1 successful transit light curve for exoplanet, Qatar-1b.

Teacher Interview Results

While analyzing the interview data qualitative coding yielded categories directly and indirectly related to our research questions. Utterance scores from interviews from each coded category are provided in Table 5. Below we also quote from interviews transcripts that exemplify passages coded for these categories. Some interview excerpts were placed in multiple categories but are titled for their primary theme.

Table 4. Teacher utterance scores by category. Each utterance found within the interviews was assigned a point value according to the rubric from Table 2. These points were then summated for *each category. "Telescope use" consisted of utterances related to LCO, DIY Planet Search/MicroObservatory, or Unistellar eVscopes. "Image analysis" consisted of utterances related to JS9 or SalsaJ. Categories with a * indicate those directly related to* research questions.

Teacher Categories	Utterance Score
*Changes in pedagogy	86
Motivation	66
Using data with students	51
*Increased student engagement	50
*Confidence/self-efficacy	49
Telescope use or image analysis	43
Competence, knowledge, or skills	30
Challenges in using Modeling Astronomy curriculum	29
Concept of exoplanets used in learning	25

Changes in pedagogy

All teachers interviewed described marked changes in how they approached teaching astronomy. For example:

"This class really showed me, like, maybe the data's not coming in a package with my textbook, but a lot of it's out there and I need to really, you know, seek out those data sets and find ways to bring that into each unit within astronomy."
(Camelia Preston, teacher)

"I would say the new part was doing more of this data processing with the lens of teaching and learning versus just pure research . . . that was pretty important."
(Melissa Fennimore, teacher)

Even so, teachers also expressed concerns with their students' ability to adjust to a more data-intensive course and 4 of the 5 (80%) interviewed expressed concern on some level with their ability to cover everything they learned in AME. These concerns could limit teacher ability to achieve their stated desire for making pedagogical changes.

"[With] data analysis there's always some sort of . . . procedure that you have to do with the data that might be a little bit of a steep learning [curve]."
(Melissa Fennimore, teacher)

"I'm trying to frame it from a half year course . . . the average student probably isn't gonna be able to do things quickly or super in-depth . . . I would definitely have to pick and choose what's done . . . definitely wouldn't get to all the units."
(Bradley Watson, teacher)

Additionally, there was also concern among two teachers about their ability to even offer an astronomy course. For example:

"[The new administration] shelved all new electives unless there was a certification that they could point to that students could like obtain."
(Bradley Watson, teacher)

Self-Efficacy & Confidence

Teachers reported their self-efficacy was improved as a result of feeling they were a part of a group of other teachers in similar situations and skill levels. Additionally, getting exposure to astronomical tools (e.g., JS9), learning image analysis, and working with provided and collected datasets in the workshop increased their confidence.

"It was just a real confidence boost because I kind of felt like I was like in my own little astronomy bubble in my school . . . Nice to just be with a group of other educators and . . . just to kind of be like, oh okay, I am doing the right things and now here's ways that I can do it better."
(Melissa Fennimore, teacher)

"I [was] intimidated by the tools . . . data taking tools . . . being forced to use them and learn how they work . . . that was really helpful and now I'm not as intimidated by them."
(Bradley Watson, teacher)

"I feel a lot more comfortable . . . [before] in astronomy, I didn't have data sets, I didn't have an idea of how to do that . . . felt like I had to just teach all the textbook and with videos . . . I didn't . . . have . . . data sets . . . I felt frustrated . . . and I feel like it was so much richer this year . . . we got kids really thinking like scientists about data . . . I really feel like we can do some original research . . . take some telescope data and you know get some photometry data and do something with it. I feel like I have capacity to do that now . . . this [workshop] gave me the foundation to at least teach in a way that's a lot more engaging, that gets kids curious and really developing habits of mind and not just memorizing facts."

(Camelia Preston, teacher)

Regardless of the increased confidence in working with astronomical data and analyzing images, teachers still felt they needed more practice with photometry skills and programs such as JS9, as follows:

"More photometry skills . . . I feel like we just didn't get enough time on the ground practice."

(Camelia Preston, teacher)

Student Engagement

Bradley Watson's comment below comes from students in his physics class as he was not able to teach a dedicated astronomy course at the time of interviews. Watson, however, did include AME activities within his traditional physics course, which he explained was engaging for his students. The excerpt below, also highlights general student interest in astronomy, which offers evidence that it is a "gateway science":

"Definitely promoted the idea that I want to use Modeling as much as possible . . . mostly for student engagement . . . I think that they actually learn better this way… I put out a survey asking the students if they'd be interested in an astronomy elective just to see what they'd say. I gave it to every physics student I have . . . about a hundred . . . I think we had 49 or something that said that they would be interested in taking it, which is pretty good."

(Bradley Watson, teacher)

The following interview excerpt gives interesting details about one teacher's experience with increased student engagement in his astronomy course:

"We're not just building bridges with popsicle sticks, you know . . . [we're] using photometry and images and [exoplanet] transit data . . . that's STEM, you know . . . [and it] doesn't have to [only] be in an astronomy course…I was integrating exoplanet[s] into my class . . . [exoplanet] transit data . . . [we] talked about the Trappist [exoplanet] system . . . talked about exoplanets quite a bit . . . then we went and saw [a] movie [at] the planetarium . . . [students] were like, 'oh, well,

> they need to update their movie. We [students] know a lot more than that movie because [it] was a few years old' . . . So yeah . . . I thought that was pretty neat! . . . I've actually doubled you know, almost doubled the number of kids taking astronomy."
>
> (Percy Munoz, teacher)

There was no evidence from teacher interviews that indicated any decrease in or difficulty with student engagement.

The Percy Munoz Case Study

Percy Munoz is a 60-year-old Caucasian male who became a credentialed teacher after working as an engineer. He has primarily taught physics for the past 12 years and only recently began teaching astronomy. His post-secondary education was in physics, and he had no formal education in astronomy before AME. To complement his participation in this study, Mr. Munoz received a Unistellar eVscope for use with his students. He communicated more often with the researchers than other teacher participants, particularly with respect to training in how to operate his Unistellar eVscope and integrate its use into his astronomy course. Munoz also participated in the same semi-structured teacher interviews as other teacher participants. Table 6 summarizes important changes for Munoz from pre and post intervention.

Table 5. Summary of interesting results related to changes in pedagogy, self-efficacy, and identity from before and after the AME Workshop with Percy Munoz.

Percy Munoz Case Study Summary	
Pre AME Workshop	Post AME Workshop
No involvement in local astronomy clubs.	Very active member of a local astronomy club.
Had a telescope, but hadn't used it in years.	Uses eVscope regularly (~5 times/month) and attributes better understanding of astronomy and motivation for teaching to it, as well as student excitement/engagement around his use and sharing with class.
Used "Starry Night" astronomy curriculum and student complained about "oh another worksheet".	Students are more engaged in a more active (Modeling) class using whiteboards, real data, and Google Jamboards.
Never involved students in his own observation of an exoplanet.	Included students in an attempted observation of a real exoplanet and students were engaged/excited about this.

Taught only a 1 semester-long section of astronomy for the academic year.	Went from 1 section of astronomy (2020-2021) when teaching with "Starry Night" curriculum to 1 section for each semester when first starting astronomy Modeling (2021-2022) to 3 sections in the current academic year (2022-2023).
Self-assessed himself 3/10 on confidence in teaching astronomy.	Self-assessed himself 8/10 on confidence in teaching astronomy.

Munoz details increased motivation for offering astronomy as a year-long elective to stand alongside other rigorous courses offered at his school and an increase in his enthusiasm for teaching it:

> "Some of [Astronomy Modeling] is more difficult than my school has typically put into an elective . . . we [do] have electives [that] are sort of serious electives . . . rigorous . . . like human anatomy and physiology . . . or AP environmental . . . then we have other electives that are like marine science and wildlife and astronomy and those are all sort of been in the more general easier survey level electives . . . [with] the material [I'm using now] it's become more serious in content, which is why I'm trying to push for [astronomy] to become a yearlong course."
> (Percy Munoz, teacher)
>
> "Every time I show [students] something, I'm like, God, this is, this is real. We're not just reading about a planet in a textbook. This is, this is real stuff that real astronomers are doing right now . . . I will say very clearly that [the workshop] has increased my enthusiasm to teach astronomy."
> (Percy Munoz, teacher)

Munoz increased his use of telescopes both personally and within his class, which also showed changes in how he taught and increased self-efficacy:

> "I've never really looked through a telescope that much. I've done it more in the past six months than I have ever."
> (Percy Munoz, teacher)
>
> "The eVscope for me is a game change . . . [I'm] more confident . . . When I talk [to students] about that [eVscope exoplanet] observation . . . present [the data] to the kids . . . the mistakes I made [observing] . . . that's like what it's all about to be a teacher . . . I was able to talk about my [exoplanet observation] . . . we're bringing real data into the classroom. We're not just [doing] the same old experiment . . . when you show that to the kids . . . you're showing them something that's actually happening right now . . . working with real data . . . that's gonna hook kids . . . it's not a textbook."
> (Percy Munoz, teacher)

Although Munoz brought in a unique experience to his students with the eVscope, use of it to collect original data for his classes was limited because of a lack of experience observing exoplanets, weather, and time to commit to long exoplanet observations which take 3-5 hours on average to capture. Munoz did attempt the exoplanet observation of HAT-P-32b in December 2022, which his students helped him to plan as part of their learning experience. However, this was the only attempt, and it did not result in a detection because of poor focusing and collimation of the instrument, which resulted in unusable data. Even so, Munoz shared students had some of the highest levels of engagement and excitement during this exercise and learned fundamental observational astronomy techniques not typical in a high school course. Additionally, Munoz shared that learning from the challenges encountered in conducting an exoplanet observation was also a valuable learning experience for his students to understand how real science can be messy and not always successful, but that it does give investigators important lessons to learn from.

Student Interview Results

As with teacher interview data, qualitative coding yielded categories directly and indirectly related to our research questions. Utterance scores from interviews from each coded category for students are provided in Table 7. Excerpts are reported in similar fashion as teachers excerpts.

Table 6. Student interview utterance scores by category. The same utterance scoring methodology and definitions for *"Telescope use" and "image analysis" as used in Table 4 were followed here. Categories with a * indicate those* related to research questions.

Student Categories	Utterance Score
*Competence, knowledge, or skills	43
*Increased student interest and engagement	41
Concept of exoplanets used in learning	27
Motivation to learn about astronomy and STEM	26
Using data in class learning	14
Challenges in learning in the Modeling Astronomy course	12
Noticing a different way of teaching/learning, i.e., Modeling Instruction	11
Telescope use or image analysis	9
Motivation in pursuing astronomy or STEM career	7
Science identity	5

Competence, Knowledge, or Skills

The following excerpts illustrate increases in student competence related to spatial reasoning, celestial mechanics, observational astronomy, and exoplanets:

"It makes sense now . . . I can look up in the sky and understand when things are gonna happen and why."

(Loren, high school student)

"[I learned] how they map out the planets and like the stars and all that stuff . . . around the . . . Earth . . . you gotta have a way to tell other people where things are . . . pretty interesting learning how they do that. And then, yeah the exoplanets."

(Bobby, high school student)

All students reported increases in competence, however, two students also detailed specific concepts that were especially challenging:

"Sometimes it's hard to understand like the measurement or like how far away things are to like process it cause it's just so big or measurements are so big."

(Courtney, high school student)

"Coordinates and how to locate something in the sky . . . that was pretty difficult . . . I wish I got a bit more experience in actually working with the night sky instead of on the computer."

(Loren, high school student)

And one student shared concern about the amount of material in his astronomy course:

"You can't cover all of astronomy in half a semester."

(Emmett, high school student)

Student Engagement

Students expressed interest and enthusiasm for the more explorative and research-based nature of their astronomy Modeling course, such as:

"In most [other] science classes, it's a bit more strict . . . [This] astronomy class is more explorative . . . [Interesting] knowing that there's other stuff out there that we barely even hear of, and we recently just did the Drake equation and stuff and calculating chances of [extraterrestrial intelligence]. I thought that was interesting."

(Courtney, high school student)

"This [astronomy course is] more research based and you're trying to figure it out on your own by doing your own research . . . rather than the other thing, which is basically they lead you along the entire way . . . it's like more independent . . . not that much lecturing . . . other ways of teaching."

(Bobby, high school student)

Only one student shared a specific aspect of the course (lecturing) related to these categories that was not engaging for him:

"The [parts] I don't really care for . . . maybe just the sitting there and listening portions."

(Emmett, high school student)

Unistellar Telescopes & Student Engagement

Several students sounded excited about the prospect of using the telescope:

> "[The telescope] seems pretty cool. It seems fancy and like we could see some pretty cool things with it."
>
> (Courtney, high school student)
>
> "I do know we're gonna do some more stuff with telescopes . . . I'm excited."
>
> (Loren, high school student)
>
> "[Our teacher] said that he has like this telescope thing. It's the fancy telescope and you tell it where you wanted to look at, you know, like swivel around and look at that . . . he was planning to take some photos and some stuff and then bring them in and then teach us about that . . . that's gonna be pretty cool because, you know it's like more hands-on stuff . . . the stars and all that stuff . .. it gives us a way to actually see stuff."
>
> (Bobby, high school student)

In contrast, one student shared she wished there was more time and practice with the eVscope and was disappointed that her class did not get the data they attempted:

> ". . . more familiarity with the tools we're using. Like it was a great opportunity to have that telescope and everything, but it was brand new, so we didn't have enough practice with it, and we weren't able to get like great data I guess."
>
> (Courtney, high school student)

Motivation, Using Data, Competence, & Student Engagement

The following excerpt illustrates the convergence of several coded categories in a single statement and the excitement around the topic of exoplanets:

> "Oh this [exoplanet data] is real. Data that's happening right now, and not just like something that was discovered 50 years ago . . . learning about more current events and being able to understand that data was really exciting . . . I found [it] wasn't too complicated . . . I want to know a bit more about exoplanets . . . finding planets . . . comparing it to Earth or other planets we know . . . I find very interesting. Cause we live on a planet. So what's so different about all of them?"
>
> (Loren, high school student)

It is worthy of note that student interviews were much shorter and not as in-depth as teacher interviews. Students had limited time to speak with the investigator and seemed hesitant to express more critical feedback related to the categories shared here.

Discussion

Even with a small sample size, we saw significant increases in teacher (TOAST and OATS) and student scores (TOAST) that indicate increases in astronomy content knowledge and skills. STEBI-AST results suggest that teachers experienced shifts in their confidence and self-efficacy. The three questions reporting a slight decrease in median from the STEBI-AST were statements having more to do with a general philosophy of student learning than teachers' self-efficacy for astronomy teaching. Moreover, the interviews gave context for what teachers and students were thinking and helped us to draw tentative conclusions when comparing qualitative and quantitative results. As such, teacher interviews provided context for the increases we saw in self-efficacy, such as teachers feeling a part of a group and getting exposure to previously intimidating skills such as photometry and image analysis.

On the basis of the highest interview utterance scores from teachers (i.e., changes in pedagogy) and students (i.e., increase in competence and engagement), it appears that teachers noticed a change in how they taught and this resulted in students having positive classroom outcomes. Teachers were motivated to use astronomical data with their students, and both teachers and students agreed that engagement was improved in the classroom. Another theme that was consistent across teacher and student responses was the excitement about active student-driven learning using real astronomical data from exoplanets using telescopes that students controlled rather than just learning things from lectures or a textbook.

One student shared difficulty in understanding astronomical distance scales. However, this student also expressed the most excitement about working with and analysing real astronomical data. This supports the notion that rigor, in the right context, can be a motivating factor for students. Another student shared problems with finding things in the sky from a lack of practice doing so away from a computer, which suggests more attention should be paid to providing student activities with such experiences.

With Percy Munoz, we saw changes in confidence, motivation, competence, pedagogy, and even teacher identity. Munoz considers himself an active citizen astronomer now, whereas before he had only a mild interest in astronomy and no formal training in it. Additionally, his excitement about teaching and doing astronomy and his motivation and confidence from his growing astronomy skills seems to have rubbed off on his students, as evident in their increased interest and engagement in class. Munoz is the only AME teacher who received and used an eVscope with his students. The availability of this in situ telescope (versus the remotely operated DIY or LCO) clearly brought additional excitement, learning, and motivation to him and his students.

Other programs, such as Course-based Undergraduate Research Experiences (CUREs) are exploring similar avenues as AME. The Arizona State University (ASU) CUREs project to bring exoplanet research to online astronomy classrooms is a noteworthy example where students use remote robotic telescopes (e.g., LCO) and work to interpret and analyze exoplanet data (Hewitt et al., 2023; Simon et al, 2022). Our AME program, and the exoplanet content of which is very similar to that of CUREs (a program for college undergrads), was presented to and utilized by high school teachers in their elective astronomy courses. Comparing these studies showcases that programs such as AME and CUREs can be effective for both high school and college level students. Additionally, workshops like AME can allow out-of-field high school teachers with educational backgrounds below instructors at the college and university level (e.g., ASU) to deliver such research experiences to high school students.

For a broad implementation of AME, challenges still exist. All the teachers we spoke to who taught a dedicated astronomy class only taught a one-semester course. This points to a need for further work since the current AME curriculum is presently too extensive to fit into a one-semester high school level astronomy course. The AME course will need to be slimmed down for this use case, however, as exemplified by Mr. Munoz's efforts this also may motivate the creation of year-long astronomy courses.

Implications for Further Research

Future MI astronomy research will explore a more robust study with a larger and more diverse sample size of both teachers and students. An extended study would allow us to follow both teachers and students to assess long-term effects on teaching, learning, identity, and career interest.

We are seeking additional opportunities for teachers and their students to have more unhindered access to telescopes capable of collecting data in real time for teaching and student learning projects. One possible avenue is funding the placement of eVscopes with AME teachers and students and devoting more time and resources to a widespread UOR for Ed. program. These efforts could afford research foci on student engagement, learning, and science identity, as it is impacted by access to in situ eVscopes. Past research show increases in student engagement and learning when students acquire their own images from remote telescopes (Gould et al., 2006; Marshall et al., 2015). However, apart from results from our case study, less is known if this may be affected by, instead, using in situ telescopes capable of data collection (e.g., eVscopes). Even though our eVscope intervention showed some promise, it was not without challenges. Future work should include more teacher eVscope training, practice with collimation and focus, and additional exoplanet observations facilitated by investigators. These changes may increase data acquisition successes (e.g., exoplanet detections) to measure the success and value of such an intervention more adequately.

We also plan to add computer programming to a future MI astronomy workshop so students can use and write coding scripts with either Google Colaboratory or Jupyter Notebooks to automate and streamline the analysis of large numbers of images generated by an exoplanet transit observation. Programming and data science are ubiquitous in modern astronomy and are important skills needed for our modern economy (Kong & Abelson, 2019). In an unrelated mid-course survey, most AME teachers agreed it is essential for students to learn how to write or interpret code for data analysis, however, most also indicated discomfort or lack of training and confidence in their ability to teach these skills.

Implications for Instruction

The Percy Munoz case study has illustrated the power and potential for improving science education through the development of teacher skills and confidence to fashion a student-driven learning environment. When teachers implement more student-centered data-driven learning experiences student engagement and learning increase. Physical science and physics teachers should be encouraged to fold astrophysics into their courses to capitalize on student interest in astronomy concepts (e.g., Bradley Watson mentioned during one interview that his physics students became more excited when they discussed astronomy related topics).

It may be time to rethink the status quo B-C-P sequence. Initiatives such as Physics First (physics as a required high school freshman course) have been shown to be a promising alternative (Glasser, 2012; Lederman, 2005; Scannell, 2019). Outdated education models that do not adapt to modern education research, create opportunities to prime our STEM and space workforce pipeline, and capitalize on student interests (e.g., space and astronomy) are ripe for re-examination and reform. A data science-rich astronomy course should qualify as a college entry science requirement. Mr. Watson's account that his administration was dropping electives that did not award a certification could be an opportunity for schools to offer astronomy for college credit in dual enrolment settings. With astronomy's intrinsic motivational power and the fact that students were highly motivated by working with real astronomical data, a year-long astrophysics course should be recognized as an equivalent learning experience to high school physics as suggested by both teacher and student interviews.

Conclusions

Of the 8.8 million professional scientists worldwide (Lewis et al., 2021), only 0.114% (~10,000) are professional astronomers (Forbes, 2008). Our future economy is moving outward into space (Butow et al., 2020; Foundation, 2021) and excitement about astronomy is widespread, as evident by student interest in life beyond Earth (Morgan, 2017), public interest in the latest JWST images and the next earth-like exoplanets, and space themes in television and movies (National Academies of Sciences, 2021). Astronomy does not have to remain on the side-lines of our outdated B-C-P status quo. It can stand on its own as a rigorous science course that has the potential to engage and motivate both teachers and students and prepare our STEM and space workforce pipeline for our future economic and social success and security.

In this study, despite a modest sample size, we saw significant improvements in content knowledge in both teachers and students. Teachers reported changes in their pedagogy, motivation, and using astronomical data with students. Students reported being more engaged by working with real exoplanet data and overall excitement and interest in the course content. Students also said that they preferred exploring the cosmos and working with data they collected to search for planets around distant stars over learning from a textbook or lecture.

This work shows that a data-driven astrophysics course for regular education students is feasible at a public high school. Further, this study revealed that even if most teachers do not have post-secondary preparation in astronomy, AME and the wonders of the universe can equip them with the requisite confidence and competence to deliver a rigorous and engaging astronomy learning experience for their students.

Limitations

The primary limitation of this study was a small sample size. A larger sample would allow the study to incorporate more diverse demographics from both teacher and student populations to yield more broadly applicable conclusions and provide a more detailed picture of the effects of AME on various demographics. In addition, a larger sample size would provide the necessary data to determine the validity and reliability of our OATS and STEBI-AST survey instruments.

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References

Akbari, R., & Allvar, N. K. (2010). L2 Teacher Characteristics as Predictors of Students' Academic Achievement. Tesl-Ej, 13(4), n4.

Ames, C. (1992). Classrooms: Goals, structures, and student motivation. Journal of educational psychology, 84(3), 261.

Bandura, A. (1986). Social foundations of thought and action. Englewood Cliffs, NJ, 1986(23-28).

Bandura, A., & Wessels, S. (1994). Self-Efficacy (Vol. 4). Academic Press.

Bartlett, S., Fitzgerald, M. T., McKinnon, D. H., Danaia, L., & Lazendic-Galloway, J. (2018). Astronomy and Science Student Attitudes (ASSA): a short review and validation of a new instrument. Journal of Astronomy & Earth Sciences Education (JAESE), 5(1), 1-22.

Bishop, J. E. (1990). The Committee of Ten. International Astronomical Union Colloquium, 105, 253-257. https://doi.org/10.1017/S0252921100086899

Bishop, J. E. (2003). Pre-College Astronomy Education in the United States in the Twentieth Century. In A. Heck (Ed.), Information Handling in Astronomy - Historical Vistas (Vol. 285, pp. 207-231). Springer Netherlands. https://doi.org/10.1007/0-306-48080-8_12

Bray-Clark, N., & Bates, R. (2003). Self-efficacy beliefs and teacher effectiveness: Implications for professional development. Professional Educator, 26(1), 13-22.

Brogt, E. (2009). Pedagogical and curricular thinking of professional astronomers teaching the Hertzsprung-Russell diagram in introductory astronomy courses for non-science majors. The University of Arizona.

Brogt, E., & Draeger, J. D. (2015). Academic Rigor in General Education, Introductory Astronomy Courses for Nonscience Majors. The Journal of General Education, 64(1), 14-29.

Brown, T. M., Baliber, N., Bianco, F. B., Bowman, M., Burleson, B., Conway, P., . . . Willis, M. (2013). Las Cumbres Observatory Global Telescope Network. Publications of the Astronomical Society of the Pacific, 125(931), 1031-1055. https://doi.org/10.1086/673168

Brunsell, E., & Marcks, J. (2005). Identifying a baseline for teachers' astronomy content knowledge. Astronomy Education Review, 2(3), 38-46.

Butow, S. J., Cooley, T., Felt, E., & Mozer, J. B. (2020). State of the Space Industrial Base 2020: A Time for Action to Sustain US Economic and Military Leadership in Space. https://apps.dtic.mil/sti/citations/AD1106608

Çakiroglu, J., Çakiroglu, E., & Boone, W. J. (2005). Pre-Service Teacher Self-Efficacy Beliefs Regarding Science Teaching: A Comparison of Pre-Service Teachers in Turkey and the USA. Science Educator, 14(1), 31-40.

Carpenter, S., Colbert, S., Gosnell, R., Gould, A., Grener, D., Lohman, R., . . . Perazzo, J. (2018). The Hands-On Universe Project and Modeling Instruction Based HOU: MI-HOU. RTSRE Proceedings, 1(1). https://doi.org/10.32374/rtsre.2017.017

Cominsky, L., Peticolas, L., Bartolone, G., Dussault, M., Zellem, R., Smith, D., . . . Lestition, K. (2021). Astronomy from Home: Informal Learning with Robotic Telescopes. Astronomical Society of the Pacific Conference Series,

Council, N. R. (2012). A framework for K-12 science education: Practices, crosscutting concepts, and core ideas. National Academies Press.

Council, N. R. (2013). Next generation science standards: For states, by states. In: Washington DC: National Academy of Sciences.

Council, N. R. (2015). Guide to implementing the next generation science standards. National Academies Press.

Creswell, J. W., & Clark, V. L. P. (2017). Designing and conducting mixed methods research. Sage publications.

De Neve, D., Devos, G., & Tuytens, M. (2015). The importance of job resources and self-efficacy for beginning teachers' professional learning in differentiated instruction. Teaching and Teacher Education, 47, 30-41. https://doi.org/https://doi.org/10.1016/j.tate.2014.12.003

Descript. Retrieved 1 April 2023 from https://www.descript.com/

Doran, R., Melchior, A.-L., Boudier, T., Ferlet, R., Almeida, M. L., Barbosa, D., . . . Roberts, S. (2012). Astrophysics datamining in the classroom: Exploring real data with new software tools and robotic telescopes. arXiv preprint arXiv:1202.2764.

Forbes, D. A. (2008). So you want to be a professional astronomer! arXiv preprint arXiv:0805.2624.

Foundation, S. (2021). The Space Report 2021, Quarter 2: The Authoritative Guide to Global Space Activity. https://thespacereport.org/register/the-space-report-2021-quarter-2-pdf-download/

French, R. S. (2019). Everyone's Universe: Teaching Astronomy in Community Colleges. In Astronomy Education, Volume 1 (pp. 11-11-11-29). IOP Publishing. https://doi.org/10.1088/2514-3433/ab2b42ch11

Galletta, A. (2013). Mastering the semi-structured interview and beyond: From research design to analysis and publication (Vol. 18). NYU press.
Glasser, H. M. (2012). The Numbers Speak: Physics First Supports Math Performance. The Physics Teacher, 50(1), 53-55. https://doi.org/10.1119/1.3670088
Gomez, E. L., & Fitzgerald, M. T. (2017). Robotic telescopes in education. Astronomical Review, 13(1), 28-68. https://doi.org/10.1080/21672857.2017.1303264
Gould, R., Dussault, M., & Sadler, P. (2006). What's Educational about Online Telescopes?: Evaluating 10 Years of MicroObservatory [Article]. Astronomy Education Review, 5(2), 127-145. https://doi.org/10.3847/AER2006022
Gould, R. R., Sunbury, S., & Krumhansl, R. (2012). Using online telescopes to explore exoplanets from the physics classroom. American Journal of Physics, 80(5), 445-451.
Gray, K. M., Blanchard, M. R., & Ragan, S. R. (2017). How autonomy, competence and relatedness influence adoption of modeling instruction. European Science Education Research Association Conference, Dublin, Ireland.
Haag, S., & Megowan, C. (2012). Beyond the Transcript: Factors Influencing the Pursuit of Science and Mathematics Coursework. School Science and Mathematics, 112(8), 455-465. https://doi.org/https://doi.org/10.1111/j.1949-8594.2012.00167.x
Haag, S., & Megowan, C. (2015). Next generation science standards: A national mixed-methods study on teacher readiness. School Science and Mathematics, 115(8), 416-426.
Haag, S., & Megowan-Romanowicz, C. (2021). Building Competence in Science and Engineering. Standards, 1(1), 39-52. https://www.mdpi.com/2305-6703/1/1/5
Hestenes, D. (1997). Modeling methodology for physics teachers. AIP Conference Proceedings, 399(1), 935-958. https://doi.org/10.1063/1.53196
Hestenes, D. (2006). Notes for a modeling theory. Proceedings of the 2006 GIREP conference: Modeling in physics and physics education, Amsterdam: University of Amsterdam.
Hestenes, D., Megowan-Romanowicz, C., Popp, S. E. O., Jackson, J., & Culbertson, R. J. (2011). A graduate program for high school physics and physical science teachers. American Journal of Physics, 79(9), 971-979. https://doi.org/10.1119/1.3602122
Hewitt, H., Simon, M., Mead, C., Haverstock, G., & Anbar, A. (2023). Bringing Exoplanet Research to the Online Astronomy Classroom. American Astronomical Society Meeting Abstracts.
Jackson, J., Dukerich, L., & Hestenes, D. (2008). Modeling Instruction: An Effective Model for Science Education. Science Educator, 17(1), 10.
Johnson, R. B., Onwuegbuzie, A. J., & Turner, L. A. (2007). Toward a Definition of Mixed Methods Research. Journal of Mixed Methods Research, 1(2), 112-133. https://doi.org/10.1177/1558689806298224
Klassen, R. M., & Chiu, M. M. (2010). Effects on teachers' self-efficacy and job satisfaction: Teacher gender, years of experience, and job stress. Journal of educational psychology, 102(3), 741.
Kong, S.-C., & Abelson, H. (2019). Computational thinking education. Springer Nature.
Krumenaker, L. (2009). The modern US high school astronomy course, its status and makeup, and the effects of No Child Left Behind. Astronomy Education Review, 8(1), 1-8. https://doi.org/10.3847/AER2009042

Lederman, L. M. (2005). Physics First? The Physics Teacher, 43(1), 6-7. https://doi.org/10.1119/1.1845981
Lent, R. W., Brown, S. D., & Hackett, G. (2000). Contextual supports and barriers to career choice: A social cognitive analysis. Journal of Counseling Psychology, 47, 36-49. https://doi.org/10.1037/0022-0167.47.1.36
Lewis, J., Schneegans, S., & Straza, T. (2021). UNESCO Science Report: The race against time for smarter development (Vol. 2021). UNESCO Publishing.
MacLeod, K., Razul, M. S. G., & Powell, J. (2015). Pedagogical changes in an astronomy course for non-physics majors: Student and professor perspectives. AIP Conference Proceedings, 1697(1), 120006. https://doi.org/10.1063/1.4937711
Marchis, F., Malvache, A., Marfisi, L., Borot, A., & Arbouch, E. (2020). Unistellar eVscopes: Smart, portable, and easy-to-use telescopes for exploration, interactive learning, and citizen astronomy. Acta Astronautica, 166, 23-28. https://doi.org/https://doi.org/10.1016/j.actaastro.2019.09.028
Marshall, P. J., Lintott, C. J., & Fletcher, L. N. (2015). Ideas for Citizen Science in Astronomy. Annual Review of Astronomy and Astrophysics, 53(1), 247-278. https://doi.org/10.1146/annurev-astro-081913-035959
Matilsky, T. (2020). JS9: An interactive tool for teaching astrophysics. The Physics Teacher, 58(8), 602-603. https://doi.org/10.1119/10.0002391
Megowan-Romanowicz, C. (2023). High School Physics Teacher Survey Data. In: Personal Communication.
Middleton, J. A. (1995). A Study of Intrinsic Motivation in the Mathematics Classroom: A Personal Constructs Approach. Journal for Research in Mathematics Education, 26(3), 254-279. https://doi.org/10.2307/749130
Middleton, J. A., Lesh, R., & Heger, M. (2003). Interest, identity, and social functioning: Central features of modeling activity. In Beyond constructivism: Models and modeling perspectives on mathematics problem solving, learning, and teaching (pp. 405-431). Taylor and Francis.
Middleton, J. A., Littlefield, J., & Lehrer, R. (1992). Gifted students' conceptions of academic fun: An examination of a critical construct for gifted education. Gifted Child Quarterly, 36(1), 38-44.
Mora, J. (2022). How to use SalsaJ Software to Perform Photometry, Astrometry, Image Processing in 3D. *Revista Mexicana de Astronomıa y Astrofisica Serie de* Conferencias (RMxAC), 54, 80-83.
Morgan, D. L. (2017). Measuring the effect of an astrobiology course on student optimism regarding extraterrestrial life. International Journal of Astrobiology, 16(3), 293-295. https://doi.org/10.1017/S1473550416000239
National Academies of Sciences, E., Medicine. (2021). Decadal survey on astronomy and astrophysics 2020. The National Academies Press.
National Academy of Sciences, N. A. o. E., and Institute of Medicine. (2007). Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future. The National Academies Press. https://doi.org/doi:10.17226/11463
Noel, A., Komacek, T., Young, D., & Team, N. A. U. (2020). Galaxy Formation and Stellar Evolution in the National Science Olympiad. American Astronomical Society Meeting Abstracts# 235,
Nurlu, Ö. (2015). Investigation of teachers' mathematics teaching self-efficacy. International Electronic Journal of Elementary Education, 8(1), 21-40. https://www.iejee.com/index.php/IEJEE/article/view/95

Oliveira, V. d. A. (2019). Astronomy, an Amazing First Contact with Science for High School Students. Proceedings of the International Astronomical Union, 15(S367), 439-441. https://doi.org/10.1017/S1743921321000156

Osborne, J., & Collins, S. (2001). Pupils' views of the role and value of the science curriculum: A focus-group study. International Journal of Science Education, 23(5), 441-467. https://doi.org/10.1080/09500690010006518

Peluso, D. O. C., Esposito, T. M., Marchis, F., Dalba, P. A., Sgro, L., Megowan-Romanowicz, C., . . . Scientists, U. C. (2023). The Unistellar Exoplanet Campaign: Citizen Science Results and Inherent Education Opportunities. Publications of the Astronomical Society of the Pacific, 135(1043), 015001. https://doi.org/10.1088/1538-3873/acaa58

Perera, H. N., & John, J. E. (2020). Teachers' self-efficacy beliefs for teaching math: Relations with teacher and student outcomes. Contemporary Educational Psychology, 61, 101842. https://doi.org/https://doi.org/10.1016/j.cedpsych.2020.101842

Riggs, I. M., & Enochs, L. G. (1990). Toward the development of an elementary teacher's science teaching efficacy belief instrument. Science Education, 74(6), 625-637. https://doi.org/https://doi.org/10.1002/sce.3730740605

Rollinde, E. (2019). Modeling astronomy education, the case of F-HOU tools: SalsaJ and Human Orrery. International Astronomical Union. Proceedings of the International Astronomical Union, 15(S367), 53-56. https://doi.org/https://doi.org/10.1017/S1743921321000466

Rubin, H. J., & Rubin, I. (2005). Interviewing: The art of hearing data (2nd ed.). SAGE.

Salimpour, S., Bartlett, S., Fitzgerald, M. T., McKinnon, D. H., Cutts, K. R., James, C. R., . . . Ortiz-Gil, A. (2021). The Gateway Science: a Review of Astronomy in the OECD School Curricula, Including China and South Africa. Research in Science Education, 51(4), 975-996. https://doi.org/10.1007/s11165-020-09922-0

Sarva, J., Freed, R., Fitzgerald, M. T., & Salimpour, S. (2020). An Exoplanet Transit Observing Method using LCO Telescopes, ExoRequest and astrosource. Astronomy Theory, Observations & Methods, 1(1), 34-43.

Scannell, S. G. (2019). Next Generation Science Standards and Physics First: A Case *Study of High School Teachers' Beliefs and Practices* (Publication Number Paper 5002) Portland State University].

Schleicher, A. (2019). PISA 2018: Insights and Interpretations. OECD Publishing.

Schreiner, C., & Sjøberg, S. (2004). Sowing the seeds of ROSE: background, rationale, questionnaire development and data collection for ROSE (The Relevance of *Science Education): a comparative study of students' views of science and* science education (Vol. 4). Acta Didactica.

Sheppard, K., & Robbins, D. M. (2002). Lessons from the Committee of Ten. The Physics Teacher, 40(7), 426-431. https://doi.org/10.1119/1.1517887

Simon, M., Prather, E., Rosenthal, I., Cassidy, M., Hammerman, J., & Trouille, L. (2022). A New Curriculum Development Model for Improving Undergraduate Students' Data Literacy and Self-Efficacy in Online Astronomy Classrooms. Astronomy Education Journal, 2(1).

Slater, S. J. (2014). The development and validation of the Test Of Astronomy STandards (TOAST). Journal of Astronomy & Earth Sciences Education (JAESE), 1(1), 1-22.

Statistics, N. C. f. E. (2022). High School Mathematics and Science Course Completion (Condition of Education, Issue. https://nces.ed.gov/programs/coe/indicator/sod/high-school-courses

Steidtmann, L., Kleickmann, T., & Steffensky, M. (2023). Declining interest in science in lower secondary school classes: Quasi-experimental and longitudinal evidence on the role of teaching and teaching quality. Journal of Research in Science Teaching, 60(1), 164-195. https://doi.org/https://doi.org/10.1002/tea.21794

Studies, N. E. A. o. t. U. S. C. o. T. o. S. S. (1894). Report of the Committee of Ten on Secondary School Studies: With the Reports of the Conferences Arranged by the Committee National Education Association.

Taylor, J., Banilower, E., & Clayton, G. (2020). National Trends in the Formal Content Preparation of US Science Teachers: Implications of Out-of-Field Teaching for Student Outcomes. Journal of Science Teacher Education, 31(7), 768-779. https://doi.org/10.1080/1046560X.2020.1762992

Thompson, P. W., Philipp, R., & Boyd, B. (1994). Calculational and conceptual orientations in teaching mathematics. In 1994 Yearbook of the NCTM.

Tolan, P. H., & Deutsch, N. L. (2015). Mixed methods in developmental science. In Handbook of child psychology and developmental science: Theory and method, Vol. 1, 7th ed. (pp. 713-757). John Wiley & Sons, Inc. https://doi.org/10.1002/9781118963418.childpsy119

Trumper, R. (2003). The need for change in elementary school teacher training—a cross-college age study of future teachers' conceptions of basic astronomy concepts. Teaching and Teacher Education, 19(3), 309-323. https://doi.org/https://doi.org/10.1016/S0742-051X(03)00017-9

Wells, M., Hestenes, D., & Swackhamer, G. (1995). A modeling method for high school physics instruction. American Journal of Physics, 63(7), 606-619. https://doi.org/10.1119/1.17849

Wissehr, C., Concannon, J., & Barrow, L. H. (2011). Looking Back at the Sputnik Era and Its Impact on Science Education. School Science and Mathematics, 111(7), 368-375. https://doi.org/https://doi.org/10.1111/j.1949-8594.2011.00099.x

Ethics Approval

Human research approval by the University of California Berkeley, Committee for Protection of Human Subjects (CPHS) under the CPHS Protocol Number: 2022-08-15536.

Appendices

Appendix Document 1

Observation Astronomy Test Standards (OATS)

1. What is a light-year?
    a. A measure of time
    b. A measure of distance
    c. A measure of time and distance
    d. How we assign ages to cosmological objects

2. Kepler's 3rd law combined with Newton's law of gravity allows us to determine what about an object orbiting another object?
    a. It's mass
    b. It's orbital period
    c. It's distance to the body it orbits
    d. All of the above depending on what quantities are already known
3. What is the most common and successful way to detect a planet around another star?
    a. There is no way to detect planets around other stars
    b. There are no known planets around other stars
    c. Gravitational lensing
    d. The transit method
    e. Direct imaging
4. Based upon scientific data, is there life outside of planet Earth in our universe?
    a. Yes
    b. No
    c. We do not know, but it is possible
    d. We do not know, but it is extremely unlikely
    e. Other:
5. What is the standard and most common coordinate system astronomers use for locating an object on the night sky?
    a. Latitude and longitude
    b. North, south, east, and west
    c. Right ascension and declination
    d. u, v, w space velocities
6. The apparent magnitude of a star . . .
    a. indicates the brightness of the star as seen from Earth, with the brighter stars having higher magnitudes and fainter stars having lower magnitudes
    b. indicates the brightness of the star as seen from Earth, with the brighter stars having lower magnitudes and fainter stars having higher magnitudes
    c. is the ratio of the star's luminosity to the Sun's luminosity
    d. indicates the brightness of the star as if it were placed at a distance of 10 parsecs from Earth, with the brighter stars having lower magnitudes and fainter stars having higher magnitudes
7. Why is knowing the apparent magnitude of a stellar object important to know for planning your observation?
    a. It can help determine the size of the telescope you will need for your observation
    b. Your telescope camera's sensor may only be able to successfully detect stars in certain magnitude ranges
    c. It tells you how large of a field of view you need to detect the object
    d. Both a and b

    e. Both b and c
8. Which of these time standards would be most useful by an astronomer in planning an astronomical observation?
    a. International Earth rotation time (IERT)
    b. Eastern standard time (EST)
    c. Coordinated universal time (UTC)
    d. Local apparent solar time (LAST)
9. One common measurement that astronomers perform on their images is photometry. In photometry, astronomers are doing what?
    a. Measuring the number of neutrinos captured in the image
    b. Measuring the temperature of photons that entered an image pixel
    c. Measuring the amount of light from astrophysical sources in an image
    d. Measuring the positions of astrophysical sources in an image
10. An observer is located in Boulder, Colorado at a latitude of 40° N. They plan to observe a star with a Declination of +40°. Assuming the observer can see the star continuously from the time it rises until it sets, what is the maximum altitude on the sky the star reaches during the night?
    a. 0°
    b. 40°
    c. 50°
    d. 90°

Appendix Document 2
Science Teaching Efficacy Belief Instrument for Astronomy (STEBI-AST)*

Please indicate the degree to which you agree or disagree with each statement below by circling the appropriate letters to the right of each statement.

SA = Strongly Agree
A = Agree
UN = Uncertain
D = Disagree
SD = Strongly Disagree

1. When a student does better than usual in astronomy, it is often because the teacher exerted a little extra effort.	SA A UN D SD
2. I am continually finding better ways to teach astronomy.	SA A UN D SD
3. Even when I try very hard, I don't teach astronomy as well as I do most subjects.	SA A UN D SD
4. When the astronomy grades of students improve, it is most often due to their teacher having found a more effective teaching approach.	SA A UN D SD

5. I know the steps necessary to teach astronomy concepts effectively.	SA A UN D SD
6. I am not very effective in monitoring astronomy experiments.	SA A UN D SD
7. If students are underachieving in astronomy, it is most likely due to ineffective astronomy teaching.	SA A UN D SD
8. I generally teach astronomy ineffectively.	SA A UN D SD
9. The inadequacy of a student's astronomy background can be overcome by good teaching.	SA A UN D SD
10. The low astronomy achievement of some students cannot generally be blamed on their teachers.	SA A UN D SD
11. When a low achieving child progresses in astronomy, it is usually due to extra attention given by the teacher.	SA A UN D SD
12. I understand astronomy concepts well enough to be effective in teaching elementary astronomy.	SA A UN D SD
13. Increased effort in astronomy teaching produces little change in some students' astronomy achievement.	SA A UN D SD
14. The teacher is generally responsible for the achievement of students in astronomy.	SA A UN D SD
15. Students' achievement in astronomy is directly related to their teacher's effectiveness in astronomy teaching.	SA A UN D SD
16. If parents comment that their child is showing more interest in astronomy at school, it is probably due to the performance of the child's teacher.	SA A UN D SD
17. I find it difficult to explain to students why astronomy experiments work.	SA A UN D SD
18. I am typically able to answer students' astronomy questions.	SA A UN D SD
19. I wonder if I have the necessary skills to teach astronomy.	SA A UN D SD
20. Effectiveness in astronomy teaching has little influence on the achievement of students with low motivation.	SA A UN D SD
21. Given a choice, I would not invite the principal to evaluate my astronomy teaching.	SA A UN D SD
22. When a student has difficulty understanding an astronomy concept, I am usually at a loss as to how to help the student understand it better.	SA A UN D SD
23. When teaching astronomy, I usually welcome student questions.	SA A UN D SD
24. I don't know what to do to turn students on to astronomy.	SA A UN D SD
25. Even teachers with good astronomy teaching abilities cannot help some kids learn astronomy.	SA A UN D SD

*Adapted from Riggs, I., & Knochs, L. (1990). Towards the development of an elementary teacher's science teaching efficacy belief instrument. Science Education, 74, 625-637.

4.3 Links and Implications

The Astronomy Modeling Instruction with Exoplanets (AME) study resulted in measurable improvements in teacher and student motivation, engagement, and astronomy knowledge and skills through the use of astrophysics data and data analysis techniques (e.g., exoplanet observation planning, photometry, and transit light curve creation and analysis). By incorporating real and teacher collected astrophysics data into the G-HOU framework and Modeling Instruction pedagogy, we witnessed the evolution of teachers into capable amateur astronomers with new motivation to incorporate their new skills into their classrooms. The findings of this study also provide a promising case study with Percy Munoz and his high school astronomy students. In addition to Munoz's transformations, such as becoming an active citizen astronomer and increasing the offerings of astronomy at his school, his students shared that they were more engaged when learning and working with real data and exoplanets. The engaging nature of hands-on data-driven learning with AME highlights the potential for high school teachers and their students to participate in more astrophysical research and "learn by doing" (e.g., AstroReMixEd).

CHAPTER 5: CONFIRMING THE WARM AND DENSE SUB-SATURN TIC 139270665 B WITH AUTOMATED PLANET FINDER AND UNISTELLAR CITIZEN SCIENCE NETWORK

"You sprinkle stardust on my pillow case
It's like a moonbeam brushed across my face
Nights are good and that's the way it should be."
-"Bright" by Echosmith

5.1 Introduction

The following manuscript paper by Peluso et al. (2024), *Confirming the Warm and Dense Sub-Saturn TIC 139270665 b with the Automated Planet Finder and the Unistellar Citizen Science Network*, was submitted for publication to the Astronomical Journal (AJ) on 28 October 2023 with the reference manuscript number AAS50575. It was assigned an editor and went into peer-review on 31 October 2023. I received the first referee report in November 2023 and resubmitted to the journal in January 2024. On 6 February 2024, the paper was accepted to the journal, AJ, and was passed forward into production on 8 February 2024 with the manuscript ID AAS50575R1. Section 5.2 is the accepted version of the paper for the journal, which is now in production for release in early 2024.

This paper reports the discovery and confirmation of the warm and dense sub-Saturn, TIC 139270665 b, which was aided by citizen scientists and the Unistellar network. RV characterization confirmed the planet b, but also provided evidence for another planet, c. In addition to confirming the planet, TIC 139270665 b, the combined efforts by professional telescopes (e.g., APF) and citizen scientist operated telescopes (e.g., Unistellar eVscopes) refine the planet's period. This work also offers a rich case for the AstroReMixEd initiative and insights into planetary formation and evolution models.

5.2 Submitted Paper

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Confirming the Warm and Dense Sub-Saturn TIC 139270665 b with the Automated Planet Finder and Unistellar Citizen Science Network

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ABSTRACT

We report the discovery and confirmation of the TESS single-transit warm and dense sub-Saturn, TIC 139270665 b. This planet is unusually dense for its size, with a bulk density of 2.13g cm^{-3} (0.645 R_J, 0.463 M_J) it is the densest warm sub-Saturn of the TESS family. It orbits a metal-rich G2 star. We also found evidence of a second planet, TIC 139270665 c, with a longer period of 1010^{+780}_{-220} days and minimum mass $M_P \sin i$ of $4.89^{+0.66}_{-0.37}$ M_J. First clues of TIC 139270665 b's existence were found by citizen scientists inspecting TESS photometric data from sector 47 in January 2022. Radial velocity measurements from the Automated Planet Finder combined with TESS photometry and spectral energy distributions via `EXOFASTv2` system modeling suggested a $23.624^{+0.030}_{-0.031}$ day orbital period for TIC 139270665 b and also showed evidence for the second planet. Based on this estimated period, we mobilized the Unistellar citizen science network for photometric follow-up, capitalizing on their global distribution to capture a second transit of TIC 139270665 b. This citizen science effort also served as a test bed for an education initiative that integrates young students into modern astrophysics data collection. The Unistellar photometry did not definitively detect a second transit, but did enable us to further constrain the planet's period. As a transiting, warm, and dense sub-Saturn, TIC 139270665 b represents an interesting laboratory for further study to enhance our models of planetary formation and evolution.

Keywords: Exoplanet astronomy (486), Amateur astronomy (35), Radial velocity (1332), Transit photometry (1709), Extrasolar gaseous giant planets (509), Extrasolar gaseous planets (2172)

1. INTRODUCTION

The scientific exploration of exoplanets has revealed a striking diversity of planetary systems very different from our own. Our solar system is not the archetype of all planetary systems. The rapid success in exoplanet science over roughly three decades is in part owed to large survey missions such as *Kepler* (Borucki et al. 2010) and the Transiting Exoplanet Survey Satellite (TESS) (Ricker et al. 2014). While hot Jupiters–orbital periods <10 days and masses $\geq 0.25 M_J$–are now recognized as rarities (Mayor et al. 2011; Wright et al. 2012; Petigura et al. 2018), their existence has prompted us to revisit and revise our planetary formation and evolutionary models. These revisions include origin hypotheses such as in-situ formation, disk migration, and high eccentricity tidal migration (Dawson & Johnson 2018; Fortney et al. 2021). As our investigations broaden to include lesser-documented exoplanets, such as warm Jupiters (gas giants with periods >10 days and <100 days), we further the refinement of our planetary birth and evolution models. Additionally, the merging of new technologies and outreach initiatives has empowered citizen astronomers (e.g., the general public, educators, and students) to fill a critical role in exoplanet discovery and follow-up (Fischer et al. 2012; Mousis et al. 2014; Gomez & Fitzgerald 2017; Zellem et al. 2020; Kokori et al. 2022a,b; Peluso et al. 2023). Consequently, this can drive us into a new era where democratized astronomical research can benefit both the professional and non-professional community.

Warm Jupiters are of particular interest to us because they are less prevalent (Jones et al. 2003; Wittenmyer et al. 2010; Santerne et al. 2016) and their existence prompts us to further question our formation and migration theories since it is unknown why they did not migrate closer to become hot Jupiters or remain in orbits farther out (Dawson & Johnson 2018). Additional interest stems from the desire to better understand the observed orbital "period valley" that warm Jupiters occupy between their hot and cold counterparts (Wittenmyer et al. 2010; Mayor et al. 2011; Wright et al. 2012; Santerne et al. 2016). To capture the diversity of other giant planetary phenomena in the not too hot or too cold regions, researchers might propose the more encompassing term "warm giants". This would include a variety of planetary types in addition to warm Jupiters, such as warm Neptunes and warm Saturns. These warm giants may provide clues to internal planetary structures with their lack of inflated atmospheres unlike their hot counterparts

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(Fortney & Nettelmann 2010; Grieves et al. 2022). Additionally, in our solar system, as noted by Brady et al. (2018), there is a distinct size gap among planets, with none found between the sizes of $4.0R_\oplus$ (Uranus) and $9.1R_\oplus$ (Saturn). This void offers an intriguing area of study presented by warm giants.

Although warm giants are exciting to study, they are hard to detect. Most wide-field photometry surveys have limitations for longer period exoplanets, such as warm giants with $P > 10$ d (Bakos et al. 2004; Bakos et al. 2013; Pollacco et al. 2006). Even so, there is high enthusiasm for TESS' wide field surveys of bright stars (Ricker et al. 2014), which we anticipate to discover more than 10,000 new exoplanets in its lifetime (Barclay et al. 2018). Among TESS exoplanets discovered to date, a significant portion of TESS Objects of Interest (TOIs) exhibit a short period system, with the median orbital period of 5.42 d. Since TESS' observational baseline window only allots 27 d for most stars observed, longer period exoplanets are less likely to be caught. However, it has been predicted that single transit events from TESS light curves may produce hundreds of potential longer period exoplanets (Cooke et al. 2018; Villanueva et al. 2019). Currently, the NASA Exoplanet Archive reports only 27 confirmed TESS exoplanets with $10 < P < 100$ d and a confirmed mass $0.25 < M_J < 13$[1]. Of TESS exoplanets with $P > 100$ d, only 4 have been confirmed (Kostov et al. 2021; Heitzmann et al. 2023; Dalba et al. 2022; Mireles et al. 2023). Since the TESS pipeline relies on observing repeated transits for detection, the majority of TOIs are not single-transits. There are approximately ∼120 single-transit TESS candidates currently proposed, but only a few that have been confirmed to date (Villanueva et al. 2019; Díaz et al. 2020; Hobson et al. 2022; Dalba et al. 2022).

Sub-Saturns, a category of exoplanets with sizes between 4.0 and $8.0R_\oplus$ (Petigura et al. 2017a) are considered to be rare (Brady et al. 2018; Addison et al. 2020). Filtering for those in a "warm" orbit, Exoplanet Archive reports 15 TESS-confirmed sub-Saturns, with 8 having mass constraints[1]. While being less in mass than Jovians (Jontof-Hutter et al. 2014; Petigura et al. 2017a), the large size and mass of sub-Saturns may be attributed to their expansive envelopes of H/He (Lopez & Fortney 2014; Petigura et al. 2017a). Because of the lower masses of sub-Saturns found to date, Petigura et al. (2017a) suggest that methods of runaway accretion of gas that explain Jupiter's large mass envelope may not have occurred. Instead, alternative ideas such as formation in a gas-depleted disk have been suggested (Lee & Chiang 2015; Lee et al. 2018). Discovering and studying more sub-Saturns will help researchers better understand their formation environment and migration histories.

Due to the unknown timing of the next transit event for single-transit TOIs, their follow-up is challenging due to the need for extensive photometry. An emerging solution is to leverage the collective efforts of the growing global citizen science community to increase observation time across many geographic regions. Unlike professional telescopes which are concentrated in select regions, citizen scientists are dispersed across the world, offering a unique geographic advantage for continuous and diverse observation opportunities. The impact and usefulness of citizen astronomer programs such as NASA's Exoplanet Watch (Zellem et al. 2020), ExoClock (Kokori et al. 2022a,b), the Kilodegree Extremely Little Telescope (KELT) Follow-Up Network (Collins et al. 2018), and the Unistellar Exoplanet Campaign (Peluso et al. 2023) are significant. They not only help address some of the infrastructural challenges faced by professional telescopes but also offer a broader pool of photometry for follow-up, confirmation, and possible discovery. Further, programs like these allow opportunities for educators and students to participate in professional exoplanet campaigns (Collins et al. 2018; Edwards et al. 2020; Sarva et al. 2020; Fowler 2019; Mizrachi et al. 2021; Peluso et al. 2023) where they can *learn by doing* and likely improve motivation, learning, and self-efficacy (Freeman et al. 2014), as well as contribute the important photometry needed for the challenging follow-up of exoplanets like our single-transit TOIs. This is a symbiotic relationship in which astrophysical research, education, and community engagement are combined, which we will refer to in this paper as "AstroReMixEd" for brevity.

In this paper, we announce the discovery and confirmation of the TESS warm and dense sub-Saturn, TIC 139270665 b, orbiting a metal-rich G2 star with $V = 10.385$ and distance of $147.80^{+0.69}_{-0.68}pc$. This planet stands out as the most densely constrained warm sub-Saturn known and represents a rare TESS single-transit event that was subsequently confirmed through ground-based follow-ups. Section 2 details TESS's initial observations and our subsequent spectroscopic and photometric follow-ups. Section 3 combines observations to discuss the radial velocity (RV) validation of the planet using `ExoFastv2` model fits across TESS data, a stellar spectral energy distribution (SED) analysis, and the efforts by the Unistellar citizen science network to capture a second transit. Interestingly, our RV data also gives evidence of the non-transiting orbiting planetary companion, TIC 139270665 c, which has high value for future investigations. In Section 4, we discuss TIC 139270665 b and the impact of this unique and high density warm sub-Saturn and the implications its existence may have on our planetary formation and migration theories. Additionally, we describe the rewarding nature of involving high school students in these observations for learning and personal enrichment as well as the lessons learned from our citizen science campaign. Lastly, in Section 5, we summarize our discoveries.

[1] From NASA Exoplanet Archive (Akeson et al. 2013) website, accessed 6 August 2023.

2. OBSERVATIONS

2.1. *TESS Photometry*

TIC 139270665 was observed by the TESS extended mission in Year 4, sector 47 with a 2-minute cadence from 2021 December 31 to 2022 January 27. TESS photometry was initially processed by the Science Processing Operations Centers (SPOC) pipeline (Jenkins et al. 2016). Highlighting the value of citizen science collaboration, the transit was found in the SPOC light curve by a group of citizen scientists called the Visual Survey Group (Kristiansen et al. 2022) that has been finding transiting planets, including other warm giants (Dalba et al. 2022), in space telescope data since the *Kepler* era.

Our own re-reduction using archival TESS light curves (Team 2021) reproduced the initial discovery made by the Visual Survey Group, and this data was subsequently used in the joint modeling of the planetary system. For our reduction, we accessed the TESS data with the `lightkurve` package (Lightkurve Collaboration et al. 2018) and flattened the data using the `lightkurve.flatten` routine with a `window_length=501` and default `polyorder`. This produced a light curve showing a single transit of TIC 139270665 b as seen in Figure 1. This independent recovery of the transit motivated us to follow-up TIC 139270665 with RV measurements, which then led us to initiate UCSN to attempt to detect a second transit of TIC 139270665 b.

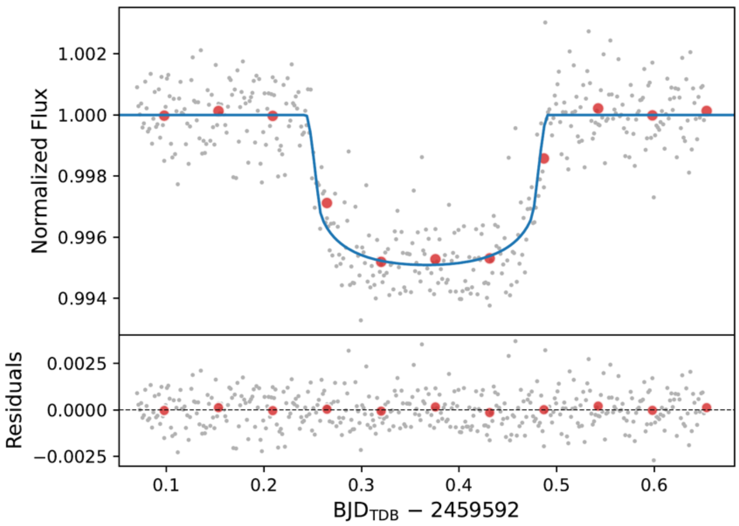

Figure 1. Single TESS transit of TIC 139270665 b (0.645 R_J) in Sector 47 detected on 2022 January 12. Long cadence TESS data are gray, bins of 80 minutes are red (purely for visual aid), and the best fit `EXOFASTv2` model is blue. See Section 3.1 for EXOFASTv2 details.

2.2. *Speckle Imaging*

We observed TIC 139270665 with the WIYN telescope at the Kitt Peak National Observatory on 20 April 2022 using the NN-Explore Exoplanet Stellar Speckle Imager (NESSI) instrument (Scott et al. 2018). Observations with NESSI were taken using the 832 nm filter on the red camera, and the image reconstruction was performed following the methods of (Howell et al. 2011) to generate contrast curves that indicate relative magnitude limits at varying angular separations from the star at the 5-sigma level. Our high resolution image led to a non-detection of any nearby companion stars within the examined range. This is illustrated in Figure 2, where our observations using the WIYN telescope achieved a contrast of approximately 4 magnitudes at an angular separation of 0.″2 and indicated a non-detection of sources with Δm ranging between 5 and 5.5 for separations from 0.″45 to 1.″2 from TIC 139270665.

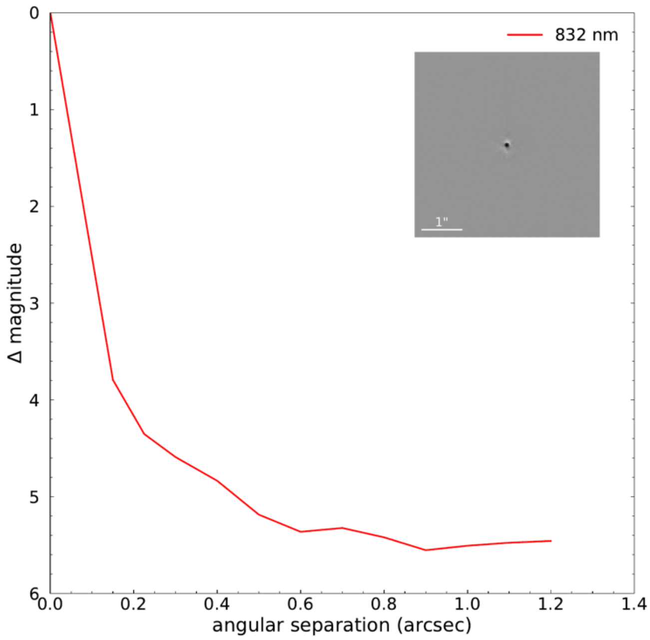

Figure 2. Limiting magnitude Δm at the 5-sigma level for the non-detection of a neighboring star based on the speckle imaging from WIYN NESSI. The inset shows the speckle image at 832 nm.

2.3. *APF & HIRES Spectroscopy*

After the single-transit discovery by the Visual Survey Group, we began RV follow up in order to measure TIC 139270665 b's orbit, mass, and to confirm the detection as a genuine planet. To this end, we initiated a Doppler monitoring campaign with the Automated Planet Finder (APF) at Lick Observatory (Radovan et al. 2014; Vogt et al. 2014). The APF leverages the capabilities of the Levy Spectrograph, a high-resolution ($R \approx 114,000$) slit-fed optical echelle spectrometer (Radovan et al. 2010). Using standard iodine techniques, we derived RV measurements from the collected data with the Levy Spectrograph. Observations utilizing APF began shortly after the TESS signal was discovered, with the first APF measurements occurring in 2022 March, but ended shortly thereafter because of the target setting. APF resumed observations in 2022 September and continued observing with varying cadence through 2023 June, except for two months when APF closed during the bad rain season in California in 2023 March and April. After cutting three spectra for low count values, our reported APF observations result in 59 measured RVs, which are listed in Table 3 of the Appendix, and the time series RVs are shown in Figure 3.

In addition to our observations with APF, we also secured a high signal-to-noise (S/N) spectrum from the W. M. Keck Observatory. This was achieved with the High Resolution Echelle Spectrometer (HIRES) on its Keck I telescope (Vogt et al. 1994). With the collected spectrum, we sought to rule out potential false positives and gain additional insights into TIC 139270665. Utilizing `SpecMatch` (Petigura et al. 2017b), we carried out a basic spectroscopic analysis to measure parameters $T_{\rm eff}$, $v \sin i$, [Fe/H], and $\log g$. The $v \sin i$ was measured to be 4.2 ± 1.0 km/s.

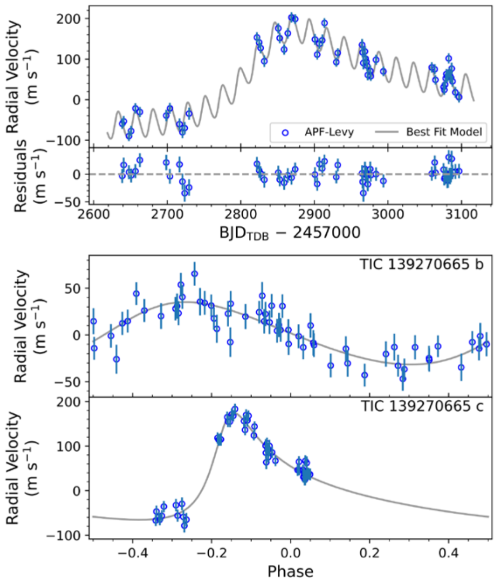

Figure 3. APF RVs of TIC 139270665. The top panel is the entire time series, while the bottom two panels are planet b and c's Keplerian signals separated and phase folded on the best fit T_C values.

Furthermore, the high S/N spectrum from Keck-HIRES was adapted to serve as a template spectrum for our APF RVs (Butler et al. 1996), ensuring consistency and accuracy across our measurements. We used HIRES to obtain this spectrum because it is much more time-efficient than getting a similarly high-S/N spectrum with APF.

2.4. *Unistellar Citizen Science Photometry*

Unistellar Enhanced Vision Telescopes (eVscopes) are portable, digital, smart telescopes manufactured and distributed by Unistellar. The Unistellar Citizen Science Network (UCSN) contains over 10,000 eVscopes in more than 60 countries. All current eVscope models are Newtonian-style reflectors with an aperture of 114 mm, focal length of 450 mm, and use a low-noise high-quantum-efficiency Sony CMOS sensor[2] at the prime focus. Full details on eVscope technical specifications (Marchis et al. 2020) and how the science team engages the network and processes Unistellar exoplanet data are in our Unistellar Exoplanet Campaign paper (Peluso et al. 2023) and other published works that have successfully employed eVscopes for transit photometry data (Perrocheau et al. 2022; Pearson et al. 2022; Wang et al. 2022; Dalba et al. 2022; Zellem et al. 2020).

To validate or refine TIC 139270665 b's orbit by observing its anticipated transits, we scheduled observations with Unistellar citizen astronomers. While the RV data provided constraints on the planet's orbital period (see Section 3.1), there were still uncertainties regarding the exact transit timing. In light of this, the globally distributed nature of UCSN and its abundant on-sky time were advantageous, and allowed us to gather many observations over large windows of time. Our outreach to the UCSN community included blog posts[3], updates on our exoplanet-dedicated Unistellar Citizen Science Slack channel, and a special overnight TIC 139270665 b observing campaign outreach event for Bay

[2] Camera specifications vary by eVscope model. eVscope/eQuinox 1: SONY IMX224 sensor, field-of-view (FOV) of 37′ X 28′, pixel scale of 1.72″ pixel^{-1}. eVscope/eQuinox 2: SONY IMX347 sensor, FOV of 45′ X 34′, pixel scale of 1.33″ pixel^{-1}.

[3] Example blog post from campaign start: https://www.unistellar.com/blog/is-a-distant-solar-system-hiding-another-planet/, accessed 2023 August 19.

Area, CA, high school students in the Chabot Space & Science Center's Galaxy Explorer program (2023 February 18–19)[4].

UCSN observations to search for five additional transits of TIC 139270665 b occurred in 2022 December and 2023 February–April, and resulted in 271 hours of data across 62 total data sets from 39 unique eVscopes and 46 eVscope operators in 10 countries. Of the eVscope operators, three were SETI Institute scientists, 16 were high school student citizen scientists, and 27 were non-student citizen scientists. High school students worked in pairs to operate eight eVscopes at the Chabot outreach event. In 2023 February, our coverage contained 25 datasets, encompassing 139.4 hours distributed within a 3-sigma observing window of 3 days. However, only 8% of the February photometry ended up falling within the highest probability predicted transit time using our final EXOFASTv2 period from Table 1 in Section 3.1. We also had observing campaigns in 2022 December, 2023 March, and two in 2023 April that had eleven datasets spanning 43 hours, seven datasets totaling 21.3 hours, 16 datasets of 60.1 hours, and three datasets of 7.2 hours, respectively. Given the extensive data from 2023 February, which also covered the highest percentage of the most probable transit time from our EXOFASTv2 model fit, it stands out as the dataset offering the highest likelihood for a transit detection. See Table 4 in the Appendix for a summary of observation details.

3. RESULTS

3.1. *EXOFASTv2 System Modeling*

We used the EXOFASTv2 modeling suite (Eastman et al. 2013, 2019) to derive the stellar and planetary parameters of the system. We used 59 RVs from APF and no priors for the orbital period, since we only had a single-transit from the TESS photometry. The EXOFASTv2 model we applied was tailored to simultaneously fit the TESS photometry, RVs, and stellar spectral energy distributions (SEDs) derived from archival photometry. Crucial priors were set on the stellar $T_{\rm eff}$ and [Fe/H], based on results from the SpecMatch analysis. Additionally, we set priors for parallax from the Gaia DR3 datasets (Gaia Collaboration et al. 2021; Lindegren et al. 2021) and for extinction using galactic dust maps (Schlafly & Finkbeiner 2011). The fitting process was continued until most parameters met standard EXOFASTv2 convergence criteria, namely $T_z > 1000$ and $GR < 1.01$. However, some parameters associated mainly with the outer planet c—namely mass, $\cos(i)$, T_C, $\sqrt{e \cdot \cos(\omega)}$, and $\sqrt{e \cdot \sin(\omega)}$—achieved GR values between 1.01 and 1.1. Given the incomplete orbit of this planetary companion, such results were anticipated.

Our primary focus remained on the inner planet, TIC 139270665 b, which we confirm in this study with a mass $0.463 \pm 0.046 M_J$, bulk density 2.13g cm^{-3}, orbital period $23.624^{+0.030}_{-0.031}$, and eccentricity $0.105^{+0.053}_{-0.050}$. As we are deferring a detailed follow-up and study of TIC 139270665 c to a later data (contingent upon acquiring a more extended RV baseline), we halted the EXOFAST runs prior to achieving full convergence on this planetary companion. It is worth noting, however, that our preliminary estimates place this outer object's minimum mass of $M_P \sin i = 4.89^{+0.66}_{-0.37} M_J$ within the planetary regime. TIC 139270665 c's minimum mass, as well as all relevant stellar and planetary parameters for TIC 139270665 and TIC 139270665 b from our EXOFASTv2 model fit are presented in Table 1.

Table 1. Median values and 68% confidence interval for TIC 139270665

Parameter	Units	Values
Stellar Parameters:		
M_* . . .	Mass ($M_\odot$)	$1.035^{+0.052}_{-0.062}$
R_* . . .	Radius ($R_\odot$)	$1.016^{+0.035}_{-0.031}$
L_* . . .	Luminosity ($L_\odot$)	$1.077^{+0.089}_{-0.060}$
F_{Bol} . .	Bolometric Flux (cgs)	$1.577E-9^{+1.3E-10}_{-8.7E-11}$
ρ_* . . .	Density (cgs)	$1.39^{+0.15}_{-0.16}$
$\log g$ . .	Surface gravity (cgs)	$4.439^{+0.032}_{-0.041}$

Table 1 *continued on next page*

[4] For more information on the high school outreach observation campaign event: https://www.seti.org/high-school-galaxy-explorers-team-search-exoplanet-transit, accessed 2023 August 19.

Table 1 *(continued)*

Parameter	Units	Values	
$T_{\rm eff}$ ...	Effective Temperature (K)	5844^{+84}_{-82}	
[Fe/H] .	Metallicity (dex)	$0.156^{+0.057}_{-0.056}$	
$[{\rm Fe/H}]_0$.	Initial Metallicity[1]	0.146 ± 0.059	
Age ..	Age (Gyr)	$3.4^{+3.8}_{-2.4}$	
EEP ..	Equal Evolutionary Phase[2]	345^{+40}_{-35}	
A_V ...	V-band extinction (mag)	$0.115^{+0.10}_{-0.075}$	
σ_{SED} ..	SED photometry error scaling ...	$0.65^{+0.27}_{-0.17}$	
ϖ ...	Parallax (mas)	6.766 ± 0.031	
d	Distance (pc)	$147.80^{+0.69}_{-0.68}$	
Planetary Parameters:		b	c
P ...	Period (days)	$23.624^{+0.030}_{-0.031}$	1010^{+780}_{-220}
R_P ...	Radius ($R_{\rm J}$)	$0.645^{+0.024}_{-0.022}$	...
M_P ..	Mass ($M_{\rm J}$)	0.463 ± 0.046	...
$M_P \sin i$	Minimum mass ($M_{\rm J}$)	0.463 ± 0.046	$4.89^{+0.66}_{-0.37}$
T_C ...	Time of conjunction ($\rm BJD_{TDB}$) ...	$2459592.36614^{+0.00096}_{-0.00093}$	2460042^{+14}_{-11}
a	Semi-major axis (AU)	$0.1630^{+0.0027}_{-0.0033}$	$2.00^{+0.93}_{-0.31}$
i	Inclination (Degrees)	$89.76^{+0.17}_{-0.23}$	...
e	Eccentricity	$0.105^{+0.053}_{-0.050}$	$0.566^{+0.12}_{-0.069}$
ω_* ...	Argument of Periastron (Degrees) .	-62^{+26}_{-32}	$-44.3^{+9.6}_{-9.5}$
T_{eq} ...	Equilibrium temperature[3] (K) ...	703^{+14}_{-11}	200^{+18}_{-35}
$\tau_{\rm circ}$ ..	Tidal circularization timescale (Gyr)	9800 ± 2000	$4600000000^{+9000000000}_{-2700000000}$
K ...	RV semi-amplitude (m/s)	$32.4^{+3.0}_{-3.1}$	$116.8^{+6.6}_{-4.4}$
R_P/R_* .	Radius of planet in stellar radii ..	$0.06519^{+0.00093}_{-0.00090}$	...
a/R_* ..	Semi-major axis in stellar radii ..	$34.5^{+1.2}_{-1.3}$	423^{+200}_{-67}
δ	$(R_P/R_*)^2$	0.00425 ± 0.00012	...
$\delta_{\rm TESS}$.	Transit depth in TESS (fraction) ..	$0.00498^{+0.00015}_{-0.00014}$	...
τ	Ingress/egress transit duration (days)	$0.01549^{+0.0013}_{-0.00043}$	...
T_{14} ...	Total transit duration (days)	$0.2475^{+0.0025}_{-0.0024}$	...
b	Transit Impact parameter	$0.16^{+0.16}_{-0.11}$	310^{+140}_{-200}
b_S ...	Eclipse impact parameter	$0.134^{+0.12}_{-0.092}$	...
τ_S ...	Ingress/egress eclipse duration (days)	$0.01319^{+0.0012}_{-0.00093}$	...
$T_{S,14}$ ..	Total eclipse duration (days)	$0.210^{+0.019}_{-0.016}$	...
ρ_P ...	Density (cgs)	$2.13^{+0.32}_{-0.29}$	...
$logg_P$ ..	Surface gravity	$3.440^{+0.050}_{-0.054}$	...
Θ ...	Safronov Number	0.226 ± 0.022	...
$\langle F \rangle$ ...	Incident Flux (10^9 erg s^{-1} cm^{-2}) ..	$0.0548^{+0.0046}_{-0.0037}$	$0.00028^{+0.00014}_{-0.00016}$
T_P ...	Time of Periastron ($\rm BJD_{TDB}$) ...	$2459582.8^{+2.0}_{-2.6}$	$2459837.3^{+8.4}_{-8.3}$

Table 1 *continued on next page*

Table 1 *(continued)*

Parameter	Units	Values	
T_S ...	Time of eclipse (BJD_{TDB})	$2459581.18^{+0.84}_{-0.69}$	$2459804.4^{+4.6}_{-5.8}$
$e\cos\omega_*$.	....	$0.042^{+0.055}_{-0.046}$	$0.40^{+0.16}_{-0.11}$
$e\sin\omega_*$.	....	-0.084 ± 0.046	$-0.395^{+0.032}_{-0.034}$
Wavelength Parameters:		TESS	
u_1 ...	linear limb-darkening coeff	$0.304^{+0.046}_{-0.047}$	
u_2 ...	quadratic limb-darkening coeff ...	0.290 ± 0.049	
Telescope Parameters:		APF	
$\gamma_{\rm rel}$ ...	Relative RV Offset (m/s)......	-69^{+13}_{-27}	
σ_J ...	RV Jitter (m/s)	$11.5^{+2.0}_{-1.7}$	
Transit Parameters:		TESS UT 2022-01-12 (TESS)	
σ^2 ...	Added Variance	$-0.000004905^{+0.000000072}_{-0.000000065}$	
F_0 ...	Baseline flux	$1.000052^{+0.000065}_{-0.000064}$	

See Table 3 in Eastman et al. (2019) for a detailed description of all parameters.

[1] The metallicity of the star at zero-age main sequence.

[2] Corresponds to static points in a star's evolutionary history. See §2 in Dotter (2016).

[3] Assumes no albedo and perfect redistribution.

3.2. *Unistellar Network Light Curves*

The improved constraints on TIC 139270665 b's orbital period from the `EXOFASTv2` modeling provided predicted transit windows for future attempts to detect a second transit via photometric follow-up with UCSN. However, we note that when searching for the transit with UCSN, we were chasing a moving target and therefore the uncertainties in the predicted mid-transit times were high. RV collection was ongoing during that process, so the best fit orbital period was regularly changing. Even small changes to the period were then propagated over all the orbits that had occurred since the initial single transit discovery by TESS. This is a particular challenge facing any single-transit follow-up effort.

To account for the uncertainty in mid-transit times, our UCSN campaigns spanned multiple days surrounding each of the five predicted transit windows between 2022 December and 2023 April. Initial examination of the UCSN photometry did not reveal a clear transit signal for any of the five predicted transits.

With no clear detection from the individual light curves, we performed a joint modeling of all light curves via a Markov Chain Monte Carlo (MCMC) approach with the `emcee` package (Foreman-Mackey et al. 2013). Employing the `EXOFASTv2` TIC 139270665 b planetary parameters (i, e, ω_*, u_1, u_2) from Table 1, these parameters were initialized in our log likelihood function through the `batman` package (Kreidberg 2015). Normal priors, centered on these parameters and scaled by their respective uncertainties (e.g., the `EXOFASTv2` errors from P, R_P/R_*, and T_C), were used to guide our MCMC analysis. Additional details on the MCMC parameterization are in Appendix A.

With the median length of individual Unistellar light curves only 3.97 hours long, and the expected transit duration being 5.9 hours, we introduced an *offset* parameter to normalize the relative fluxes of each light curve with respect to an out-of-transit mean of 1. This offset adjustment aids the MCMC simulation in navigating and effectively sampling the parameter space, ensuring that data—particularly those captured entirely within an expected transit—are accurately normalized. We initialized the walker locations for most offsets with a flat prior in the range (-0.001, 0.001), although we did have custom ranges for four datasets as detailed in Appendix A. The MCMC model contained 65 dimensions: three for the planet's P, R_P/R_*, and T_C parameters, and 62 offset values, one corresponding to each Unistellar data set. We kept the a, i, e, ω_*, and u_1 and u_2 wavelength parameters of limb-darkening fixed.

Table 2. MCMC posterior distributions and confidence intervals for P, R_P/R_*, and T_C.

Parameter	Max Likelihood	68.3% Confidence Range	99.7% Confidence Range
P	23.627585	±0.000252	±0.007389
R_P/R_*	0.065792	±0.000508	±0.001894
T_C	2459592.366264	±0.000515	±0.002011

The estimated values for P, R_P/R_*, and T_C from the resulting posterior distributions are given in Table 2 and the marginalized distributions are provided in Figure 13 in the Appendix. The maximum likelihood period of 23.627 d is 4.3 minutes longer than the RV-derived period but within the RV 1σ uncertainty. Additionally, a lower significance secondary peak in the period posterior is centered at 23.620 d that indicates a second family of solutions that we cannot statistically rule out.

We constructed a best-fit `batman` model (Kreidberg 2015) from the MCMC's max likelihood parameters, then phase-folded our data and the model to visualize the quality of fit, shown in Figure 4. The results do not indicate a transit was detected with statistical certainty in comparison to a flat model given the phase-folded light curve data. The level of noise and systematic error, particularly at critical times near predicted ingress and egress, were unfortunately high, primarily due to bursts of poor weather and brief gaps in telescope coverage. Additionally, there is insufficient data spanning across at least two stages of the transit (i.e., baseline plus ingress or egress), which makes a confident declaration of even a partial transit challenging. Thus, we can neither confirm nor rule out detections of either ingress or egress individually. We do note, however, that long flat sections of the light curve with high SNR allowed the MCMC to rule out some of the period parameter space still allowed by the EXOFASTv2 modeling (e.g., phases -0.01 to -0.005 in Figure 4).

While we did not detect transits with statistical certainty in our UCSN data, valuable insights for citizen science exoplanet follow-ups were discovered from this analysis, as detailed in Section 4. A deeper discussion on the examination of the UCSN photometry during the five predicted transit windows and analysis of the multimodal posterior space associated with our many independent UCSN datasets can be found in Appendix A.

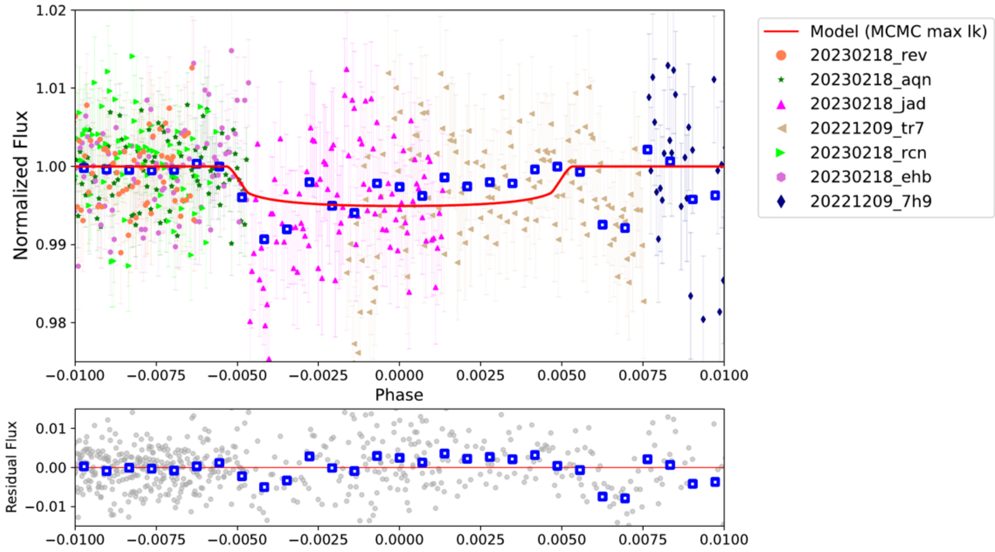

Figure 4. Normalized and phase-folded light curve from 7 of our Unistellar citizen scientist datasets with the MCMC max likelihood model fit (*top*) and residuals from the best-fit model (*bottom*). Unistellar data is labeled with observation date and abbreviated serial number, e.g. "YYYYMMDD_abc", where "abc" represents serial number. The max likelihood period value was P=23.627 d. The blue squares represent the weighted means of the individual relative fluxes within each phase bin. On average, each blue square represents about 28.3 data points.

4. DISCUSSION

4.1. *An Unusually High Density Sub-Saturn*

TIC 139270665 is a metal rich $1.035^{+0.052}_{-0.062}\ M_\odot$ and $1.016^{+0.035}_{-0.031}\ R_\odot$ solar-like G2V star hosting at least one, but likely two planets. TIC 139270665 b is an exoplanet confirmed from a single TESS transit and subsequent RV detection. We characterize it as a warm sub-Saturn exoplanet with a radius of 0.645 R_J ($7.23 R_\oplus$), a mass of 0.463 M_J, an orbital period of 23.624 d, and an equilibrium temperature of 703 K. Additionally, we report its density as 2.13 g cm^{-3}, which is more dense than any of the gas giants in our solar system[5]. Comparing TIC 139027665 b to other discovered TESS exoplanets in its class shows that it is also the densest TESS sub-Saturn known to date. Among the TESS-confirmed warm sub-Saturns, only eight possess a constrained mass[1] and we note their densities are <1g cm^{-3} (Kostov et al. 2020; Addison et al. 2020; Carleo et al. 2020; Kunimoto et al. 2023; König et al. 2022; Dransfield et al. 2022; Dawson et al. 2021; Ulmer-Moll et al. 2023). TOI-1710 b is the next most-dense after TIC 139270665 b with a density of 0.940g cm^{-3} (König et al. 2022). The average density of all the other eight warm sub-Saturns is 0.681g cm^{-3}. In Figure 5, we give TIC 139270665 b context by comparing to these and other discovered exoplanets.

[5] E.g., TIC 139270665 b is ≈ 1.3 times denser than Neptune and ≈ 1.7 times denser than Jupiter.

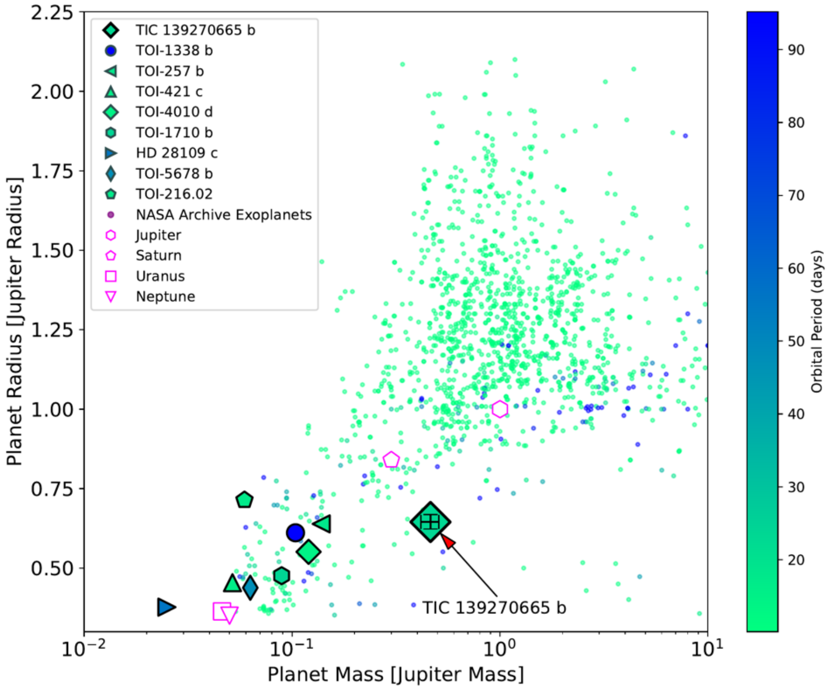

Figure 5. Mass versus radius for confirmed exoplanets including TIC 139270665 b. TOIs noted in the legend represent other dense warm sub-Saturns. Solar system planets (magenta outline) have $P >> 100d$. This demonstrates TIC 139270665 b's discovery and high density to be a valuable addition to our taxonomy of planets to help us further understand the evolutionary history of such bodies. 1σ error bars for TIC 139270665 b displayed in black.

The empirical planet mass-radius relationship of Chen & Kipping (2017) shows that radius increases with mass for sub-Jovian worlds and then this relation inverts to become slightly negative for masses above $\sim$0.41 M_J. TIC 139270665 b's mass places it approximately at that inflection point, meaning we would expect its radius to be most likely 1 R_J or larger. Instead, we find it to be just 0.645 R_J, far into the small-radius tail of the mass-radius relation's distribution. This begs multiple questions about the planet's formation and evolution.

Exploring the reasons for TIC 139270665 b's mass and size dynamics, we note that sub-Saturns can possess similar physical dimensions but diverge significantly in mass. The formation of this planetary type, particularly one like TIC 139270665 b, might lack a runaway gas accretion phase that other Jovians undergo (Petigura et al. 2017a). An alternative explanation suggests they might take shape within a gas-depleted disk, leaving them enhanced in heavy elements (Lee & Chiang 2015; Lee et al. 2018). Contemplating its history, it also is conceivable that TIC 139270665 b may have lost a portion of its atmosphere at some earlier time when it orbited closer to its star. The early intense UV and X-ray fluxes from a youthful star might have led to substantial envelope loss due to photoevaporation (Lopez et al. 2012) that was then followed by an outward migration. It is also worth considering that the outer planet, TIC 139270665 c, introduces an added layer of complexity to this system. Its likely high eccentricity could indicate an intricate dynamical past for this interesting planetary system.

To explore deeper into the density of TIC 139270665 b, future studies might consider employing a combination of planet structure models, as detailed by Thorngren & Fortney (2019), and spectroscopic analyses to determine its heavy-element composition and potential formation history. With TIC 139270665's $v \sin i$ measured at a relatively low value of 4.2 ± 1.0 km/s, it makes the star a good candidate for future RV observations for further characterization and study. Additionally, we recommend future photometry for long-term transit modeling to search for transit timing variations (TTVs) to help to narrow down the nature of planet c and search for other possible non-transiting exoplanets in the system. We also considered the possibility of suggesting the following up of TIC 139270665 b with the James Webb Space Telescope (JWST) for transmission spectroscopy. While it is a candidate for JWST spectroscopic follow up, using the transmission spectroscopy metric (TSM) by Kempton et al. (2018) we find a TSM of 28.3, which makes this a less than ideal candidate. Another consideration could be to attempt direct imaging of reflected light planets with future coronagraphic instruments on 30-meter class or space-based telescopes because of the system's proximity to Earth.

There are some types of planets to which our current observations are not sensitive and may remain undetected in this system. In particular, planets or brown dwarfs on low inclination orbits close to the star would have very weak RV signals and be undetectable by direct imaging or transits. Also, planets with very long periods (>1000 days) would require a longer RV baseline for detection.

To fully understand the nuances of planets like TIC 139270665 b and c, we need a larger observational sample of such planets. As our field gathers more data, we will likely improve our ability to categorize and refine our formation and evolutionary history models of these interesting exoplanets.

4.2. *Unistellar Network Photometry and Education & Outreach Opportunities*

Regarding our photometry from the Unistellar Network, we do not have enough data at the most critically important phases of the transit to draw definitive conclusions for declaring a transit or lack of transit with high confidence. It is challenging to constrain a single transit TESS candidate like TIC 139270665 b, even with updated parameters from the `EXOFASTv2` model fit in Table 1. While RV data reveals the orbital period, it still includes large uncertainties and does not provide the exact timing for a transit follow-up. The uncertainties from the only TESS-observed transit in January 2022, combined with those from the RV data, compound over each orbital period to make predicting subsequent transits less and less precise. By the time UCSN was deployed to capture a potential second transit, around 11 months had passed since the single-transit was observed by TESS. During this time, about 14 orbital periods of TIC 139270665 b would have passed, however, TESS did not detect any additional transits as it was no longer observing TIC 139270665 after January 2022. This led to an uncertainty window of roughly 10-11 hours on the expected mid-transit time when UCSN attempted to catch another transit in December 2022. Furthermore, ground-based follow-up observations are challenged by an average nighttime duration of only 8 hours. This limited window restricts visibility of the planet, and it is crucial within this time frame to capture not only the transit (at least the ingress or egress) but also the essential out-of-transit baseline data. Despite the 271 hours of eVscope data collected, we needed more to confidently capture a second transit for this planet. We also highlight the challenges posed by constraints of citizen science telescopes, like eVscopes, emphasizing the necessity for a comprehensive consideration of these limitations in terms of photometric precision and accuracy when planning observations with this type of equipment.

Even though we were unable to constrain the period and transit timing from our UCSN photometry, there are valuable insights and lessons for campaigns such as this in the future. The multi-modal period posterior from the MCMC (e.g., the second family of solutions in Figure 11 in the Appendix) reflects the complex structure of the data received from such a massively multi-site, multi-telescope campaign and points to a need for reducing systematic errors between data sets. The UCSN data may also be telling us that the segments of their data that are flat allow us to rule out an ingress or egress at certain times (e.g., such as with the high SNR flat segment from the high school Galaxy Explorers in Figure 14 in the Appendix). Additionally, we note that future long campaigns such as this would benefit by more strongly encouraging citizen astronomers to conduct observations long-enough to cover critical stages of the transit event such as ingress and egress plus significant out-of-transit baseline. Future Unistellar exoplanet campaigns may also encourage additional collaboration with other citizen science exoplanet programs, such as Exoplanet Watch or ExoClock to increase coverage and probability of detection, such as was done with HD 80606 b (Pearson et al. 2022) and Kepler-167 e (Perrocheau et al. 2022).

Lastly, we provide a proof of concept that citizen astronomer campaigns such as ours can offer more than a mere data collection tool for researchers. Instead, they can be a platform where educators, students, and citizen astronomers can engage in genuine scientific endeavors to bridge the gap between advanced astrophysical research and community engagement and student learning. We name such an initiative, "AstroReMixEd", to symbolize this harmonious fusion of astrophysical research, education, and community engagement. Our 16 Chabot Space & Science Center "Galaxy Explorer" high school students reported high excitement and engagement leading up to and during our overnight observation session of TIC 139270665 b. High school students learned introductory photometry skills and participated in advanced exoplanet observation planning and execution. Students also reported an increased excitement to know that their data, whether we detected a transit or not, would be useful and that they would be included as co-authors in this publication. Some of these students are now galvanized by this experience and are undertaking new research activities and plans to study and pursue careers in physics or astrophysics in college and beyond. With new telescope technology and innovative education programs and events such as these (e.g., Galaxy Explorer's TIC 139270665 b observation and others detailed in Peluso et al. (2023)), students can *learn by doing*, and we can also simultaneously further modern astrophysical research. AstroReMixEd initiatives could be a win-win scenario for both research and education, and could contribute to the ambitious goal of democratizing science and astronomy for all.

5. CONCLUSION

The investigation of single-transit events offers researchers a window into worlds beyond those that orbit in the "hot zone" of their stars (e.g., hot Jupiters) and provides insights into the evolution of planetary systems beyond our own. The paradigm of our own solar system, namely gas giants only residing far from their stars beyond the snow line, is now known to be just one type of the many diverse planetary systems in our expanding universe.

Here we detail and confirm the planetary nature of a new warm and uniquely dense sub-Saturn, TIC 139270665 b, with a $0.645R_J(7.23R_\oplus)$ and a mass of $0.463M_J$. Contextualized among other similar exoplanets, TIC 139270665 b emerges as the densest known TESS sub-Saturn, illuminating the dynamism and diversity of exoplanetary systems awaiting discovery. Citizen scientists from the Visual Survey Group discovered the TESS single-transit by TIC 139270665 b in 2022 January (Figure 1), and then we initiated RV follow-up in 2022 March with APF (Section 2.3). After we confidently ruled out a stellar binary (Figure 2) and our RV data confirmed TIC 139270665 b's existence (Figure 3), we engaged citizen scientists from the Unistellar Network. UCSN was selected due to its growing track record of success in exoplanet follow-up and its globally distributed network (see Section 2.4).

TIC 139270665 b orbits a G2 star in approximately 23.6d and is of a rare class of warm sub-Saturns with a density of 2.13g cm^{-3}. Our RV data also reveals TIC 139270665 b to have the longer-period outer planet, TIC 139270665 c, with a high eccentricity and a minimum mass consistent with being another planet. Future work aims to conduct additional transit follow-ups of TIC 139270665 b with UCSN to firmly detect a second transit. We encourage further work to quantify TIC 139270665 b's bulk heavy elements, as well as more observations and characterization of the outer planetary companion. There is also room for study on the dynamics of this system with its interactions between the eccentric outer planet c and the more circular, lower mass inner planet b. Future work should aim to further investigate TIC 139270665's system dynamics and planetary compositional intricacies.

Furthermore, UCSN offered the potential to underscore a dual objective with our photometry campaign: merging hands-on educational experiences with the rigor of actual scientific investigation. In this symbiotic approach, students do not simply *learn by doing* — they actively contribute to and shape the frontier of modern astrophysics, thereby proving that educational empowerment and cutting-edge research can be harmoniously interwoven (i.e. AstroReMixEd). Although UCSN was unable to tightly constrain TIC 139270665 b's period via a second transit detection, valuable lessons were learned about ground-based citizen astronomer campaigns, a proof of concept for combining education and astronomical research was realized, and possible transit times were negated when high SNR flat segments of the Unistellar light curves ruled out an ingress or egress.

As the technical capabilities of our astronomical community expand, so too does the scope of our data collection methods and results. For instance, the soon-to-be operational Vera C. Rubin Observatory is set to launch an ambitious time domain survey. Anticipated data sets from Rubin Observatory will be immense, with its Legacy Survey of Space and Time (LSST) alone projecting over 35 billion entries that will necessitate collaboration with citizen scientists to follow up on transient events (Higgs 2023). The growing prominence of citizen scientist endeavors underscores their invaluable role in shaping the future of scientific research. Additionally, citizen science may also help to revolutionize the field of education with more initiatives such as AstroReMixEd where both the research community, students, and public can contribute directly to the rewarding field of astronomy and astrophysics.

6. ACKNOWLEDGMENTS

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We have utilized resources from the NASA Exoplanet Archive, a service managed by the California Institute of Technology, in collaboration with the National Aeronautics and Space Administration as part of the Exoplanet Exploration Program. Observations in the paper made use of the NN-EXPLORE Exoplanet and Stellar Speckle Imager (NESSI). NESSI was funded by the NASA Exoplanet Exploration Program and the NASA Ames Research Center. NESSI was built at the Ames Research Center by Steve B. Howell, Nic Scott, Elliott P. Horch, and Emmett Quigley. We also express our gratitude to Ken and Gloria Levy for their generous support in the creation of the Levy Spectrometer on the Automated Planet Finder. Our appreciation extends to the University of California and Google for their backing of Lick Observatory, and to the UCO staff for their dedication in both scheduling and managing the Lick Observatory telescopes. Portions of the data discussed in this paper were sourced from the W. M. Keck Observatory, a joint venture between the California Institute of Technology, the University of California, and NASA. The authors acknowledge and respect the significant cultural value and importance that the summit of Maunakea holds within the indigenous Hawaiian community. We express our profound gratitude for the privilege of conducting observations from this sacred site.

This research incorporates data gathered by the TESS mission, a project generously funded by NASA's Science Mission Directorate. We recognize and value the public TESS data derived from pipelines at both the TESS Science Office and the TESS Science Processing Operations Center. We also acknowledge data from TESS that was sourced from the MAST data archive at the Space Telescope Science Institute (STScI). The STScI operates under the care of the Association of Universities for Research in Astronomy, Inc., in accordance with NASA contract NAS 5-26555.

To educators globally, we extend our profound appreciation. Your contributions are pivotal. The world looks to you to continue kindling inspiration and guiding future generations.

Facilities: TESS, Automated Planet Finder (Levy), Keck:I (HIRES), Unistellar Enhanced Vision Telescopes (eVscopes, citizen science network).

Data: All the TESS data used in this paper can be found in MAST: 10.17909/t9-nmc8-f686. All the NASA Exoplanet Archive data can be found on the NASA Exoplanet Archive: 10.26133/NEA1

Software: `SpecMatch` (Petigura et al. 2017b), `lightkurve` (Lightkurve Collaboration et al. 2018), `EXOFASTv2` (Eastman et al. 2013, 2019), `emcee` (Foreman-Mackey et al. 2013), `batman` (Kreidberg 2015).

APPENDIX

A. UCSN PHOTOMETRY: TRANSIT WINDOW & MCMC POSTERIOR ANALYSIS

A.1. *Observed Transit Windows*

For our five UCSN transit window campaigns and multimodal posterior analysis, we provide extended details here.

In our 2022 December UCSN campaign, we examined eleven data sets across four nights of observations. None of these data sets showed significant evidence of an ingress or egress, either individually or in the combined light curve. Figure 6 shows a flat subsection of the light curve from the 2022 December campaign. The data quality is representative of the larger light curve, with a standard deviation of 0.11% in the binned fluxes from our 2-minute integration images. Short-term systematic trends in individual data sets like the one seen in the first ∼20 flux measurements, particularly those at the start or end of an observation when airmass was high, were considered unlikely to be true ingress or egress signals.

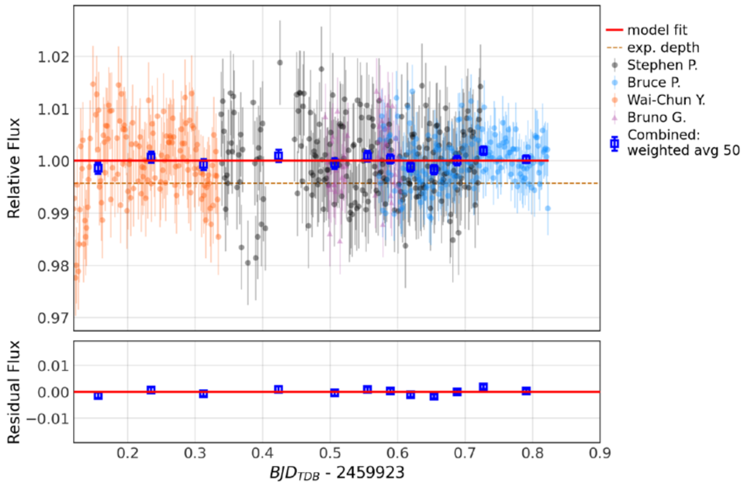

Figure 6. Example subsection of the December light curve from 2022-12-09, which we reported back to UCSN observers. This represents data from four citizen astronomer observers from one of four days during the 2022 December campaign. Colored points are fluxes measured from images totaling 2 minutes of integration each. Blue squares are weighted averages of 50 individual flux points. The dashed line is the predicted depth of TIC 139270665 b's transit. This light curve was chosen to present here as it had the most observers and data for the four-day December campaign. We note the photometric stability and precision, which allows sensitivity to < 1% transit depths and improved where we had overlapping data sets from multiple telescopes. The other individual December light curves were similarly flat, with no transit detection, or there was not enough coverage or data to make substantial conclusions.

The 2023 February campaign gave us data across three nights of the predicted transit window (Figure 7). Most of the data remained flat, presenting no ingress or egress. However, a potential egress signal was noted on 2023-02-17 with an end at UTC 22:27:58 (2459993.44173 BJD_{TDB}), but because it occurred at the start of an observation where airmass was greatest and systematic errors are most difficult to rule out, we could not conclude a detection with high confidence.

The 2023 March campaign mainly targeted North American citizen astronomers, but poor weather across the region limited data collection. Some data was captured slightly before our predicted transit, but it was statistically flat. Non-North American observers who attempted to observe for this campaign had statistically flat data as well.

In 2023 April, we had two predicted transit windows for our Unistellar citizen astronomers to observe. Data from 2023-04-05 hinted at a potential ingress with a transit centered at 10:08:10 UTC (2460039.92449 BJD_{TDB}) (see Figure 8). Our subsequent end-of-April campaign aimed at confirming this tentative signal was hindered by limited data collection due to poor weather and the star being only 15° away from a moon that was over 50% illuminated.

The maximum likelihood period of 26.627 d identified by our MCMC analysis meant that TIC 139270665 b transits should have intersected our UCSN observing windows in 2022 December and 2023 February. Our observations in the other windows would not have intersected transits. The (retroactively) predicted transit models centered on UTC 2022-12-09 and 2023-02-18 are shown compared to the UCSN data in Figures 9 and 10. As before, the data are generally insufficiently dense and precise to confidently confirm or definitely reject the presence of a transit. That said, the first 0.13 d of the February light curve are high SNR, flat during the expected pre-transit phase, and show a ∼0.4% drop in flux during the predicted ingress based on 15 overlapping measurements from two telescopes. The significance of this drop is limited, however, because those high SNR data stop at the end of ingress, so we cannot tell

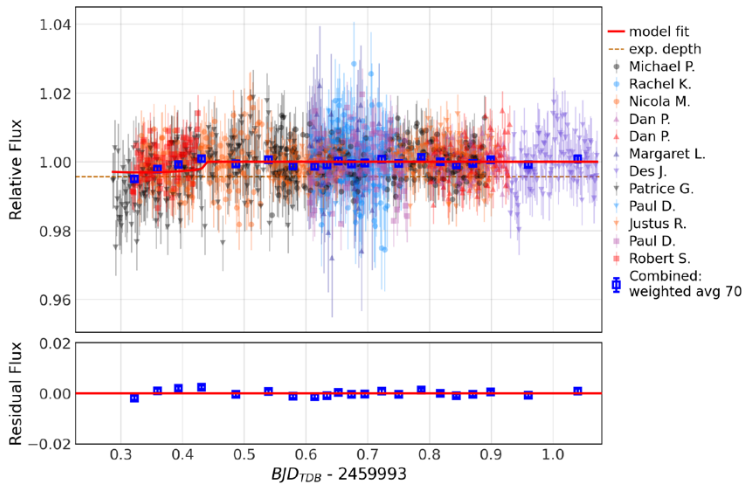

Figure 7. Transit light curve for the second night of our February campaign on 2023-02-17 shared with UCSN. The red line is the fitted transit model to the data. A model was fitted to this data because the moving average dropped below the expected transit depth threshold. This represents close to 19 hours of continuous data. The one-hour integrations show an achieved precision better than 0.1%, and the standard deviation of the fluxes from 2-minute integrations is only 0.67%. Our light curve model fitting routine identified an egress at the beginning of the sequence, which we subsequently rejected as unreliable. The original prediction times are based on our best estimate of the orbital period at the time of observation.

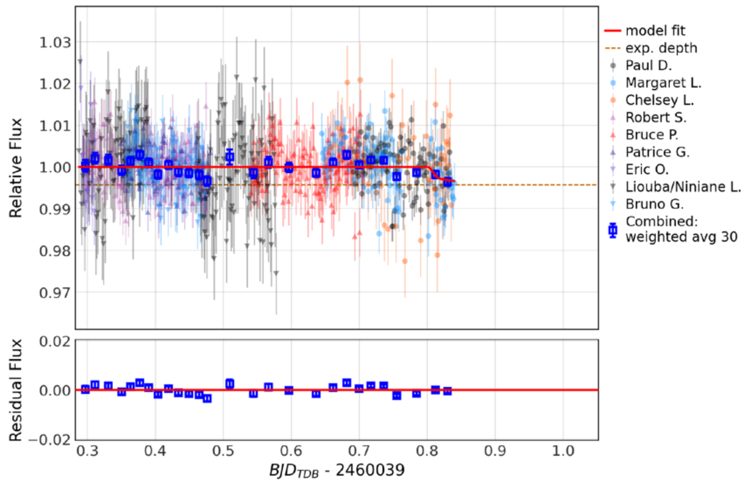

Figure 8. Transit light curve for 2023-04-05 from our April campaign, shared with UCSN. The red line the fitted transit model to the data. A model was fitted to this data because the moving average dropped below the expected transit depth threshold. Although an ingress like feature is seen here, we do not declare transit detection as we were unable to confirm this with a follow-up detection later in the month.

if the flux remained low during the expected in-transit time. The measurements after that point come from a single data set that shows stronger than normal systematic errors, making interpretation difficult.

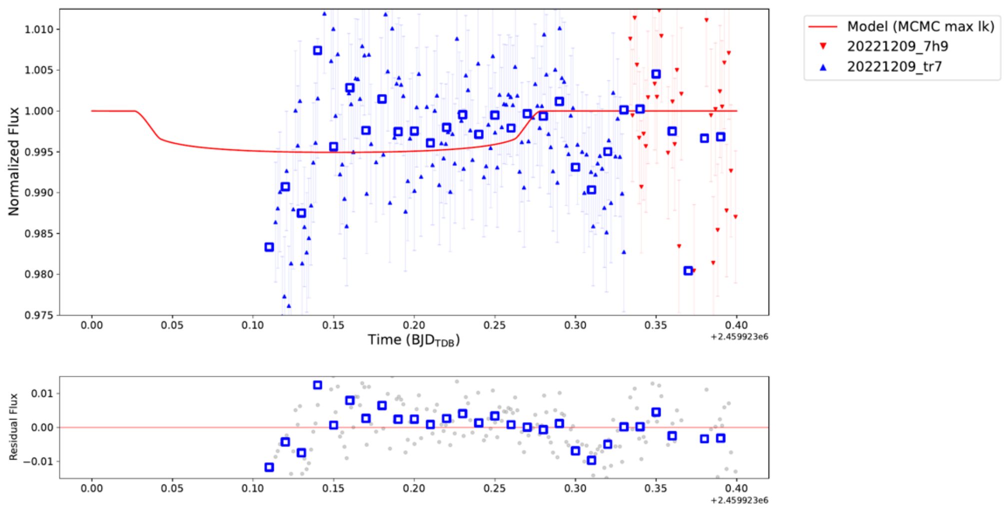

Figure 9. Maximum likelihood model from the MCMC plotted over the UCSN light curve on UTC 2022-12-09. The UCSN data in the light exhibits relatively large scatter compared to the expected transit depth, likely due to a combination of variable atmospheric conditions, systematic instrumental noise, and the inherent complexities of ground-based observations. Thus, drawing definitive conclusions from these data is challenging. The blue squares in the plot represent the weighted averages of fluxes and residuals, respectively, within each time bin of 0.01 days. On average, each blue square is derived from approximately 6 individual data points.

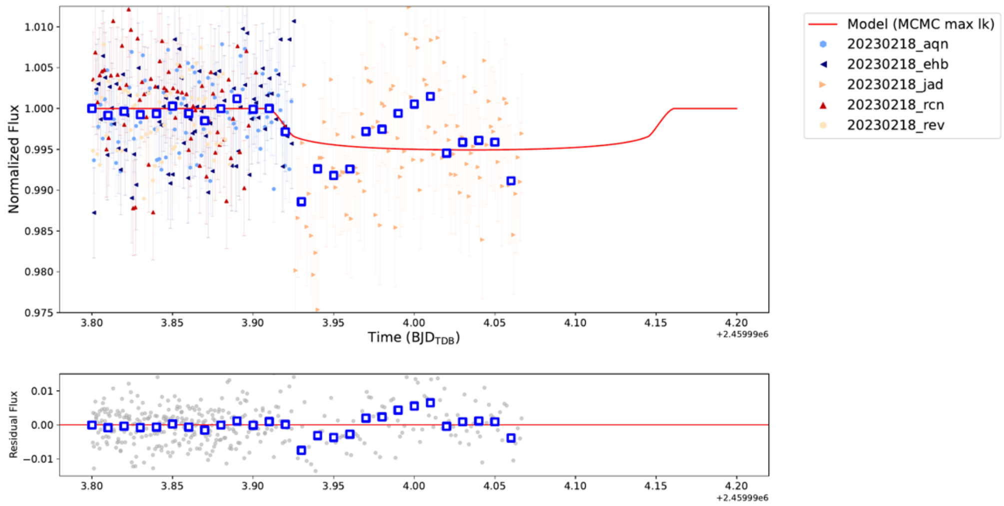

Figure 10. Maximum likelihood model from the MCMC plotted over the UCSN light curve on UTC 2023-02-18. Due to data gaps at critical transit stages, transit detection remains uncertain, though there is a possible ingress signal. The blue squares in the plot represent the weighted averages of fluxes and residuals, respectively, within each time bin of 0.01 days. On average, each blue square is derived from approximately 14.6 individual data points.

A.2. *MCMC Posterior Analysis and Multimodality*

For our MCMC used to identify transit signals in our UCSN light curve, we initialized it with 1,040 walkers, a "burn-in" phase of 3,250 iterations per walker that was then discarded, and finally 10,000 iterations per walker from which we drew the posterior distribution. Different exploration strategies were incorporated using various walker "moves" from the `emcee` package, settling on a fraction per move type of `emcee.moves.DEMove(0.05)`, `emcee.moves.DESnookerMove(0.2)`, and `emcee.moves.KDEMove(0.75)`. The complex parameter space meant that walkers were often getting stuck in islands of local high probability but not reaching the global probability maximum, and we found that different most types were better at avoiding those local islands. Experimenting with the move sets, we found that including a fraction of the snooker and the majority of KDEMove was most successful.

During our MCMC analysis, we observed a walker divergence in the period parameter trace plot (Figure 11). This led us to investigate a second set of solutions with a period of $P = 23.620$ d, which was where the second largest cluster of walkers was centered. This model is statistically less preferred when compared to the maximum likelihood period of $P = 23.627$ d (i.e., it produced a larger χ^2); however, it is still possible given our data, so we provide the phase-folded light curve corresponding to this second family of solutions in Figure 12.

After our initial MCMC, we recognized that, while the *offset* parameter converged on a single value for most data sets, it ended up bimodal for four data sets. This suggested a possible additional, lower probability solutions dependent on how these data sets were normalized compared to the others. There was an observed divergence in the trace plots from the chain for the *offsets*. After investigating the divergence through specified offset ranges for different data sets, we were unable to discover any convincing transit detections.

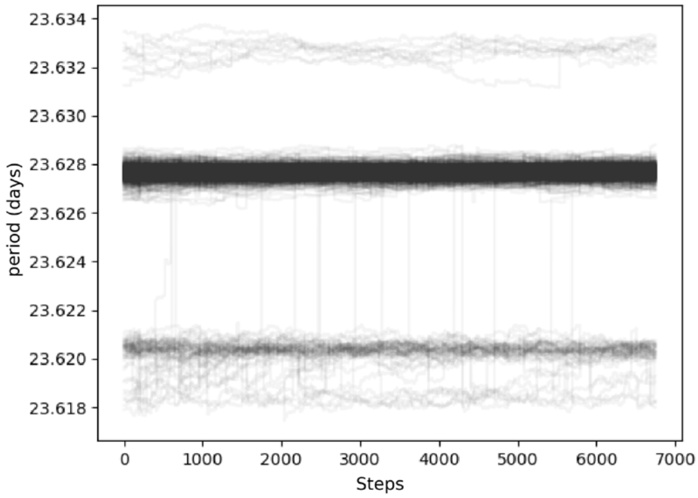

Figure 11. MCMC walker trace plot for the period (in days) after trimming the initial 3250 steps (iterations) as burn-in. The bottom group of walkers, clustered between $P = 23.620d$ and $P = 23.621d$, were investigated as a possible second set of solutions.

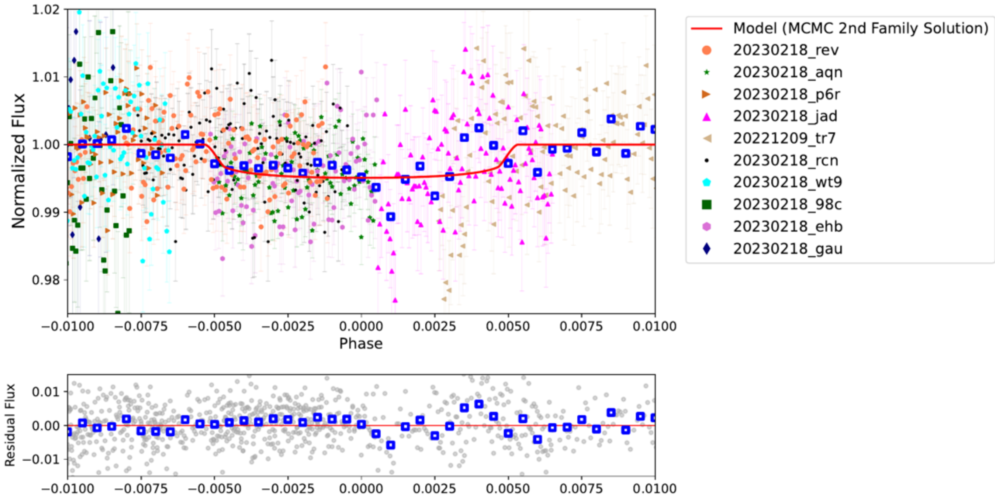

Figure 12. (*top*) Normalized and phase-folded light curve using ten data sets from our Unistellar citizen scientists that encompassed the transit window defined by the MCMC's secondary (i.e., less preferred) set of solutions from Figure 11. This secondary solution corresponds to a period of $P = 23.620d$. *bottom* Residuals from this secondary model. Unistellar data are labeled by observation date followed by an abbreviated serial number in the format "YYYYMMDD_abc", where "abc" denotes the serial number. The blue squares represent the weighted means of the individual relative fluxes within each phase bin. On average, each blue square represents about 20.5 data points.

B. ADDITIONAL TABLES & DATA

Table 3. RV Measurements of TIC 139270665 From APF-Levy.

BJD_{TDB}	RV (m s^{-1})
2459638.798167	-138.7 ± 7.8
2459640.803143	-133.0 ± 8.5
2459647.901770	-169.2 ± 7.7
2459650.882322	-156.7 ± 7.8
2459656.756404	-100.9 ± 7.7
2459662.739474	-109.9 ± 7.6
2459698.689303	-118.7 ± 9.7
2459703.685927	-100.9 ± 9.1
2459716.681231	-139.8 ± 10.3
2459720.678592	-159.7 ± 10.8
2459723.683151	-149.6 ± 11.8
2459729.685929	-113.9 ± 11.2
2459822.019650	73.8 ± 7.9
2459825.000669	61.4 ± 9.2
2459827.004468	47.7 ± 8.4
2459831.998564	15.2 ± 10.2

Table 3 *continued on next page*

Table 3 *(continued)*

BJD_{TDB}	RV (m s^{-1})
2459850.945055	96.3 ± 7.7
2459852.962331	72.1 ± 7.8
2459858.918770	44.2 ± 7.9
2459863.925319	84.0 ± 8.3
2459868.940071	123.2 ± 7.7
2459873.947061	119.0 ± 6.9
2459900.805350	69.0 ± 9.2
2459903.880661	31.6 ± 7.0
2459906.895891	58.6 ± 8.3
2459910.791877	66.8 ± 10.1
2459913.843048	109.3 ± 6.9
2459929.872693	13.0 ± 5.6
2459931.883288	35.8 ± 5.9
2459964.900397	55.4 ± 10.7
2459965.730187	36.9 ± 6.8
2459966.706965	10.8 ± 12.2
2459968.810077	39.3 ± 8.3
2459969.715243	21.6 ± 7.8
2459970.795047	14.1 ± 8.0
2459971.713010	3.9 ± 7.9
2459972.711943	-18.7 ± 7.9
2459976.013552	-8.7 ± 9.4
2459976.742448	-21.7 ± 6.1
2459983.870853	18.7 ± 7.3
2459993.816766	-9.9 ± 6.5
2460059.665795	0.1 ± 8.0
2460063.666801	-4.6 ± 7.6
2460064.668268	-30.8 ± 5.8
2460075.673304	-48.4 ± 6.4
2460076.676316	-55.3 ± 7.1
2460077.679583	-42.4 ± 7.7
2460078.676741	-27.0 ± 7.1
2460079.676306	-16.1 ± 7.1
2460080.674796	-22.4 ± 9.5
2460081.719219	-19.7 ± 8.3
2460082.683708	22.1 ± 7.9
2460083.679226	-12.3 ± 6.5
2460084.680507	-21.3 ± 9.3
2460085.725536	-24.8 ± 9.0
2460086.726195	-2.9 ± 10.7
2460087.726738	-34.5 ± 8.2
2460091.729524	-61.5 ± 9.0
2460096.702127	-73.3 ± 8.6

Table 4. Unistellar Observations Summary

eVscope ID	UTC Start Date	Start Time (hh:mm:ss)	End Time (hh:mm:ss)	Observer	Location
tr7	2022-12-09	14:44:01.730	19:55:14.411	Wai-Chun Yue	Hong Kong
7h9	2022-12-09	20:00:54.902	05:14:28.856	Stephen Price	UK
wfb	2022-12-09	23:43:50.126	02:24:24.992	Bruno Guillet	France
9vr	2022-12-10	01:37:40.515	07:38:01.165	Bruce Parker	United States
tr7	2022-12-10	14:20:12.158	20:03:47.817	Wai-Chun Yue	Hong Kong
26e	2022-12-10	15:36:04.481	20:27:52.326	Keiichi Fukui	Japan
v8v	2022-12-10	16:16:36.247	20:18:27.103	Keiichi Fukui	Japan
vfq	2022-12-11	02:00:56.288	02:33:16.447	Liouba and Niniane Leroux	France
8cm	2022-12-11	15:07:25.376	15:56:18.982	Masao Shimizu	Japan
za9	2022-12-11	15:52:22.620	16:51:05.748	Ryuichi Kukita	Japan
qer	2022-12-12	05:30:37.785	08:28:54.148	Stefan Will	United States
98c	2023-02-17	02:39:01.835	04:15:11.047	Rachel Knight	United States
rev	2023-02-17	04:06:03.171	10:01:04.595	Michael Primm	United States
26e	2023-02-17	10:13:19.827	15:37:21.822	Keiichi Fukui	Japan
knr	2023-02-17	18:46:25.599	01:56:53.791	Patrice Girard	France
8zz	2023-02-17	19:29:48.030	22:05:17.829	Robert Savonnet	France
3mh	2023-02-17	19:46:21.475	00:33:55.606	Nicola Meneghelli	Italy
rcn	2023-02-18	00:45:09.996	09:38:29.238	Justus Randolph	United States
rev	2023-02-18	00:57:32.154	09:15:08.067	Michael Primm	United States
gau	2023-02-18	02:20:52.438	05:07:04.920	Margaret A. Loose	United States
wt9	2023-02-18	02:24:58.621	06:12:17.053	Paul A. Dalba	United States
p6r	2023-02-18	02:28:08.211	06:04:25.788	Paul A. Dalba	United States
98c	2023-02-18	02:50:55.578	05:25:37.018	Rachel Knight	United States
ehb	2023-02-18	06:59:58.033	10:12:20.105	Daniel O. Peluso	United States
aqn	2023-02-18	07:05:50.118	10:10:12.866	Daniel O. Peluso	United States
jad	2023-02-18	10:13:56.165	13:35:48.356	Des Janke	Australia
wfb	2023-02-18	21:46:50.433	23:44:19.937	Bruno Guillet	France
aqn	2023-02-19	04:09:39.246	13:02:51.181	Daniel O. Peluso	United States
epz	2023-02-19	04:14:43.344	13:04:29.038	Aditya Kapur & Nathan Jay	United States
9bn	2023-02-19	04:26:27.565	13:04:25.036	Josephine Oesterer & Astha Verma	United States
ehb	2023-02-19	04:28:30.613	13:09:45.740	Ananya Balakrishnan & Christopher Seo	United States
wt9	2023-02-19	04:31:20.968	07:59:41.797	Marco Hovland & Jonah Morgan	United States
p6r	2023-02-19	04:31:58.118	13:08:22.219	Serina Jain & Divya Bhamidipati	United States
qm6	2023-02-19	04:32:40.684	12:32:43.246	Olivia Woo & Naina Srivastava	United States
mgc	2023-02-19	04:42:01.448	13:04:37.092	Dean Ramos & Richard Purev	United States
b64	2023-02-19	05:44:30.266	12:37:58.673	Hanna Johnson & Vibha Sriramkumar	United States
26e	2023-03-11	11:59:02.839	17:00:16.386	Keiichi Fukui	Japan
e7m	2023-03-11	13:22:35.620	16:20:54.828	Tateki Goto	Japan
5wz	2023-03-11	18:28:17.501	20:11:16.812	Andre Katterfeld	Germany
vfq	2023-03-11	19:15:18.673	01:40:41.001	Liouba and Niniane Leroux	France
j9z	2023-03-12	00:44:30.867	01:33:18.721	Neil Yoblonsky	United States
t8m	2023-03-12	01:39:06.100	02:00:44.262	Eric Lawson	United States
23d	2023-03-12	19:21:20.172	23:19:22.225	Petri Tikkanen	Finland
vfq	2023-04-04	18:51:59.468	01:49:28.117	Liouba and Niniane Leroux	France
p4e	2023-04-04	18:56:15.401	19:26:03.944	Eric Oulevey	France
8zz	2023-04-04	19:01:10.585	23:20:49.732	Robert Savonnet	France
g3e	2023-04-04	20:20:29.767	23:30:15.731	Patrice Girard	France

Table 4 *continued on next page*

Table 4 *(continued)*

eVscope ID	UTC Start Date	Start Time (hh:mm:ss)	End Time (hh:mm:ss)	Observer	Location
2rz	2023-04-04	20:31:01.852	23:17:41.093	Bruno Guillet	France
wfb	2023-04-04	20:32:52.335	23:15:05.130	Bruno Guillet	France
9vr	2023-04-05	00:56:22.558	04:54:24.960	Bruce Parker	United States
gau	2023-04-05	03:25:55.589	08:07:13.575	Margaret A. Loose	United States
qrb	2023-04-05	03:45:11.828	08:00:12.271	Chelsey Logan	United States
p6r	2023-04-05	04:33:17.876	07:57:20.504	Paul A. Dalba	United States
8zz	2023-04-05	18:52:57.274	22:51:00.049	Robert Savonnet	France
aij	2023-04-05	20:25:10.527	00:23:12.806	Steven Adkinson	Portugal
vfq	2023-04-05	20:47:48.397	23:03:13.420	Liouba and Niniane Leroux	France
gau	2023-04-06	02:43:18.258	08:37:57.255	Margaret A. Loose	United States
wt9	2023-04-06	04:02:15.493	07:55:39.704	Paul A. Dalba	United States
p6r	2023-04-06	04:26:52.729	07:48:43.814	Paul A. Dalba	United States
jad	2023-04-28	08:35:54.386	11:07:32.178	Des Janke	Australia
934	2023-04-29	01:38:30.415	02:08:17.048	Lauren A. Sgro	United States
ya3	2023-04-29	02:30:43.198	06:42:46.062	David Koster	United States

Highlighted rows represent the high school student observers in the Chabot Space & Science Center's Galaxy Explorers program.

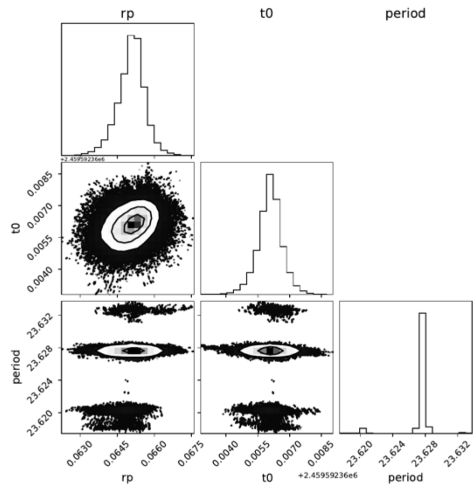

Figure 13. Marginalized posterior distributions from the MCMC that searched for a transit signal in the Unistellar eVscope light curve data. Only the planet's period, radius (rp), and date of mid-transit (t0) are shown (`offsets` are excluded). The period distribution is multimodal, with one period range strongly preferred. Despite the seemingly well-constrained parameters, a Bayesian Information Criterion (BIC) test showed that these transit models did not provide significantly better fits to the data than a flat model.

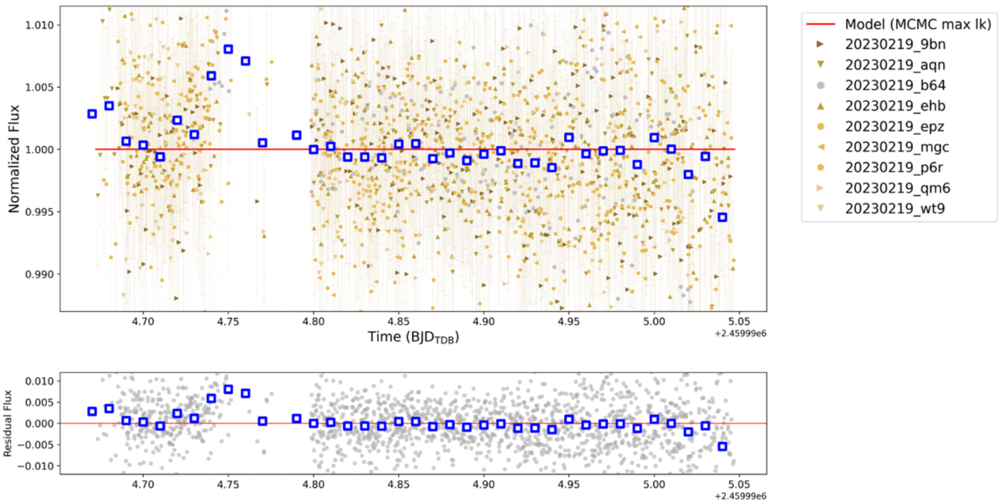

Figure 14. Maximum likelihood model from the MCMC plotted over only the Chabot Space & Science Center's Galaxy Explorer High School students' Unistellar data sets, on UTC 2023-02-19. Initial variability likely stems from partly cloudy weather, which transitioned to clearer skies after a data gap of ∼1.2 hours. The subsequent flat light curve, a result of combined observations from nine eVscopes, has a high SNR and indicates the absence of any ingress or egress by TIC 139270665 b. The increase variability at the very end of the light curve can be attributed to the target's high air mass at the end of the observation. The blue squares in the plot represent the weighted averages of fluxes and residuals, respectively, within each time bin of 0.01 days. On average, each blue square is derived from approximately 43.6 individual data points.

REFERENCES

Addison, B. C., Wright, D. J., Nicholson, B. A., et al. 2020, arXiv preprint arXiv:2001.07345. https://arxiv.org/abs/2001.07345

Akeson, R. L., Chen, X., Ciardi, D., et al. 2013, Publications of the Astronomical Society of the Pacific, 125, 989, doi: 10.1086/672273

Bakos, G., Noyes, R. , Kovács, G., et al. 2004, Publications of the Astronomical Society of the Pacific, 116, 266, doi: 10.1086/382735

Bakos, G. Á., Csubry, Z., Penev, K., et al. 2013, PASP, 125, 154, doi: 10.1086/669529

Barclay, T., Pepper, J., & Quintana, E. V. 2018, The Astrophysical Journal Supplement Series, 239, 2, doi: 10.3847/1538-4365/aae3e9

Borucki, W. J., Koch, D., Basri, G., et al. 2010, Science, 327, 977

Brady, M. T., Petigura, E. A., Knutson, H. A., et al. 2018, AJ, 156, 147, doi: 10.3847/1538-3881/aad773

Butler, R. P., Marcy, G. W., Williams, E., et al. 1996, PASP, 108, 500, doi: 10.1086/133755

Carleo, I., Gandolfi, D., Barragán, O., et al. 2020, AJ, 160, 114, doi: 10.3847/1538-3881/aba124

Chen, J., & Kipping, D. 2017, ApJ, 834, 17, doi: 10.3847/1538-4357/834/1/17

Collins, K. A., Collins, K. I., Pepper, J., et al. 2018, The Astronomical Journal, 156, 1, doi: 10.3847/1538-3881/aae582

Cooke, B. F., Pollacco, D., West, R., McCormac, J., & Wheatley, P. J. 2018, A&A, 619, A175, doi: 10.1051/0004-6361/201834014

Dalba, P. A., Kane, S. R., Dragomir, D., et al. 2022, The Astronomical Journal, 163, 61, doi: 10.3847/1538-3881/ac415b

Dalba, P. A., Kane, S. R., Dragomir, D., et al. 2022, AJ, 163, 61, doi: 10.3847/1538-3881/ac415b

Dawson, R. I., & Johnson, J. A. 2018, ARA&A, 56, 175, doi: 10.1146/annurev-astro-081817-051853

Dawson, R. I., Huang, C. X., Brahm, R., et al. 2021, AJ, 161, 161, doi: 10.3847/1538-3881/abd8d0

Díaz, M. R., Jenkins, J. S., Feng, F., et al. 2020, MNRAS, 496, 4330, doi: 10.1093/mnras/staa1724

Dotter, A. 2016, ApJS, 222, 8, doi: 10.3847/0067-0049/222/1/8

Dransfield, G., Triaud, A. H. M. J., Guillot, T., et al. 2022, MNRAS, 515, 1328, doi: 10.1093/mnras/stac1383

Eastman, J., Gaudi, B. S., & Agol, E. 2013, PASP, 125, 83, doi: 10.1086/669497

Eastman, J. D., Rodriguez, J. E., Agol, E., et al. 2019, arXiv e-prints, arXiv:1907.09480, doi: 10.48550/arXiv.1907.09480

Edwards, B., Changeat, Q., Yip, K. H., et al. 2020, Monthly Notices of the Royal Astronomical Society, 504, 5671, doi: 10.1093/mnras/staa1245

Fischer, D. A., Schwamb, M. E., Schawinski, K., et al. 2012, Monthly Notices of the Royal Astronomical Society, 419, 2900, doi: 10.1111/j.1365-2966.2011.19932.x

Foreman-Mackey, D., Hogg, D. W., Lang, D., & Goodman, J. 2013, PASP, 125, 306, doi: 10.1086/670067

Fortney, J. J., Dawson, R. I., & Komacek, T. D. 2021, Journal of Geophysical Research (Planets), 126, e06629, doi: 10.1029/2020JE006629

Fortney, J. J., & Nettelmann, N. 2010, SSRv, 152, 423, doi: 10.1007/s11214-009-9582-x

Fowler, M. J. F. 2019, Journal of the British Astronomical Association, 129, 174

Freeman, S., Eddy, S. L., McDonough, M., et al. 2014, Proceedings of the national academy of sciences, 111, 8410

Gaia Collaboration, Brown, A. G. A., Vallenari, A., et al. 2021, A&A, 649, A1, doi: 10.1051/0004-6361/202039657

Gomez, E. L., & Fitzgerald, M. T. 2017, Astronomical Review, 13, 28, doi: 10.1080/21672857.2017.1303264

Grieves, N., Bouchy, F., Ulmer-Moll, S., et al. 2022, A&A, 668, A29, doi: 10.1051/0004-6361/202244077

Heitzmann, A., Zhou, G., Quinn, S. N., et al. 2023, AJ, 165, 121, doi: 10.3847/1538-3881/acb5a2

Higgs, C. 2023, in American Astronomical Society Meeting Abstracts, Vol. 55, American Astronomical Society Meeting Abstracts, 140.03

Hobson, M. J., Jordan, A., Henning, T., et al. 2022, in Bulletin of the American Astronomical Society, Vol. 54, 102.260

Howell, S. B., Everett, M. E., Sherry, W., Horch, E., & Ciardi, D. R. 2011, AJ, 142, 19, doi: 10.1088/0004-6256/142/1/19

Jenkins, J. M., Twicken, J. D., McCauliff, S., et al. 2016, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 9913, Software and Cyberinfrastructure for Astronomy IV, ed. G. Chiozzi & J. C. Guzman, 99133E, doi: 10.1117/12.2233418

Jones, H. R. A., Butler, R. P., Tinney, C. G., et al. 2003, MNRAS, 341, 948, doi: 10.1046/j.1365-8711.2003.06481.x

Jontof-Hutter, D., Lissauer, J. J., Rowe, J. F., & Fabrycky, D. C. 2014, ApJ, 785, 15, doi: 10.1088/0004-637X/785/1/15

Kempton, E. M. R., Bean, J. L., Louie, D. R., et al. 2018, PASP, 130, 114401, doi: 10.1088/1538-3873/aadf6f

Kokori, A., Tsiaras, A., Edwards, B., et al. 2022a, Experimental Astronomy, 53, 547, doi: 10.1007/s10686-020-09696-3

—. 2022b, The Astrophysical Journal Supplement Series, 258, 40, doi: 10.3847/1538-4365/ac3a10

König, P. C., Damasso, M., Hébrard, G., et al. 2022, A&A, 666, A183, doi: 10.1051/0004-6361/202143002

Kostov, V. B., Orosz, J. A., Feinstein, A. D., et al. 2020, AJ, 159, 253, doi: 10.3847/1538-3881/ab8a48

Kostov, V. B., Powell, B. P., Orosz, J. A., et al. 2021, AJ, 162, 234, doi: 10.3847/1538-3881/ac223a

Kreidberg, L. 2015, PASP, 127, 1161, doi: 10.1086/683602

Kristiansen, M. H. K., Rappaport, S. A., Vanderburg, A. M., et al. 2022, PASP, 134, 074401, doi: 10.1088/1538-3873/ac6e06

Kunimoto, M., Vanderburg, A., Huang, C. X., et al. 2023, AJ, 166, 7, doi: 10.3847/1538-3881/acd537

Lee, E. J., & Chiang, E. 2015, ApJ, 811, 41, doi: 10.1088/0004-637X/811/1/41

Lee, E. J., Chiang, E., & Ferguson, J. W. 2018, MNRAS, 476, 2199, doi: 10.1093/mnras/sty389

Lightkurve Collaboration, Cardoso, J. V. d. M., Hedges, C., et al. 2018, Lightkurve: Kepler and TESS time series analysis in Python, Astrophysics Source Code Library, record ascl:1812.013. http://ascl.net/1812.013

Lindegren, L., Klioner, S. A., Hernández, J., et al. 2021, A&A, 649, A2, doi: 10.1051/0004-6361/202039709

Lopez, E. D., & Fortney, J. J. 2014, ApJ, 792, 1, doi: 10.1088/0004-637X/792/1/1

Lopez, E. D., Fortney, J. J., & Miller, N. 2012, ApJ, 761, 59, doi: 10.1088/0004-637X/761/1/59

Marchis, F., Malvache, A., Marfisi, L., Borot, A., & Arbouch, E. 2020, Acta Astronautica, 166, 23, doi: https://doi.org/10.1016/j.actaastro.2019.09.028

Mayor, M., Marmier, M., Lovis, C., et al. 2011, arXiv e-prints, arXiv:1109.2497, doi: 10.48550/arXiv.1109.2497

Mireles, I., Dragomir, D., Osborn, H. P., et al. 2023, ApJL, 954, L15, doi: 10.3847/2041-8213/aceb69

Mizrachi, R., Ly, D., Bewersdorff, L., & Tock, K. 2021, Journal of the American Association of Variable Star Observers (JAAVSO), 49, 186

Mousis, O., Hueso, R., Beaulieu, J. P., et al. 2014, Experimental Astronomy, 38, 91, doi: 10.1007/s10686-014-9379-0

Pearson, K. A., Beichman, C., Fulton, B. J., et al. 2022, The Astronomical Journal, 164, 178, doi: 10.3847/1538-3881/ac8dee

Peluso, D. O., Esposito, T. M., Marchis, F., et al. 2023, Publications of the Astronomical Society of the Pacific, 135, 015001, doi: 10.1088/1538-3873/acaa58

Perrocheau, A., Esposito, T. M., Dalba, P. A., et al. 2022, The Astrophysical Journal Letters, 940, L39, doi: 10.3847/2041-8213/aca073

Petigura, E. A., Sinukoff, E., Lopez, E. D., et al. 2017a, AJ, 153, 142, doi: 10.3847/1538-3881/aa5ea5

Petigura, E. A., Howard, A. W., Marcy, G. W., et al. 2017b, AJ, 154, 107, doi: 10.3847/1538-3881/aa80de

Petigura, E. A., Marcy, G. W., Winn, J. N., et al. 2018, AJ, 155, 89, doi: 10.3847/1538-3881/aaa54c

Pollacco, D. , Skillen, I., Cameron, A. , et al. 2006, Publications of the Astronomical Society of the Pacific, 118, 1407, doi: 10.1086/508556

Radovan, M. V., Cabak, G. F., Laiterman, L. H., Lockwood, C. T., & Vogt, S. S. 2010, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 7735, Ground-based and Airborne Instrumentation for Astronomy III, ed. I. S. McLean, S. K. Ramsay, & H. Takami, 77354K, doi: 10.1117/12.857726

Radovan, M. V., Lanclos, K., Holden, B. P., et al. 2014, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 9145, Ground-based and Airborne Telescopes V, ed. L. M. Stepp, R. Gilmozzi, & H. J. Hall, 91452B, doi: 10.1117/12.2057310

Ricker, G., Winn, J., Vanderspek, R., et al. 2014, Journal of Astronomical Telescopes, Instruments, and Systems, 1, 014003, doi: 10.1117/1.JATIS.1.1.014003

Santerne, A., Moutou, C., Tsantaki, M., et al. 2016, A&A, 587, A64, doi: 10.1051/0004-6361/201527329

Sarva, J., Freed, R., Fitzgerald, M. T., & Salimpour, S. 2020, Astronomy Theory, Observations Methods, 1, 34

Schlafly, E. F., & Finkbeiner, D. P. 2011, ApJ, 737, 103, doi: 10.1088/0004-637X/737/2/103

Scott, N. J., Howell, S. B., Horch, E. P., & Everett, M. E. 2018, PASP, 130, 054502, doi: 10.1088/1538-3873/aab484

Team, M. 2021, TESS Light Curves - All Sectors, STScI/MAST, doi: 10.17909/T9-NMC8-F686

Thorngren, D., & Fortney, J. J. 2019, ApJL, 874, L31, doi: 10.3847/2041-8213/ab1137

Ulmer-Moll, S., Osborn, H. P., Tuson, A., et al. 2023, A&A, 674, A43, doi: 10.1051/0004-6361/202245478

Villanueva, S., Dragomir, D., & Gaudi, B. S. 2019, The Astronomical Journal, 157, 84, doi: 10.3847/1538-3881/aaf85e

Vogt, S. S., Allen, S. L., Bigelow, B. C., et al. 1994, in Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series, Vol. 2198, Instrumentation in Astronomy VIII, ed. D. L. Crawford & E. R. Craine, 362, doi: 10.1117/12.176725

Vogt, S. S., Radovan, M., Kibrick, R., et al. 2014, PASP, 126, 359, doi: 10.1086/676120

Wang, X.-Y., Rice, M., Wang, S., et al. 2022, The Astrophysical Journal Letters, 926, L8, doi: 10.3847/2041-8213/ac4f44

Wittenmyer, R. A., O'Toole, S. J., Jones, H. R. A., et al. 2010, ApJ, 722, 1854, doi: 10.1088/0004-637X/722/2/1854

Wright, J. T., Marcy, G. W., Howard, A. W., et al. 2012, The Astrophysical Journal, 753, 160, doi: 10.1088/0004-637X/753/2/160

Wright, J. T., Marcy, G. W., Howard, A. W., et al. 2012, ApJ, 753, 160, doi: 10.1088/0004-637X/753/2/160

Zellem, R. T., Pearson, K. A., Blaser, E., et al. 2020, Publications of the Astronomical Society of the Pacific, 132, 054401, doi: 10.1088/1538-3873/ab7ee7

5.3 Links and Implications

The discovery and confirmation of the TESS single-transit warm and dense sub-Saturn, TIC 139270665 b, enabled by the collaboration between citizen scientists, students, and professional astronomers, represents a tangible outcome of the combined efforts between these three groups. While the collected Unistellar photometric data encountered some challenges in constraining the orbital period definitively, it was able to rule out some orbital periods and several valuable lessons were gained that will be useful for future long-period exoplanet citizen science campaigns. Additionally, the combined collected data (i.e., photometric and RV) expanded our understanding of a unique exoplanet, which adds value to our inventory of planets that can help researchers better understand planetary formation and evolution theories. Further, this work showcased the effectiveness of the AstroReMixEd approach, where high school students actively contributed to cutting-edge astrophysical research while also learning. By incorporating more citizen scientist observers for long-period exoplanet observations, researchers can expand their photometric baseline and increase their chances of capturing additional transits of these hard to detect exoplanets. Additionally, the inclusion of students in these observations not only benefits both research and education but also contributes significantly to the overarching goal of democratizing science and science education.

CHAPTER 6: DISCUSSION

"The important thing to remember
is that you must never under any
circumstances, cross the streams."
-Dr. Egon Spengler (Ghostbusters, 1984)

6.1 The Unistellar Exoplanet Campaign

In 2019, the inaugural work of my thesis was initiated through a collaborative effort to establish the first global citizen science exoplanet network using app-controlled smart digital telescopes operated in-situ by citizen astronomers. While being a part of this pioneering team, I played a significant role in the network's early developments and growth. The early stages were marked by trial and error in both instrument and various target testing and network outreach. Notably, and possibly the first documented communication to the network still exists in blog posts on the SETI Institute's Cosmic Diary[23]. By 2020, the Unistellar Exoplanet Campaign (UE) flourished, involving 163 citizen scientists in 21 countries, and achieving a 43.2% transit detection success rate. Standout moments include precise mid-transit time measurements for the TESS planet candidate TOI 2031.01 from observers 6700 km apart, and the revision of TOI 3799.01's orbital period. Further, the pioneering "Gee Whiz Astronomy" inspired observations highlight the potential that exists when education and research intertwine (e.g., AstroReMixEd).

6.2 Astronomy Modeling Instruction with Exoplanets Intervention

In the study, *Astronomy Modeling Instruction with Exoplanets: Motivating Science Teaching and Learning in the 21st Century*, real astrophysics data sourced from NASA's Universe of Learning MicroObservatory, LCO, and the Unistellar citizen science network was integrated within the G-HOU framework and Modeling Instruction pedagogy. This combination that heavily focused on Modeling Instruction and active astrophysics data collection and analysis, resulted in measurable improvements in both teacher and student astronomy knowledge and skills. Data showed that 14 AME teachers requested celestial images and 90% of citizen scientists in the Unistellar network were willing to support educational exoplanet observations. After our 15-week workshop, teachers, even those new to astronomy, were equipped to use professional telescopes, perform photometry, analyze exoplanet data, and integrate astrophysics

[23] E.g., http://cosmicdiary.org/dpeluso/2020/01/11/get-your-unistellar-evscopes-and-help-observe-an-exoplanet-this-weekend/ | Accessed 7 September 2023.

into high school curricula at depths rivaling many introductory university courses. Concurrently, students indicated a strong preference for hands-on learning and working with exoplanet data versus lectures or traditional textbook methods. Mr. Percy Munoz's journey (as detailed in *The Percy Munoz Case Study* section of the paper, i.e., Chapter 4) epitomizes the study's findings, accentuating the pivotal role of experiential, data-driven Modeling Instruction astronomy in reenergizing educational dynamics and fortifying the essence of authentic, immersive astronomical education interventions.

6.3 Discovery and Confirmation of Warm Sub-Saturn TIC 139270665 b with APF and Unistellar and AstroReMixEd

After the citizen scientists of the Visual Survey Group's identified the potential single-transit exoplanet, TIC 139270665 b, in TESS data, our team pursued RV measurements using Lick RV instruments. With the intent on further refining its orbital period, we planned to utilize our Unistellar citizen science network. RV data confirmed the planet, and our EXOFASTv2 model pinpointed a best-fit period of 23.624 days. We engaged 43 Unistellar citizen scientists across 10 countries, including 16 high school students, to accumulate 271 hours of data spanning five months. Despite not definitively constraining the orbital period due to various limitations as detailed in the paper, lessons about optimizing citizen science observations were gained and some of the data may help to rule out ingress or egress at certain times. The high school observers showcased the power and potential of combining research and education in an AstroReMixEd effort, where students learn science by actively contributing work and data to modern astrophysical research. Our combined data confirms TIC 139270665 b as a dense warm sub-Saturn with a bulk density of 2.13 $\pm$0.31 g cm^{-3}, distinguishing it as unique among today's confirmed TESS planets. Additionally, there's evidence of a second planet, TIC 139270665 c ($M_P sini$ of ~4.89 M_J), with a much larger period and eccentricity. Challenges notwithstanding, the discovery of these exoplanets helps to expand our datasets with samples of unique exoplanets that further challenge and inform our planetary formation and evolution theories.

6.4 Unistellar's Evolution in Exoplanet Detection

The photometry used to confirm the first transiting exoplanet, HD 209458 b, was collected from a small (10 cm aperture) telescope (Sincell, 1999). Shortly thereafter, the first exoplanet discovered by a survey composed of a network of small and relatively inexpensive telescopes was made by the Trans-Atlantic Exoplanet Survey (TrES) with TrES-1b (Alonso et al., 2004). Today, Unistellar eVscopes of the Unistellar citizen science network are of comparable size (11.4 cm) and efficiency. Since the publishing of the first paper of this thesis on UE (Peluso et al., 2023), 30 additional exoplanet datasets have been published on the AAVSO and an additional 300+ successful exoplanet transit detections have been processed.

Furthermore, UE has solidified its position as an official citizen science partner with NASA through the Unistellar Network Investigating TESS Exoplanets (UNITE) program. The UNITE initiative primarily targets TESS-discovered candidates that have only one or two detected transits, and for which the orbital period remains ill-defined. Through this collaboration:

- Citizen astronomers utilizing eVscopes confirmed a 112-day orbital period for the TESS two-transit TOI 1812.01. A paper detailing this discovery is currently being prepared by H. Osborn et al.
- The orbital period of the TESS single-transit TOI 4465.01 was ascertained by detecting a second transit (with a duration of 12 hours) during a four-day intensive Unistellar campaign. This research is presently in preparation by D. Dragomir et al.
- The TESS single-transit TIC 393818343.01 was authenticated with an approximate 16-day orbital period, with a paper in the works by L. Sgro et al.

Additionally, the photometric analysis of TIC 139270665 b, as presented in Chapter 5, was conducted under the umbrella of the NASA UNITE project. This study was accepted to the Astronomical Journal (AJ) by Peluso et al. and is currently in production for publication with an expected release in early 2024.

Other notable UE detections include updating the ephemeris of the highly eccentric HD 80606 b (Pearson et al., 2022) and capturing the 16-hour long transit of Kepler-167 e (Perrocheau et al., 2022). Notably, for Kepler-167 e's 1071-day orbital period, it surpassed HIP 41378 f's 542-day period (Bryant et al., 2021) to make it the longest period exoplanet to have its transit be detected from ground-based instruments. This accentuates the importance of a globally distributed network, such as UE, since long and continuous observations of long exoplanet transits are challenging with traditional fixed-location observatories. A globally distributed network, like UE, crosses many time zones, which allows observations from long transits like

Kepler-167 e where 31 citizen astronomers collaborated globally to collect 40 hours of observations for the longest period planet detected from Earth (see Figure 11).

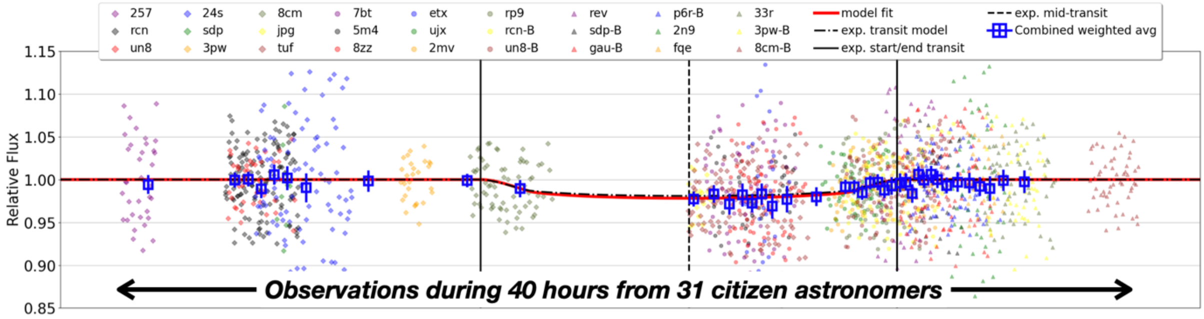

Figure 11. Annotated transit light curve of Kepler-167 e from a November 2021 Unistellar network campaign (Perrocheau et al., 2022). The confirmed transit from the Unistellar network for this 2.9-year orbital period exoplanet marks it as the longest period exoplanet ever detected from Earth known. Three-digit alpha-numeric strings in the legend represent eVscope serial numbers of Unistellar citizen scientist observers.

Exoplanet observations from UE, such as with Kepler-167 e, are important for the field of exoplanetary science. UE's detection of Kepler-167 e demonstrated that it is possible to detect long-period and long-duration transits from small citizen scientist operated digital smart telescopes. As detailed in Chapter 3, UE's benefits include having a large network of telescopes distributed globally, which enables long-duration observations beyond a single night or location, which can also mitigate localized weather events. An example map of what the global coverage looks like for a recent successful campaign is provided in Figure 12. Additionally, UE's eVscopes have the benefit of portability, effective photometry even in urban areas, and are easy to operate with a user-friendly smartphone app.

Figure 12. Screenshot from Unistellar animation[24] highlighting the distribution of its exoplanet citizen astronomers around the world in successfully capturing the transit of HD 80606 b with a total of 27 hours of network coverage and data. Spreading across time zones, UE was able to capture transit data when other locations around the world were in daylight hours.

[24] https://www.unistellar.com/citizen-science/exoplanets/results/ | Accessed 7 September 2023.

The collaborative potential with other networked citizen science programs is also substantial and important for increased success. For example, Unistellar observations of HD 80606 b and Kepler-167 e both involved photometry collected by Exoplanet Watch and ExoClock citizen scientists. Unistellar's HD 80606 b campaign also collected photometry from the sometimes citizen scientist operated LCO and MicroObservatory telescopes, however, it is unknown if these observations were initiated specifically by citizen scientists for the HD 80606 b photometry. This additional coverage and data helped to confirm and complete photometry for transit light curves. A collaboration with Exoplanet Watch, ExoClock, MicroObservatory, or LCO was not utilized for the TIC 139270665 b campaign. If it were, then that could have potentially increased our coverage and photometry, and possibly our confidence in detecting a second transit. Collaboration with other citizen science exoplanet programs would also allow more outreach and education opportunities to enrich the idea of AstroReMixEd.

UE currently has six peer-reviewed publications for its exoplanet work (Dalba et al., 2022; Pearson et al., 2022; Peluso et al., 2023; Perrocheau et al., 2022; Wang et al., 2022; Zellem et al., 2020) and at least four others in the pipeline (i.e., TOI 1812.01, TOI 4465.01, TIC 393818343.01, and mine on TIC 139270665 b). Notably, these four are all for the NASA UNITE project to capture a second or third transit from a single or double-transit TESS candidate, which is a challenging objective given the uncertainty and widespread coverage needed for such a detection.

The success of the Unistellar exoplanet citizen science network to date demonstrates its potential for further scientific research. In only three years, the network has achieved over 590 exoplanet transit detections, five peer-reviewed publications, and four in preparation for submission to academic journals. Six of these published or in-prep papers contributed to confirm TESS exoplanet candidates or update their ephemerides. Since a majority of the TESS ephemerides from TESS are predicted to be outdated (i.e., having a 1σ uncertainty in mid-transit time less than half the transit duration) only one year after the last observation (Dragomir et al., 2020), these ephemerides update are important, especially for future characterization by JWST and other space-based telescopes (Zellem et al., 2020). Additionally, given the challenges and limitations of wide-field surveys like TESS in detecting longer period exoplanets (Bakos et al., 2004; Bakos et al., 2013; Pollacco et al., 2006), Unistellar and other citizen science exoplanet programs have high value for their ability for long-period exoplanet detection with their distributed network. Thus, Unistellar exoplanet citizen scientists can update exoplanet ephemerides and help to confirm long-period or poorly constrained periods of exoplanets, however, there are other potential applications for future work (e.g., discovery, TTVs, unknown RVs, microlensing events, and detecting rings or exomoons of gas giants).

The Unistellar network is run by citizen scientists that operate in-situ digital smart telescopes (eVscopes) and has included educators and students in observations. When Unistellar citizen science data has been used in exoplanet publications the citizen scientists are included as co-authors in the peer-reviewed publication. Chapter 3 highlighted UE's ability and potential for contributing to exoplanet science, but also demonstrated its "Inherent Education Opportunities". The UE paper (Peluso et al., 2023), included 163 citizen co-author citizen scientists who contributed to the building of this exoplanet network. Current estimates across all Unistellar exoplanet papers published (or in prep) to date count ~35 co-authors who were either student or educator. Of these co-authors, nine were educators (five from UCAN), and the majority (26) were either middle/high school (19) or college students (7). The majority (16) of the total student observations resulting in (future) co-authorship come from my TIC 139270665 b campaign at the Chabot Space & Science Center in February 2023. By increasing these co-author numbers with citizen science and education initiatives combined there is an exciting potential to change the paradigm for how both science and education operate in the future.

It is also noteworthy to mention that the Unistellar Network has been successful for other citizen science programs, such as for planetary defense (Graykowski et al., 2023; Lambert et al., 2023), comets, asteroid occultation (Cazeneuve et al., 2023), transients (Sgro et al., 2023), and spacecraft monitoring (Lambert et al., 2022). Impressively, Unistellar's transiting exoplanet program stands out as it has uniquely garnered direct support from NASA. The breadth of these citizen science programs offers a wide array of opportunities for advancing astrophysics research and for creating more diverse Modeling Instruction and inquiry-based education initiatives.

6.5 The Rivers of Academia and the Zeitgeist

There's sometimes exists a subtle perception within academic circles that delineates a boundary between professional PhD level researchers and the broader populace. The National Research Council's groundbreaking 2012 framework highlighted a disconnect that exists between K-12 education and contemporary scientific research (Council, 2012). I'd like to compare this outside the context of science education, and directly to society as a whole.

The majority of the US population (91%) attends public school (Statistics, 2022), however, of the US population aged 25 and older, only 14.9% had completed some college, but no degree, and 23.5% report a bachelor's degree as their highest degree (Bureau, 2022). High school graduation requirements generally require at least 2 years of a lab science. However, they do not require astronomy or physics (see Chapter 4). In the US, college general education requirements for non-STEM majors include one or two science credits, however, the majority of adults do not complete a college degree. The exposure of many citizens to science, science practices, and scientific research could be improved. If most of the US population goes to public school where there is a disconnect with contemporary scientific research and do not take any college courses, then how is their society getting connected with contemporary scientific research? Is there a similar paradigm in other developed nations? What effect is this having on a world that is run by science and technology, if almost no one understands science and technology (Sagan, 1996)?

The effects of this may not be entirely clear until much further into our future. However, it is noted that currently we do see a marked rise in pseudoscientific beliefs such as astrology (Andersson et al., 2022) and other pseudoscience, especially after the COVID-19 pandemic (Escolà-Gascón et al., 2020). Moreover, there exists a widespread unhealthy cynicism and decrease in confidence with science (Boyle, 2022). Additionally, in the US, a prevailing cultural zeitgeist underscores a diminishing trust in public education. Since 1973, Gallup has consistently surveyed the US population to gauge their confidence in public educational institutions. Responses indicating a "great deal or quite a lot of confidence" in US public schools have shown a marked decline since these surveys began (Gallup, 2022, 2023). This downward trend has intensified in the past decade, with 2023 seeing the lowest recorded confidence level since 1973, a figure matched only in 2014 (see Figure 13).

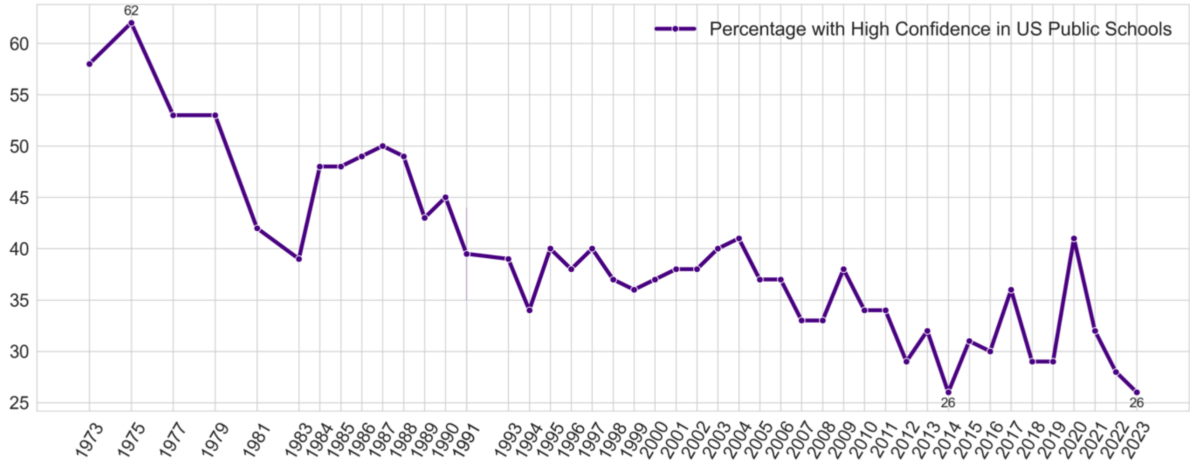

Figure 13. Percentage of polled US population that agreed with having confidence in our schools, i.e., "Great deal/Quite a lot" from Gallup (2022) but with an additional data point for 2023 added from Gallup (2023).

Another aspect of the American zeitgeist is the undervaluing of our teachers, which may possibly feed into these beliefs and our educational outcomes. A recent US study reported that teachers feel they lack the influence to effect real change, with only 24.5% of teachers expressing that they felt valued in our society, and only 18.4% reported feeling valued by the media (Akiba et al., 2023).

6.6 Crossing the Streams

There are many professional researchers that contribute valuable work and effort towards the goal of democratizing science. In astronomy and exoplanets, these include NASA Exoplanet Watch (Zellem et al., 2020), Las Cumbres Observatory (Sarva et al, 2020), Zooniverse (Eisner, Barragán, Aigrain, et al., 2020; Eisner, Barragán, Lintott, et al., 2020; Simpson, Page, & Roure, 2014), MicroObservatory (Gould et al., 2006), our current work with Unistellar, and several others mentioned elsewhere in this thesis and many more in astronomy and in other fields. Even so, media focus, biases in funding allocation, selective publication trends, and prevailing academic narratives may muddy the waters between the true potential that could exist between citizen scientist educators and students and professional researchers. Further, another aspect of the US zeitgeist around education may come from the commonly uttered quote, "Those who can, do; those who can't, teach" (Shaw, 1903)[25]. Over 100 years later, this notion is still being discussed, but with varying opinions

[25] Compare this to ancient Greek thinking from Aristotle: "Those who know, do. Those that understand, teach."

(Grant, 2018). Such negative sentiments about teachers may contribute to biases undermining the capabilities and skills of teachers in research endeavors. Additionally, the K-12 education system in the US was built to produce obedient workers (Clinchy, 1993), and not free thinkers or problem solvers. How can a society that undervalues our teachers and has an outdated education system not aligned with modern scientific practices expect to cultivate its future generation's ability to lead the world for our safety, prosperity, and economic wellbeing?

The collaborative nature highlighted throughout this thesis demonstrates that when we "cross the streams" of these diverse knowledge pools, the resultant synergy not only produces valuable and robust scientific findings but may also pave the way for groundbreaking discoveries. Furthermore, students at the public high school level can be more engaged and *learn by doing* science that directly contributes to peer-reviewed publications for exoplanets, as exemplified by TIC 139270665 b's AstroReMixEd efforts. I advocate for a merger of the knowledge streams flowing from our esteemed academic research institutions with those from the oft-overlooked public academic primary and secondary institutions and through engagement with both teachers and students. This confluence harbors the potential to reshape our view of public schools and their educators, foster a society that deeply values and comprehends the pivotal role of science and technology, and ultimately drives societal progress. Moreover, the work of the citizen astronomers in this new merger can actually push the needle of scientific results to new heights.

Examples of the value of citizen science astronomy and its contributions to the scientific community are numerous (Christian et al., 2012). Notable examples are the discovery of five new exoplanets entirely by citizen scientists using Kepler data (Christiansen et al., 2018), NASA's Sungrazer Project to discovery comets (Battams & Knight, 2017), the Aurorasaurus for studying the aurora (MacDonald et al., 2015), and the discovery of the mysteriously dimming KIC 8462852 (Boyajian et al., 2018). The forthcoming need of citizen astronomer collaboration will be even more vital. With enormous sets of data (greater than 35 billion outputs) coming online with the Vera Rubin Observatory and its Legacy Survey of Space and Time (LSST), it is clear that citizen science collaboration will not only be advantageous, but necessary for the field (Higgs, 2023). With these and the many other citizen astronomy discoveries and contributions to date and forthcoming, there is ample room for AstroReMixEd initiatives that include educators and students at all levels in this work.

6.7 Converging Astronomy Modeling and Citizen Science

The dramatic effect of the Council of Ten's B-C-P decision in the 1890s (Bishop, 1990; Bishop, 2003; Krumenaker, 2009; Sheppard & Robbins, 2002), effectively eliminated astronomy from our K-12 education system (see Chapter 4). Given that cosmic curiosity is in our nature and our current and future economic success depends on our societies' abilities and skills in STEM and space (Chapter 4), it seems fitting to push for more options for research-based and data-driven astrophysics and space courses in our K-12 systems. With AME, we showcased that out-of-field teachers and public-school students are capable of learning and practicing modern astrophysics (e.g., planning observations and analyzing exoplanet light curves, photometry, etc.). With the Unistellar exoplanet citizen science network, we've shown that small easy-to-use smartphone app-controlled eVscopes can contribute to exoplanet research with data taken in-situ from both educators and students from all levels.

The AME study from Chapter 4 revealed that the most engagement increases came from students who reported having the experience planning a live exoplanet observation and analyzing its data. With the TIC 139270665 b AstroReMixEd work (Chapter 5), 16 high school students chose to stay overnight for 12+ hours to attempt catching a transit of this TESS candidate planet, even though they knew the likelihood of catching the transit was not in their favor. As the director of this AstroReMixEd initiative, and having worked closely with the Galaxy Explorer students, I can attest to their genuine enthusiasm. Their enthusiasm was driven not just by their involvement in a project with tangible real-world applications but also from the empowering chance to be recognized as co-authors in an upcoming peer-reviewed scientific article. Numerous studies affirm that students are more engaged when their work has direct, meaningful implications in the real world (Bell, 2010; Blumenfeld et al., 1991; Fortus et al., 2005). Further, the effect of AME on teachers was substantial. Teachers changed how they taught to include more inquiry-based and data-driven astrophysics activities and had significant improvement in their self-efficacy (e.g., Percy Munoz). The fusion of Astronomy Modeling with citizen science (e.g., Unistellar) offers a uniquely potent and transformative experience for both teachers and students and lays the groundwork for future efforts to "cross the streams".

Crossing the streams may be considered a dangerous or taboo activity by some[26]. However, the explosion of such a merger has the potential for increased diversity, synergy, creativity, enlightenment, and tangible results for both education and rigorous scientific research. The democratization of astronomy and exoplanet science means that everyone is an astronomer and scientist, not just those with a PhD. This does not make PhDs or research universities obsolete, but instead compliments and enriches academic work for an all-around and more inclusive and democratic society where the sharing of knowledge and ideas is streamlined and accelerated to benefit everyone.

6.8 Challenges and Limitations

Acknowledging the various challenges and limitations associated with the Unistellar citizen science network and its eVscopes can help its initiatives and others like it to improve and grow. While eVscopes are proficient at identifying large gas giant exoplanets, they still possess a modest aperture size. This limits their light-capturing capacity and, consequently, their sensitivity, making the detection of smaller exoplanets more challenging. It's noteworthy that the primary locations of our Unistellar observers span urban and suburban light polluted environments. Although a feature of eVscope technology is their ability to still provide quality data in such environments, this also still compromises the optimal sky conditions for certain cases and the resulting data. Also, even though anecdotal evidence has shown that many Unistellar citizen scientists demonstrate admirable skill, when compared with veteran observational astronomers, there may be variation in precision and image quality that effects data quality in the Unistellar data pipelines.

For exoplanet observations, Unistellar can amass large quantities of data from around the world. This can challenge the small science team in keeping up with data processing (e.g., ~36% of the collected data in Chapter 3's UE paper was still unprocessed at the time of publication). Furthermore, well-constructed communication and education to exoplanet citizen scientists is also vital. Even though eVscopes are easy-to-use with their dedicated app, some users may still be confused or intimidated with how to observe exoplanets for science missions. Even so, it should be noted that a user's current access to exoplanet observations via the Unistellar app is still greatly

[26] In the 1984 Columbia Pictures film "Ghostbusters," the protagonists face a pivotal decision: to "cross the streams" of their proton beams from their Particle Thrower weapons. Initially believed to be a detrimental move, it ultimately proves to be beneficial, hence, this chapter's opening quote.

more accessible than any previously known in-situ telescope available to the public. Also, as learned from TIC 139270665 b, we learned that it is important to capture more data and at the right times (i.e., across two or more stages of a transit event). Future campaigns for such wide transit windows like that with TESS single-transit candidates should stress the importance for longer observation durations to the citizen science community. Additionally, Unistellar should further improve their software to simplify and further automate the exoplanet observing process to increase the likelihood of longer observation sessions from its citizen scientists.

Following the rapid growth of the Unistellar network (see Figure 8), it's important to contemplate the foundational objectives and sustainability of the citizen science initiative. Although Unistellar promotes its telescopes as instruments for citizen science, the predominant emphasis, like many commercial endeavors, understandably lies in product sales to guarantee economic viability. Such a commercial-focused strategy may at times result in altered priorities, potentially affecting the rate or orientation of updates intended for scientific objectives. Therefore, while the distinctive features of incorporating citizen science significantly set apart Unistellar's products, there exists a fine balance between commercial success and scientific progress. Prospective users, scientific investigators, and collaborators ought to recognize this interplay, as it might shape the forthcoming direction and potential of the network's scientific aspirations and outcomes.

A notable constraint of Unistellar telescopes pertains to cost and accessibility. For these telescopes to genuinely democratize astronomy, it is essential to investigate low-cost alternatives and expand geographic availability. While they are currently distributed in over 61 countries, Unistellar telescopes can only be shipped to Europe, the US, and Japan.[27]. Furthermore, the typical price of an eVscope exceeds $3,000 USD, a sum beyond the reach of many casual enthusiasts. In the educational domain, this pricing may be feasible for most major research and non-research institutions, but it remains prohibitively expensive for the majority of K-12 schools, including the typical Title I school and its educators. Other cost barriers associated with Unistellar telescope use is the need for a smartphone or tablet to operate the telescope and having high speed Wi-Fi access for data uploading, which may be another economic challenge for some. Even with these economic barriers, the emergence of easy-to-use

[27] However, they can be purchased by official distributors and resellers in various other countries: https://help.unistellar.com/hc/en-us/articles/360002269613-Which-countries-do-you-ship-to- | Accessed 7 September 2023.

technology like Unistellar eVscopes signifies a transformative step towards democratizing astronomy. Although the initial cost may be high, it mirrors the historical pattern of new technologies, which, over time, have become more accessible and contributed to the broader accessibility of scientific pursuits.

As for eVscope data, owners who wished to access their raw data previously (pre-October 2023) had to contact the science team to retrieve the corresponding FITS files, rather than downloading them directly from the telescope. From personal communications with university professors, some have reservations of adopting or have current dissatisfaction with using Unistellar telescopes due to this challenge. This has been a major problem for K-12 and university educators alike as they do not have the time to write emails to request and wait for data that they'd like to use for student learning or science objectives. This also created a challenge for the small Unistellar science team at the SETI Institute who had to funnel these requests instead of focusing more of their time doing science and writing papers. However, as of October 2023 Unistellar has announced the release of a tool for users to download their data after uploading to their database directly and without any human intervention.

One solution to the high cost of eVscopes is to secure grant funding for their acquisition for scientific and educational initiatives as the SETI team has done with the UCAN network funded, and the University of California Observatories (UCO) Astronomy experience, both funded by the Moore Foundation. However, this might present other challenges. Despite the demonstrated value and potential of eVscopes in these realms, grant committees may possess biases that prevent them from looking beyond the telescope's consumer product image. To truly expand a Unistellar or similar citizen science telescope network for an authentic democratized experience, solutions must be found to place the technology and programs in more educational institutions, research settings, and community centers, ensuring wider access and eliminating barriers associated with cost and perceptions.

Regarding education initiatives such as AME and AstroReMixEd, there are some challenges for widespread adoption. In many K-12 school science classes, science is presented to most children as a giant bucket of seemingly disconnected 'factoids' that they must learn and then regurgitate on multiple choice tests (which are easy to score). If we could learn to teach science as something they are actively doing—i.e., a set of tools for thinking that they must learn to build and use (Modeling), and skills they must master to collect data—then they will develop the competence and confidence to function and make informed decisions in the 21st century technological world. This is exactly what Modeling Instruction and AME aim to do and research has also found it to be inherently motivating (Haag & Megowan, 2012, 2015; Hestenes et al., 2011; Jackson et al., 2008). Further, this motivation could ultimately drive more students into the STEM workforce pipeline. Given that research has shown that teachers can transition from a traditional 'factoid' teaching approach to a more inquiry-based methodology with the right professional development (Haag & Megowan-Romanowicz, 2021; Hestenes, 1997; Wells et al., 1995), a challenge then lies in providing more educators with access to professional development in Modeling Instruction, AME, and similar inquiry-driven pedagogies.

While the Committee of Ten was instrumental in sidelining astronomy in our curriculum (Sheppard & Robbins, 2002), they, along with other foundational education figures and groups, through their collective recommendations and policies, further entrenched a standardized "what to think" over "how to think" approach as well as deepened educational inequities across socioeconomic and racial lines. The “what to think” approach is antithetical to AME and other inquiry-based practices. While the AMTA boasts over 15,000 members (i.e., “Modelers”), and many educators outside this group champion inquiry-based and student-centered learning, it remains an uphill battle against a system that is still predominantly driven by standardized test scores, grades, and direct-instruction models that prioritize rote learning over critical thinking. Even so, it is encouraging to know that many major US universities are now eliminating or making standardized testing optional for student applicants (FairTest, 2023), which may help future K-12 initiatives like AME to have more room for expansion.

Moreover, even if some teachers were self-motivated to enact an AME or AstroReMixEd approach, some may have their hands tied behind their back. Some teachers in the US are often restricted from having autonomy and the ability to practice more innovative and progressive education practices because of the pressures and systems (e.g., high-stakes testing) in place from their administration and school districts (Gonzalez et al., 2017; Ingersoll, 2009; Zhao, 2012). Many teachers at the K-12 level do not have the option of teaching astronomy, even if they wanted to. Recall in Chapter 4 that Salimpour et al. (2021) found that only 17% of schools across the entire planet offer astronomy. Further, even though it is possible to teach astronomy concepts in a traditional K-12 physical science or physics course, teachers may be restricted to teach a set curriculum at their school or need to align with other teachers of the same subject at their school or district. These cases would leave little room, if any, for AME or AstroReMixEd. For university or college-level implementation, although some college and university-level teachers adopt more innovative and inquiry-based teaching practices, traditional methods still abound (Kay et al., 2019), which leaves us with real challenges for implementing this work at all levels of our education system. This may be a systemic battle in some ways. Although a challenge, I do note that AME has been successfully enrolling a full roster of teachers two years in a row (approximately 45 total) and is set for its third year in the spring of 2024. The desire does exist for astronomy, we just have to explore new avenues for implementation and encourage school district leaders to adopt astronomy curricula.

Funding is also a large limitation for such programs. Even though modestly priced[28], most teachers may not have funds or intrinsic motivation to spend their own funds on a dedicated AME workshop or Unistellar eVscope. Obtaining grant funding, which has been successful for other AMTA teacher workshops and research initiatives, could eliminate the cost barrier, provide eVscopes, and even provide a stipend to participating teachers, which would increase reach and adoption. Additionally, for an authentic AME and AstroReMixEd approach that included exoplanet research, teachers would need the time and support to conduct research amidst their teaching responsibilities. Teachers at K-12 institutions in the US are largely overworked and underpaid (Garcia & Weiss, 2019).

With many PhD projects or grant-funded initiatives, promising projects often fade away after students or researchers move on to other endeavors or the grant funding runs out. To ensure the longevity and expansion of the AMTA's AME offerings, dedicated teams and personnel would need to be established. This would create redundancy and expand the program's reach, thereby reaching wider audiences and guarding against potential disruptions, such as founding members departing for other endeavors. Additionally, other programs utilizing Modeling Instruction pedagogy and other inquiry-based and project-based learning practices should be developed and implemented utilizing an AstroReMixEd model that connects university level astrophysics research with K-12 and community college level education.

[28] As of 2023, AMTA's AME is $850 USD for a 15-week 45-hour distance learning graduate-level course with up to 3 credits available at $79/credit hour through the University of Pacific. Costs retrieved from https://www.eweblife.com/prm/AMTA/apply-rsvp?rsvp=1713 | Accessed 7 September 2023.

CHAPTER 7: CONCLUSION

"If you wanna fill your bottle up with lightning
You're gonna have to stand in the rain."
-"Silver Lining" by Kacey Musgraves

7.1 Broader Implications

The vast and intricate landscape of exoplanetary research is reshaping our comprehension of the universe at a rapid pace. With thousands of confirmed transiting exoplanets and many more awaiting confirmation and characterization (e.g., with JWST, ARIEL, or PLATO space missions), the field has demonstrated a heightened need for sustained and meticulous follow-up observations. These observations serve to filter out false positives, maintain the precision of established planetary ephemerides, and to help to confirm and constrain orbital parameters. As the queue of exoplanetary candidates grows, the infrastructure for conducting these studies faces significant challenges. However, the democratization of astronomical tools and initiatives, combined with the emergence of citizen science programs such as the Unistellar citizen science network presents a new paradigm. The collaborative efforts of professional researchers and an engaged community of citizen astronomers, educators, and students represent a promising direction for exoplanetary science, combining inclusivity with thorough scientific inquiry. This AstroReMixEd alliance has the potential to decode the enigmas of planetary formation and evolution, such as those challenged by our discovery of warm and hot Jupiters and sub-Saturns, and perhaps even lead us to the discovery of extraterrestrial life. These and many other possible discoveries will enrich our understanding of our cosmic narrative and empower us as people, especially if we are making them together instead of apart.

Five decades after the first Draw-a-Scientist Test was given, around 65% of middle and high school students who complete this brief exercise still draw a middle-aged white male (Ferguson & Lezotte, 2020; Hayes et al., 2020; Miller et al., 2018). Some modest increase in the representation of women has occurred over time, but by-and-large, students do not draw someone who looks like themselves or their parents. Unfortunately, the lack of representation and diversity persists, especially in astronomy departments. Among astronomy department faculty, only 3% are Hispanic and only 1% African American (National Academies of Sciences, 2021), which likely funnels down to influence draw-a-scientist tests. Representation matters.

At the student level, while interest and corresponding astronomy and astrophysics degrees have grown, the growth is still small, and this is especially true for underrepresented groups. For details on these statistics, see the Decadal Survey on Astronomy and Astrophysics 2020 (National Academies of Sciences, 2021). As one example, for indigenous populations, such as Native Americans, Indigenous, and Native Hawaiians, the results are worse than most other physical sciences with only ~two undergraduates engaged in astronomy per year (National Academies of Sciences, 2021). Further, only 33% percent of people who have earned an astronomy bachelor's degree were women in 2017, a trend that has been relatively consistent over 10 years (Porter & Ivie, 2019).

Through the creation of a more democratized world for science, astronomy, and education, we can break the paradigms that have held us in the past for a more diverse and inclusive future. Inquiry and project-based work similar in nature to AME and AstroReMixEd have been reported to be engaging for both female and male students from various racial, ethnic, underserved, and urban environments (Geier et al., 2008; Harris et al., 2015). By creating more opportunities at all levels of society and education around the world for the public to participate in active citizen astronomy investigations, we are broadening our reach of our scientific faculty and increasing our yield of scientific data collection and results.

Our galaxy, with its trillions of exoplanets yet to be discovered and characterized, presents an immense challenge for the limited cadre of professional astronomers. By crossing the streams of our professional research institutions with the general public, educators, and students, we can open the gates of discovery for all of humanity. This not only allows us to adopt more researchers from the pool of Earths' 8+ billion population to probe the universe for exoplanets and other cosmic phenomena, but also greatly supports our society in the effort to close the achievement gap and expand and diversify the field of astronomy and astrophysics.

7.2 Final Thoughts and the Potential of a Democratic Astronomy

Given the integration of citizen science with advances in technology, the transformative potential of newly developed inquiry-based astrophysics education, and the symbiotic relationship between research and education, this PhD project highlights a pivotal shift in both exoplanet research and educational methodologies. It suggests that democratizing the tools and methods of research can not only support and enhance our scientific understanding—e.g., exoplanet ephemerides maintenance and follow-up—but can also revolutionize educational outcomes, instilling greater confidence and competence in educators and students alike (e.g., Modeling Instruction Astronomy). This amalgamation of grassroots participation with traditional academic research paves the way for a more inclusive, collaborative, and dynamic future in astrophysics, emphasizing the profound impact of shared knowledge and collective endeavors. Such a venture between academia and the public (i.e., citizen science) has already shown to be successful with past initiatives, such as with the AAVSO, which has made vast contributions to the field since 1911 (Williams, 2001).

The Unistellar citizen science network offers something unique and profound to our society that should be reflected upon. In 2007, Steve Jobs and Apple transformed the global landscape with the introduction of the first iPhone. Fast forward to today, nearly 79% of the global population possesses a smartphone (Statista, 2023). The prevalence and effects of these devices on humanity are becoming increasing apparent to our societies. As highlighted in Chapter 1, excessive smartphone use has been linked to detrimental effects on mental health, particularly among the youth, and they potentially diminish genuine human connections. However, even though these devices are addictive and have negative side effects, they are also conduits to a vast reservoir of knowledge, serving as contemporary equivalents to the Library of Alexandria where the entire world's knowledge is at our fingertips. Additionally, their ability to bridge distances and foster positive connections also cannot be ignored. Further, smartphones are equipped with an array of sensors, such as magnetometers, gyroscopes, and accelerometers, making them valuable tools for various citizen science endeavors. The challenge for our society lies in harnessing the immense potential of these devices while maintaining a balanced and healthy relationship with them. The prospects, especially in the realm of science, are vast. Envision a scenario with eight billion data collectors worldwide; it's a latent potential waiting to be explored.

Even though we cannot currently use smartphones for exoplanet science, we can use them to control in-situ digital smart telescopes, such as with Unistellar eVscopes. Modern day astronomy at large telescopes like Keck are most often operated remotely. Even on site at Mauna Kea in Hawaii most operators are not physically at the telescope but are located down the mountain using computers to control them remotely. The process of physically pointing professional telescopes in-situ and squinting through an eyepiece is as outdated as keypunch cards are for computers. Astronomers enter their celestial coordinates in a computer interface not too different than an eVscope app on a smartphone and after some image calibration (e.g., darks, flats, bias) science begins. The process for a Unistellar citizen scientist is not too different, but is streamlined in its native app. Now anyone in the world with very little training and practice can point and target a scientific object like an exoplanet with a couple presses on a smartphone and then upload their data for a professional science team to process. Why should using a telescope be more challenging, frustrating, and much less technological than what professional astronomers are using when the technology exists for simple to use instruments? Further, why not take advantage of tens of thousands (and growing numbers) of mobile digital telescopes capable of collecting data for scientific research projects, especially when it can produce valuable results and help to democratize both science and education? NASA's Exoplanet Watch, ExoClock, and Unistellar have begun to show the value in such citizen science telescope networks, however, there is still a lot of room for growth for new technology and initiatives to help the field of exoplanets evolve even further.

Even though there exist many challenges to enact some of my visions in both exoplanet research and education in this thesis work, there also exists high potential. Further, my research has demonstrated the possibilities and has laid the groundwork for future work. Even if Unistellar were to stop operating, the telescopes would still operate, and the software could be maintained or made open source to keep the existing telescopes continuing to do science. Other telescope companies (e.g., Vaonis[29]) should continue to compete and new digital smart telescopes should be developed. Competition is good for evolution.

The convergence of professional exoplanetary studies via transit photometry and RV spectroscopy, together with the transformative power of the Unistellar exoplanet citizen science network, holds immense promise to both advance exoplanet research and foster community engagement through AstroReMixEd. However, with such a network, there is much more potential for the field of astronomy and astrophysics and education in other research areas as well (Barbosa et al., 2022; Cazeneuve et al., 2023; Graykowski et al., 2023; Lambert et al., 2022; Popescu, 2023; Sibbernsen, 2022; Yoshida et al., 2022). Historically, the realm of astronomers was minuscule, spanning only a handful of individuals. Over the past half-century, while the field has expanded, it remains relatively niche. Yet now, with the advent of

[29] https://vaonis.com/ | Accessed 7 September 2023.

technologies like the Unistellar eVscope and the anticipated emergence of future digital smart telescopes, smartphone applications, and groundbreaking online platforms, we stand on the brink of an astronomical renaissance, one that has the potential to involve billions in cosmic exploration and discovery (Figure 14).

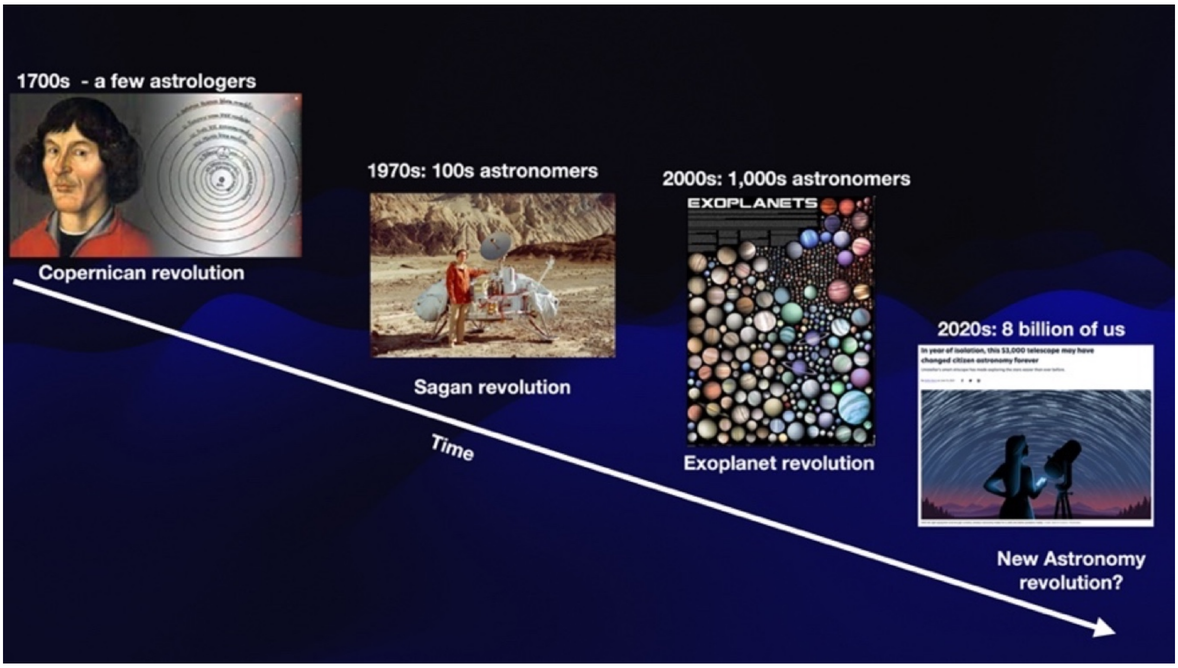

Figure 14. The evolution and revolution of astronomy when you look at it through the AstroReMixEd lens that utilizes powerful new technology (e.g. Unistellar eVscopes) and education initiatives. Image courtesy Franck Marchis (SETI Institute, Unistellar).

When we truly recognize that we share this planet, perhaps we'll embrace our cosmic origin and destiny. Such a cosmic perspective holds the power to redefine humanity, ushering us into a new era where we can leave behind our tumultuous past marred by war, hunger, and division. A new frontier awaits us in the stars, and potentially on the exoplanets that orbit them. Even when our world seems to be in turmoil, it's up to each of us to keep looking up. For even on the darkest and cloudiest of nights, stars continue to shine brightly, reminding us of hope beyond the clouds.

References

Akeson, R. L., Chen, X., Ciardi, D., Crane, M., Good, J., Harbut, M., . . . Zhang, A. (2013). The NASA Exoplanet Archive: Data and Tools for Exoplanet Research. *Publications of the Astronomical Society of the Pacific*, *125*(930), 989-999. https://doi.org/10.1086/672273

Akiba, M., Byun, S.-y., Jiang, X., Kim, K., & Moran, A. J. (2023). Do Teachers Feel Valued in Society? Occupational Value of the Teaching Profession in OECD Countries. *AERA Open*, *9*, 23328584231179184. https://doi.org/10.1177/23328584231179184

Akram, T. M., Ijaz, A., & Ikram, H. (2017). Exploring the factors responsible for declining students' interest in chemistry. *International Journal of Information and Education Technology*, *7*(2), 88.

Alonso, R., Brown, T. M., Torres, G., Latham, D. W., Sozzetti, A., Mandushev, G., . . . Stefanik, R. P. (2004). TrES-1: The Transiting Planet of a Bright K0 V Star. *The Astrophysical Journal*, *613*(2), L153. https://doi.org/10.1086/425256

Andersson, I., Persson, J., & Kajonius, P. (2022). Even the stars think that I am superior: Personality, intelligence and belief in astrology. *Personality and Individual Differences*, *187*, 111389. https://doi.org/https://doi.org/10.1016/j.paid.2021.111389

Bakos, G., Noyes, R. W., Kovács, G., Stanek, K. Z., Sasselov, D. D., & Domsa, I. (2004). Wide-Field Millimagnitude Photometry with the HAT: A Tool for Extrasolar Planet Detection. *Publications of the Astronomical Society of the Pacific*, *116*(817), 266. https://doi.org/10.1086/382735

Bakos, G. Á., Csubry, Z., Penev, K., Bayliss, D., Jordán, A., Afonso, C., . . . Ueltzhoeffer, K. (2013). HATSouth: A Global Network of Fully Automated Identical Wide-Field Telescopes1. *Publications of the Astronomical Society of the Pacific*, *125*(924), 154. https://doi.org/10.1086/669529

Barbosa, D., Coelho, B., Bergano, M., Magalhães, C., Mendonça, D., Silva, D., . . . Esposito, T. (2022). Cyber-Cosmos: A new citizen science concept in a dark sky destination. *Acta Astronautica*, *200*, 612-619.

Batalha, N. M., Rowe, J. F., Bryson, S. T., Barclay, T., Burke, C. J., Caldwell, D. A., . . . Welsh, W. F. (2013). PLANETARY CANDIDATES OBSERVED BY KEPLER. III. ANALYSIS OF THE FIRST 16 MONTHS OF DATA. *The Astrophysical Journal Supplement Series*, *204*(2), 24. https://doi.org/10.1088/0067-0049/204/2/24

Battams, K., & Knight, M. M. (2017). SOHO comets: 20 years and 3000 objects later. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*, *375*(2097), 20160257. https://doi.org/doi:10.1098/rsta.2016.0257

Batygin, K., & Laughlin, G. (2015). Jupiter's decisive role in the inner Solar System's early evolution. *Proceedings of the National*

Academy of Sciences, *112*(14), 4214. https://doi.org/10.1073/pnas.1423252112

Beaugé, C., & Nesvorný, D. (2013). EMERGING TRENDS IN A PERIOD–RADIUS DISTRIBUTION OF CLOSE-IN PLANETS. *The Astrophysical Journal*, *763*(1), 12. https://doi.org/10.1088/0004-637X/763/1/12

Beichman, C., Benneke, B., Knutson, H., Smith, R., Lagage, P.-O., Dressing, C., . . . Sing, D. (2014). Observations of Transiting Exoplanets with the James Webb Space Telescope (JWST). *Publications of the Astronomical Society of the Pacific*, *126*(946), 1134. https://doi.org/10.1086/679566

Bell, S. (2010). Project-based learning for the 21st century: Skills for the future. *The Clearing House: A Journal of Educational Strategies*, *83*(2), 39-43. https://doi.org/10.1080/00098650903505415

Bishop, J. E. (1990). The Committee of Ten. *International Astronomical Union Colloquium*, *105*, 253-257. https://doi.org/10.1017/S0252921100086899

Bishop, J. E. (2003). Pre-College Astronomy Education in the United States in the Twentieth Century. In A. Heck (Ed.), *Information Handling in Astronomy - Historical Vistas* (Vol. 285, pp. 207-231). Springer Netherlands. https://doi.org/10.1007/0-306-48080-8_12

Blumenfeld, P. C., Soloway, E., Marx, R. W., Krajcik, J. S., Guzdial, M., & Palincsar, A. (1991). Motivating project-based learning: Sustaining the doing, supporting the learning. *Educational Psychologist*, *26*(3-4), 369-398.

Bonney, R., Cooper, C. B., Dickinson, J., Kelling, S., Phillips, T., Rosenberg, K. V., & Shirk, J. (2009). Citizen Science: A Developing Tool for Expanding Science Knowledge and Scientific Literacy. *BioScience*, *59*(11), 977-984. https://doi.org/10.1525/bio.2009.59.11.9

Borden, K., Whyte, L., Smith, A., Tarnoff, A., & Schmitt, H. (2012). The Zooniverse: Cutting Edge Scientific Research in the Classroom. *AGUFM*, *2012*, ED14A-02.

Borucki, W. J., Koch, D., Basri, G., Batalha, N., Brown, T., Caldwell, D., . . . DeVore, E. (2010). Kepler planet-detection mission: introduction and first results. *Science*, *327*(5968), 977-980.

Borucki, W. J., Koch, D. G., Basri, G., Batalha, N., Brown, T. M., Bryson, S. T., . . . Still, M. (2011). CHARACTERISTICS OF PLANETARY CANDIDATES OBSERVED BYKEPLER. II. ANALYSIS OF THE FIRST FOUR MONTHS OF DATA. *The Astrophysical Journal*, *736*(1), 19. https://doi.org/10.1088/0004-637x/736/1/19

Bouchy, F., Moutou, C., & Queloz, D. (2008). Radial velocity follow-up for confirmation and characterization of transiting exoplanets. *Proceedings of the International Astronomical Union*, *4*(S253), 129-139. https://doi.org/10.1017/S174392130802632X

Boyajian, T. S., Alonso, R., Ammerman, A., Armstrong, D., Ramos, A. A., Barkaoui, K., . . . Zsidi, G. (2018). The First Post-Kepler Brightness

Dips of KIC 8462852. *The Astrophysical Journal Letters*, *853*(1), L8. https://doi.org/10.3847/2041-8213/aaa405

Boyle, P. (2022). *Why do so many Americans distrust science?* Association of American Medical Colleges. Retrieved September 7, 2023 from https://www.aamc.org/news/why-do-so-many-americans-distrust-science

Brown, T., Baliber, N., Bianco, F., Bowman, M., Burleson, B., Conway, P., . . . Dilday, B. (2013). Las Cumbres Observatory global telescope network. *Publications of the Astronomical Society of the Pacific*, *125*(931), 1031.

Bryant, E. M., Bayliss, D., Santerne, A., Wheatley, P. J., Nascimbeni, V., Ducrot, E., . . . de Wit, J. (2021). A transit timing variation observed for the long-period extremely low-density exoplanet HIP 41378 f. *Monthly Notices of the Royal Astronomical Society: Letters*, *504*(1), L45-L50. https://doi.org/10.1093/mnrasl/slab037

Burdanov, A., Benni, P., Sokov, E., Krushinsky, V., Popov, A., Delrez, L., . . . Ivanov, K. (2018). KPS-1b: The First Transiting Exoplanet Discovered Using an Amateur Astronomer's Wide-field CCD Data. *Publications of the Astronomical Society of the Pacific*, *130*(989), 1-10. https://doi.org/10.1088/1538-3873/aabde2

Bureau, U. S. C. (2022). *Educational Attainment in the United States: 2021*. https://www.census.gov/data/tables/2021/demo/educational-attainment/cps-detailed-tables.html

Burger, D. (2023). *KELT*. Retrieved September 7, 2023 from https://keltsurvey.org/

Cameron, A. C. (2012). Astrophysical false positives. *Nature*, *492*, 48. https://doi.org/10.1038/492048a

Campbell, B., Walker, G. A., & Yang, S. (1988). A search for substellar companions to solar-type stars. *The Astrophysical Journal*, *331*, 902-921.

Carpenter, S., Colbert, S., Gosnell, R., Gould, A., Grener, D., Lohman, R., . . . Perazzo, J. (2018). The Hands-On Universe Project and Modeling Instruction Based HOU: MI-HOU. *RTSRE Proceedings*, *1*(1). https://doi.org/10.32374/rtsre.2017.017

Cartier, K. M. S. (2018, 19 April 2018). Exoplanet-Hunting Telescope Launches *Eos*, *99*. https://doi.org/https://doi.org/10.1029/2018EO096785

Cassan, A., Kubas, D., Beaulieu, J. P., Dominik, M., Horne, K., Greenhill, J., . . . Wyrzykowski, Ł. (2012). One or more bound planets per Milky Way star from microlensing observations. *Nature*, *481*(7380), 167-169. https://doi.org/10.1038/nature10684

Cazeneuve, D., Marchis, F., Blaclard, G., Dalba, P. A., Martin, V., & Asencio, J. (2023). ODNet: A Convolutional Neural Network for Asteroid Occultation Detection. *The Astronomical Journal*, *165*(1), 11. https://doi.org/10.3847/1538-3881/ac9c69

Charbonneau, D., Brown, T. M., Latham, D. W., & Mayor, M. (2000). Detection of Planetary Transits Across a Sun-like Star. *The Astrophysical Journal*, *529*(1), L45-L48. https://doi.org/10.1086/312457

Chen, J., & Kipping, D. (2017). PROBABILISTIC FORECASTING OF THE MASSES AND RADII OF OTHER WORLDS. *The Astrophysical Journal*, *834*(1), 17. https://doi.org/10.3847/1538-4357/834/1/17

Christian, C., Lintott, C., Smith, A., Fortson, L., & Bamford, S. (2012). Citizen science: Contributions to astronomy research. *arXiv preprint arXiv:1202.2577*.

Christiansen, J. L., Crossfield, I. J. M., Barentsen, G., Lintott, C. J., Barclay, T., Simmons, B. D., . . . Kristiansen, M. H. (2018). The K2-138 System: A Near-resonant Chain of Five Sub-Neptune Planets Discovered by Citizen Scientists. *The Astronomical Journal*, *155*(2), 57. https://doi.org/10.3847/1538-3881/aa9be0

Clinchy, E. (1993). Needed: A Clinton Crusade for Quality and Equality. *The Phi Delta Kappan*, *74*(8), 605-612. http://www.jstor.org/stable/20404952

Collins, K. A., Collins, K. I., Pepper, J., Labadie-Bartz, J., Stassun, K. G., Gaudi, B. S., . . . Zambelli, R. (2018). The KELT Follow-up Network and Transit False-positive Catalog: Pre-vetted False Positives for TESS. *The Astronomical Journal*, *156*(5), 1-19. https://doi.org/10.3847/1538-3881/aae582

Conti, D. M. (2016). The Role of Amateur Astronomers in Exoplanet Research 35th Annual Conference of the Society for Astronomical Sciences Ontario, CA.

Cooke, B. F., Pollacco, D., West, R., McCormac, J., & Wheatley, P. J. (2018). Single site observations of TESS single transit detections. *A&A*, *619*, A175. https://doi.org/10.1051/0004-6361/201834014

Costello, K., Reilly, E., Bracey, G., & Gay, P. (2012). Hanny and the Mystery of the Voorwerp: Citizen Science in the Classroom. Connecting People to Science: A National Conference on Science Education and Public Outreach,

Council, N. R. (2012). *A framework for K-12 science education: Practices, crosscutting concepts, and core ideas*. National Academies Press.

Council, N. R. (2015). *Guide to implementing the next generation science standards*. National Academies Press.

Croll, B. (2012). How Amateurs Can Contribute to the Field of Transiting Exoplanets. *Journal of the American Association of Variable Star Observers 40*, 456-466. https://www.aavso.org/media/jaavso/2833.pdf

Dai, X., & Guerras, E. (2018). Probing Extragalactic Planets Using Quasar Microlensing. *The Astrophysical Journal Letters*, *853*(2), L27. https://doi.org/10.3847/2041-8213/aaa5fb

Dalba, P. A., Kane, S. R., Dragomir, D., Villanueva, S., Collins, K. A., Jacobs, T. L., . . . Villaseñor, J. N. (2022). The TESS-Keck Survey. VIII. Confirmation of a Transiting Giant Planet on an Eccentric 261

Day Orbit with the Automated Planet Finder Telescope*. *The Astronomical Journal*, *163*(2), 61. https://doi.org/10.3847/1538-3881/ac415b
Dalba, P. A., & Muirhead, P. S. (2016). NO TIMING VARIATIONS OBSERVED IN THIRD TRANSIT OF SNOW-LINE EXOPLANET KEPLER-421b. *The Astrophysical Journal*, *826*(1), L7. https://doi.org/10.3847/2041-8205/826/1/l7
Dawson, R. I., & Johnson, J. A. (2018). Origins of Hot Jupiters. *Annual Review of Astronomy and Astrophysics*, *56*(1), 175-221. https://doi.org/10.1146/annurev-astro-081817-051853
Dawson, R. I., Johnson, J. A., Fabrycky, D. C., Foreman-Mackey, D., Murray-Clay, R. A., Buchhave, L. A., . . . Valenti, J. A. (2014). LARGE ECCENTRICITY, LOW MUTUAL INCLINATION: THE THREE-DIMENSIONAL ARCHITECTURE OF A HIERARCHICAL SYSTEM OF GIANT PLANETS. *The Astrophysical Journal*, *791*(2), 89. https://doi.org/10.1088/0004-637X/791/2/89
Des Marais, D. J., Harwit, M. O., Jucks, K. W., Kasting, J. F., Lin, D. N., Lunine, J. I., . . . Woolf, N. J. (2002). Remote sensing of planetary properties and biosignatures on extrasolar terrestrial planets. *Astrobiology*, *2*(2), 153-181.
Dewey, J. (1916). *Democracy and education: An introduction to the philosophy of education*. Macmillan.
Dong, S., Katz, B., & Socrates, A. (2014). WARM JUPITERS NEED CLOSE "FRIENDS" FOR HIGH-ECCENTRICITY MIGRATION—A STRINGENT UPPER LIMIT ON THE PERTURBER'S SEPARATION. *The Astrophysical Journal Letters*, *781*(1), L5. https://doi.org/10.1088/2041-8205/781/1/L5
Doran, R., Melchior, A.-L., Boudier, T., Ferlet, R., Almeida, M. L., Barbosa, D., . . . Roberts, S. (2012). Astrophysics datamining in the classroom: Exploring real data with new software tools and robotic telescopes. *arXiv preprint arXiv:1202.2764*.
Dragomir, D., Harris, M., Pepper, J., Barclay, T., Villanueva, S., Ricker, G. R., . . . Yahalomi, D. (2020). Securing the Legacy of TESS through the Care and Maintenance of TESS Planet Ephemerides. *The Astronomical Journal*, *159*(5), 219. https://doi.org/10.3847/1538-3881/ab845d
Ehrenfreund, P., & Charnley, S. B. (2000). Organic Molecules in the Interstellar Medium, Comets, and Meteorites: A Voyage from Dark Clouds to the Early Earth. *Annual Review of Astronomy and Astrophysics*, *38*(1), 427-483. https://doi.org/10.1146/annurev.astro.38.1.427
Eisner, N. L., Barragán, O., Aigrain, S., Lintott, C., Miller, G., Zicher, N., . . . Tsymbal, A. (2020). Planet Hunters TESS I: TOI 813, a subgiant hosting a transiting Saturn-sized planet on an 84-day orbit. *Monthly Notices of the Royal Astronomical Society*, *494*(1), 750-763. https://doi.org/10.1093/mnras/staa138

Eisner, N. L., Barragán, O., Lintott, C., Aigrain, S., Nicholson, B., Boyajian, T. S., . . . Hoffman, T. (2020). Planet Hunters TESS II: findings from the first two years of TESS. *Monthly Notices of the Royal Astronomical Society, 501*(4), 4669-4690. doi:10.1093/mnras/staa3739

Escolà-Gascón, Á., Marín, F.-X., Rusiñol, J., & Gallifa, J. (2020). Pseudoscientific beliefs and psychopathological risks increase after COVID-19 social quarantine. *Globalization and Health*, *16*(1), 72. https://doi.org/10.1186/s12992-020-00603-1

Extrasolar planets: the Holy Grail of astronomers. (2007). In *The New Worlds: Extrasolar Planets* (pp. 1-11). Springer New York. https://doi.org/10.1007/978-0-387-44907-4_1

FairTest. (2023). *Test Optional and Test Free Colleges*. https://fairtest.org/test-optional-list/

Falk, J. H., Staus, N., Dierking, L. D., Penuel, W., Wyld, J., & Bailey, D. (2016). Understanding youth STEM interest pathways within a single community: the Synergies project. *International Journal of Science Education, Part B*, *6*(4), 369-384. https://doi.org/10.1080/21548455.2015.1093670

Fara, P. (2004). *Sex, botany and empire: the story of Carl Linnaeus and Joseph Banks*. Icon Books.

Ferguson, S. L., & Lezotte, S. M. (2020). Exploring the state of science stereotypes: Systematic review and meta-analysis of the Draw-A-Scientist Checklist. *School Science and Mathematics*, *120*(1), 55-65. https://doi.org/10.1111/ssm.12382

Fischer, D. A., Schwamb, M. E., Schawinski, K., Lintott, C., Brewer, J., Giguere, M., . . . Zimmermann, V. (2012). Planet Hunters: the first two planet candidates identified by the public using the Kepler public archive data★. *Monthly Notices of the Royal Astronomical Society*, *419*(4), 2900-2911. https://doi.org/10.1111/j.1365-2966.2011.19932.x

Foreman-Mackey, D., Hogg, D. W., Lang, D., & Goodman, J. (2013). emcee: The MCMC Hammer. *Publications of the Astronomical Society of the Pacific*, *125*(925), 306. https://doi.org/10.1086/670067

Foreman-Mackey, D., Morton, T. D., Hogg, D. W., Agol, E., & Schölkopf, B. (2016). THE POPULATION OF LONG-PERIOD TRANSITING EXOPLANETS. *The Astronomical Journal*, *152*(6), 206. https://doi.org/10.3847/0004-6256/152/6/206

Fortney, J. J., Dawson, R. I., & Komacek, T. D. (2021). Hot Jupiters: Origins, Structure, Atmospheres. *Journal of Geophysical Research: Planets*, *126*(3), e2020JE006629. https://doi.org/https://doi.org/10.1029/2020JE006629

Fortney, J. J., & Nettelmann, N. (2010). The Interior Structure, Composition, and Evolution of Giant Planets. *Space Science Reviews*, *152*(1), 423-447. https://doi.org/10.1007/s11214-009-9582-x

Fortus, D., Krajcik, J., Dershimer, R. C., Marx, R. W., & Mamlok-Naaman, R. (2005). Design-based science and real-world problem-solving. *International Journal of Science Education*, *27*(7), 855-879.
Foundation, Q. (2023). *Qatar Expolanet Survey (QES)*. Retrieved September 7, 2023 from https://www.qatarexoplanet.org/
Gallup. (2022). *Confidence in Public Schools Turns More Partisan*. https://news.gallup.com/poll/394784/confidence-public-schools-turns-partisan.aspx
Gallup. (2023). *Historically Low Faith in U.S. Institutions Continues*. https://news.gallup.com/poll/508169/historically-low-faith-institutions-continues.aspx
Garcia, E., & Weiss, E. (2019). *The Teacher Shortage Is Real, Large and Growing, and Worse than We Thought. The First Report in "The Perfect Storm in the Teacher Labor Market" Series* (ED598211). https://eric.ed.gov/?id=ED598211
Gardner, J. P., Mather, J. C., Abbott, R., Abell, J. S., Abernathy, M., Abney, F. E., . . . Zondag, E. (2023). The James Webb Space Telescope Mission. *Publications of the Astronomical Society of the Pacific*, *135*(1048), 068001. https://doi.org/10.1088/1538-3873/acd1b5
Gardner, J. P., Mather, J. C., Clampin, M., Doyon, R., Greenhouse, M. A., Hammel, H. B., . . . Wright, G. S. (2006). The James Webb Space Telescope. *Space Science Reviews*, *123*(4), 485-606. https://doi.org/10.1007/s11214-006-8315-7
Gaudi, B. S. (2012). Microlensing Surveys for Exoplanets. *Annual Review of Astronomy and Astrophysics*, *50*(1), 411-453. https://doi.org/10.1146/annurev-astro-081811-125518
Gaze, E. (2015). *Addressing the Skills Gap for Students and Young Adults*. Diverse: Issues in Higher Education Retrieved 8 June 2020 from https://diverseeducation.com/article/76145/
Geier, R., Blumenfeld, P. C., Marx, R. W., Krajcik, J. S., Fishman, B., Soloway, E., & Clay-Chambers, J. (2008). Standardized test outcomes for students engaged in inquiry-based science curricula in the context of urban reform. *Journal of Research in Science Teaching*, *45*(8), 922-939. https://doi.org/10.1002/tea.20248
Gomes, R. S., Morbidelli, A., & Levison, H. F. (2004). Planetary migration in a planetesimal disk: why did Neptune stop at 30 AU? *Icarus*, *170*(2), 492-507. https://doi.org/https://doi.org/10.1016/j.icarus.2004.03.011
Gomez, E. L., & Fitzgerald, M. T. (2017). Robotic telescopes in education. *Astronomical Review*, *13*(1), 28-68. https://doi.org/10.1080/21672857.2017.1303264
Gonzalez, A., Peters, M. L., Orange, A., & Grigsby, B. (2017). The influence of high-stakes testing on teacher self-efficacy and job-related stress. *Cambridge Journal of Education*, *47*(4), 513-531. https://doi.org/10.1080/0305764X.2016.1214237

Gould, R., Dussault, M., & Sadler, P. (2006). What's Educational about Online Telescopes?: Evaluating 10 Years of MicroObservatory [Article]. *Astronomy Education Review*, *5*(2), 127-145. https://doi.org/10.3847/AER2006022
Grant, A. (2018, August 26, 2018). Those Who Can Do, Can't Teach. *The New York Times*. https://www.nytimes.com/2018/08/25/opinion/sunday/college-professors-experts-advice.html
Graykowski, A., Lambert, R. A., Marchis, F., Cazeneuve, D., Dalba, P. A., Esposito, T. M., . . . Transom, I. M. (2023). Light curves and colours of the ejecta from Dimorphos after the DART impact. *Nature*. https://doi.org/10.1038/s41586-023-05852-9
Greene, T. P., Line, M. R., Montero, C., Fortney, J. J., Lustig-Yaeger, J., & Luther, K. (2016). CHARACTERIZING TRANSITING EXOPLANET ATMOSPHERES WITH JWST. *The Astrophysical Journal*, *817*(1), 17. https://doi.org/10.3847/0004-637X/817/1/17
Grinspoon, D. (2016). *Earth in human hands: Shaping our planet's future*. Grand Central Publishing Group.
Group, K. U. A. (2023). *WASP Planets*. Retrieved September 7, 2023 from https://wasp-planets.net/
Guerrero, N. M., Seager, S., Huang, C. X., Vanderburg, A., Soto, A. G., Mireles, I., . . . Winn, J. N. (2021). The TESS Objects of Interest Catalog from the TESS Prime Mission. *The Astrophysical Journal Supplement Series*, *254*(2), 39. https://doi.org/10.3847/1538-4365/abefe1
Haag, S., & Megowan, C. (2012). Beyond the Transcript: Factors Influencing the Pursuit of Science and Mathematics Coursework. *School Science and Mathematics*, *112*(8), 455-465. https://doi.org/https://doi.org/10.1111/j.1949-8594.2012.00167.x
Haag, S., & Megowan, C. (2015). Next generation science standards: A national mixed-methods study on teacher readiness. *School Science and Mathematics*, *115*(8), 416-426.
Haag, S., & Megowan-Romanowicz, C. (2021). Building Competence in Science and Engineering. *Standards*, *1*(1), 39-52. https://www.mdpi.com/2305-6703/1/1/5
Hamacher, D. W., Anderson, G. M., Barsa, J., Bosun, D., Day, R., Passi, S., & Tapim, A. (2022). *The first astronomers : how Indigenous elders read the stars*. Allen & Unwin.
Harris, C. J., Penuel, W. R., D'Angelo, C. M., DeBarger, A. H., Gallagher, L. P., Kennedy, C. A., . . . Krajcik, J. S. (2015). Impact of project-based curriculum materials on student learning in science: Results of a randomized controlled trial. *Journal of Research in Science Teaching*, *52*(10), 1362-1385. https://doi.org/10.1002/tea.21263
Hatzes, A. P., Cochran, W. D., Endl, M., McArthur, B., Paulson, D. B., Walker, G. A. H., . . . Yang, S. (2003). A Planetary Companion to γ Cephei A. *The Astrophysical Journal*, *599*(2), 1383-1394. https://doi.org/10.1086/379281

Hayes, C. R., Matthews, A. M., Song, Y., Linden, S. T., Wilson, R. F., Finn, M., . . . Troup, N. (2020). First results from the Dark Skies, Bright Kids astronomy club draw-a-scientist test. *Physical Review Physics Education Research*, *16*(1), 010131. https://doi.org/10.1103/PhysRevPhysEducRes.16.010131

Heitzmann, A., Zhou, G., Quinn, S. N., Huang, C. X., Dong, J., Bouma, L. G., . . . Daylan, T. (2023). TOI-4562b: A Highly Eccentric Temperate Jupiter Analog Orbiting a Young Field Star. *The Astronomical Journal*, *165*(3), 121. https://doi.org/10.3847/1538-3881/acb5a2

Henden, A. A. (2011). Amateur Community and “Citizen Science”. *Proceedings of the International Astronomical Union*, *7*(S285), 255-260. https://doi.org/10.1017/s1743921312000695

Heng, K., & Winn, J. (2015). The Next Great Exoplanet Hunt: What strange new worlds will our future telescopes find? *American Scientist*, *103*(3), 196-203. https://www.americanscientist.org/article/the-next-great-exoplanet-hunt

Henry, G. W., Marcy, G. W., Butler, R. P., & Vogt, S. S. (2000). A Transiting “51 Peg–like” Planet. *The Astrophysical Journal*, *529*(1), L41-L44. https://doi.org/10.1086/312458

Hestenes, D. (1997). Modeling methodology for physics teachers. *AIP Conference Proceedings*, *399*(1), 935-958. https://doi.org/10.1063/1.53196

Hestenes, D. (2013). Remodeling Science Education. *European Journal of Science and Mathematics Education*, *1*(1), 13-22.

Hestenes, D., Megowan-Romanowicz, C., Popp, S. E. O., Jackson, J., & Culbertson, R. J. (2011). A graduate program for high school physics and physical science teachers. *American Journal of Physics*, *79*(9), 971-979. https://doi.org/10.1119/1.3602122

Higgs, C. (2023). Citizen Science with the Vera C. Rubin Observatory. *55*(2). https://baas.aas.org/pub/2023n2i140p03

Hord, B. J., Kempton, E. M.-R., Mikal-Evans, T., Latham, D. W., Ciardi, D. R., Dragomir, D., . . . de Beurs, Z. L. (2023). Identification of the Top TESS Objects of Interest for Atmospheric Characterization of Transiting Exoplanets with JWST. *arXiv preprint arXiv:2308.09617*.

Horner, J., Jones, B. W., & Chambers, J. (2010). Jupiter – friend or foe? III: the Oort cloud comets. *International Journal of Astrobiology*, *9*(1), 1-10. https://doi.org/10.1017/S1473550409990346

Howell, S. B., Sobeck, C., Haas, M., Still, M., Barclay, T., Mullally, F., . . . Fortney, J. J. (2014). The K2 Mission: Characterization and Early Results. *Publications of the Astronomical Society of the Pacific*, *126*(938), 398. https://doi.org/10.1086/676406

Ingersoll, R. M. (2009). *Who controls teachers' work?: Power and accountability in America's schools*. Harvard University Press.

Institute, N. s. E. S. (2023). *Exoplanet Archive* https://exoplanetarchive.ipac.caltech.edu/

Institution, S. (2023). *MicroObservatory Robotic Telescope Network*. Retrieved September 7, 2023 from https://mo-www.cfa.harvard.edu/MicroObservatory/
Jackson, J., Dukerich, L., & Hestenes, D. (2008). Modeling Instruction: An Effective Model for Science Education. *Science Educator*, *17*(1), 10.
Kay, R., MacDonald, T., & DiGiuseppe, M. (2019). A comparison of lecture-based, active, and flipped classroom teaching approaches in higher education. *Journal of Computing in Higher Education*, *31*(3), 449-471. https://doi.org/10.1007/s12528-018-9197-x
Kempton, E. M., Bean, J. L., Louie, D. R., Deming, D., Koll, D. D. B., Mansfield, M., . . . Valenti, J. A. (2018). A framework for prioritizing the TESS planetary candidates most amenable to atmospheric characterization. *Publications of the Astronomical Society of the Pacific*, *130*(993), 1-14. https://doi.org/10.1088/1538-3873/aadf6f
Kokori, A., Tsiaras, A., Edwards, B., Rocchetto, M., Tinetti, G., Bewersdorff, L., . . . Zíbar, M. (2022). ExoClock Project. II. A Large-scale Integrated Study with 180 Updated Exoplanet Ephemerides. *The Astrophysical Journal Supplement Series*, *258*(2), 40. https://doi.org/10.3847/1538-4365/ac3a10
Kokori, A., Tsiaras, A., Edwards, B., Rocchetto, M., Tinetti, G., Wünsche, A., . . . Tomatis, A. (2022). ExoClock project: an open platform for monitoring the ephemerides of Ariel targets with contributions from the public. *Experimental Astronomy*, *53*(2), 547-588. https://doi.org/10.1007/s10686-020-09696-3
Kostov, V. B., Powell, B. P., Orosz, J. A., Welsh, W. F., Cochran, W., Collins, K. A., . . . Winn, J. N. (2021). TIC 172900988: A Transiting Circumbinary Planet Detected in One Sector of TESS Data. *The Astronomical Journal*, *162*(6), 234. https://doi.org/10.3847/1538-3881/ac223a
Krajcik, J. S., & Shin, N. (2014). Project-Based Learning. *The Cambridge Handbook of the Learning Sciences*, 275-297.
Krumenaker, L. (2009). The modern US high school astronomy course, its status and makeup, and the effects of No Child Left Behind. *Astronomy Education Review*, *8*(1), 1-8. https://doi.org/10.3847/AER2009042
Kushlev, K., Hunter, J. F., Proulx, J., Pressman, S. D., & Dunn, E. (2019). Smartphones reduce smiles between strangers. *Computers in Human Behavior*, *91*, 12-16. https://doi.org/https://doi.org/10.1016/j.chb.2018.09.023
Lambert, R., Marchis, F., Asencio, J., Blaclard, G., Sgro, L., Giorgini, J., . . . Fairfax, M. (2022). Citizen science astronomy with a network of small telescopes: the launch and deployment of JWST. SPIE Astronomical Telescopes + Instrumentation,
Lambert, R. A., Archer, J., Billiani, M., Bradley, J. K., Breeze-Lamb, P., Camilleri, M., . . . Fukui, K. (2023). Rotation Period Determination for (7335) 1989 JA. *Minor Planet Bulletin*, *50*(1), 16-17.

Lavi, R., Tal, M., & Dori, Y. J. (2021). Perceptions of STEM alumni and students on developing 21st century skills through methods of teaching and learning. *Studies in Educational Evaluation*, *70*, 101002. https://doi.org/https://doi.org/10.1016/j.stueduc.2021.101002

Lendl, M., Bouchy, F., Gill, S., Nielsen, L. D., Turner, O., Stassun, K., . . . Ziegler, C. (2019). TOI-222: a single-transit TESS candidate revealed to be a 34-d eclipsing binary with CORALIE, EulerCam, and NGTS. *Monthly Notices of the Royal Astronomical Society*, *492*(2), 1761-1769. https://doi.org/10.1093/mnras/stz3545

Ligterink, N. F. W., Ahmadi, A., Coutens, A., Tychoniec, Ł., Calcutt, H., van Dishoeck, E. F., . . . Bouwman, J. (2021). The prebiotic molecular inventory of Serpens SMM1. *A&A*, *647*, A87. https://doi.org/10.1051/0004-6361/202039619

Lissauer, J. J., Dawson, R. I., & Tremaine, S. (2014). Advances in exoplanet science from Kepler. *Nature*, *513*(7518), 336-344. https://doi.org/10.1038/nature13781

Lund, M. N., Handberg, R., Kjeldsen, H., Chaplin, W. J., & Christensen-Dalsgaard, J. (2016). Data preparation for asteroseismology with TESS. Seismology of the Sun and the Distant Stars 2016 – Using Today's Successes to Prepare the Future – TASC2 & KASC9 Workshop – SPACEINN & HELAS8 Conference, Acores Islands, Portugal.

Lykawka, P. S., Horner, J., Jones, B. W., & Mukai, T. (2009). Origin and dynamical evolution of Neptune Trojans – I. Formation and planetary migration. *Monthly Notices of the Royal Astronomical Society*, *398*(4), 1715-1729. https://doi.org/10.1111/j.1365-2966.2009.15243.x

MacDonald, E. A., Case, N. A., Clayton, J. H., Hall, M. K., Heavner, M., Lalone, N., . . . Tapia, A. (2015). Aurorasaurus: A citizen science platform for viewing and reporting the aurora. *Space Weather*, *13*(9), 548-559. https://doi.org/https://doi.org/10.1002/2015SW001214

Marchis, F., Arbouch, E., Bertin, E., Harman, P., Malvache, A., Veres, P., & Zellem, R. T. (2019, 15-20 September 2019). Citizen Science Astronomy with the Unistellar Network: From Planetary Defence to Exoplanet Transits. EPSC-DPS Joint Meeting 2019, Geneva, Switzerland

Marchis, F., Malvache, A., Marfisi, L., Borot, A., & Arbouch, E. (2020). Unistellar eVscopes: Smart, portable, and easy-to-use telescopes for exploration, interactive learning, and citizen astronomy. *Acta Astronautica*, *166*, 23-28. https://doi.org/https://doi.org/10.1016/j.actaastro.2019.09.028

Marginson, S., Tytler, R., Freeman, B., & Roberts, K. (2013). *STEM: country comparisons: international comparisons of science, technology, engineering and mathematics (STEM) education. Final*

report. Australian Council of Learned Academies. http://hdl.handle.net/10536/DRO/DU:30059041
Marshall, P. J., Lintott, C. J., & Fletcher, L. N. (2015). Ideas for Citizen Science in Astronomy. *Annual Review of Astronomy and Astrophysics*, *53*(1), 247-278. https://doi.org/10.1146/annurev-astro-081913-035959
Mayor, M., & Queloz, D. (1995). A Jupiter-mass companion to a solar-type star. *Nature*, *378*(6555), 355-359. https://doi.org/10.1038/378355a0
McKay, C. P. (2007). The search for life on Mars. *Planetary Systems and the Origins of Life*, 225.
Megowan-Romanowicz, C. (2016). *What Is Modeling Instruction?* (NSTA Reports Issue. N. S. T. Association. http://static.nsta.org/pdfs/nstareports/nstareports201607.pdf
Melott, A. L., & Thomas, B. C. (2019). From Cosmic Explosions to Terrestrial Fires? *The Journal of Geology*, *127*(4), 475-481. https://doi.org/10.1086/703418
Middleton, J. A. (1995). A Study of Intrinsic Motivation in the Mathematics Classroom: A Personal Constructs Approach. *Journal for Research in Mathematics Education*, *26*(3), 254-279. https://doi.org/10.2307/749130
Middleton, J. A., Lesh, R., & Heger, M. (2003). Interest, identity, and social functioning: Central features of modeling activity. In *Beyond constructivism: Models and modeling perspectives on mathematics problem solving, learning, and teaching* (pp. 405-431). Taylor and Francis.
Miller, D. I., Nolla, K. M., Eagly, A. H., & Uttal, D. H. (2018). The Development of Children's Gender-Science Stereotypes: A Meta-analysis of 5 Decades of U.S. Draw-A-Scientist Studies. *Child Dev*, *89*(6), 1943-1955. https://doi.org/10.1111/cdev.13039
Morbidelli, A., Chambers, J., Lunine, J. I., Petit, J. M., Robert, F., Valsecchi, G. B., & Cyr, K. E. (2000). Source regions and timescales for the delivery of water to the Earth. *Meteoritics & Planetary Science*, *35*(6), 1309-1320. https://doi.org/10.1111/j.1945-5100.2000.tb01518.x
Morbidelli, A., & Crida, A. (2007). The dynamics of Jupiter and Saturn in the gaseous protoplanetary disk. *Icarus*, *191*(1), 158-171. https://doi.org/https://doi.org/10.1016/j.icarus.2007.04.001
Morbidelli, A., Levison, H. F., Tsiganis, K., & Gomes, R. (2005). Chaotic capture of Jupiter's Trojan asteroids in the early Solar System. *Nature*, *435*(7041), 462-465. https://doi.org/10.1038/nature03540
Morton, T. D. (2012). An Efficient Automated Validation Procedure for Exoplanet Transit Candidates. *The Astrophysical Journal*, *761*(1), 6. https://doi.org/10.1088/0004-637x/761/1/6
Mousis, O., Hueso, R., Beaulieu, J. P., Bouley, S., Carry, B., Colas, F., . . . Widemann, T. (2014). Instrumental methods for professional and amateur collaborations in planetary astronomy. *Experimental*

Astronomy, *38*(1-2), 91-191. https://doi.org/10.1007/s10686-014-9379-0
Mullally, F., Coughlin, J. L., Thompson, S. E., Rowe, J., Burke, C., Latham, D. W., . . . Zamudio, K. A. (2015). PLANETARY CANDIDATES OBSERVED BY KEPLER. VI. PLANET SAMPLE FROM Q1–Q16 (47 MONTHS). *The Astrophysical Journal Supplement Series*, *217*(2), 31. https://doi.org/10.1088/0067-0049/217/2/31
NASA, E. E. P. a. J. P. L. f. (2023). *Exoplanet Watch*. Retrieved September 7, 2023 from https://exoplanets.nasa.gov/exoplanet-watch/about-exoplanet-watch/overview/
National Academies of Sciences, E., Medicine. (2021). *Decadal survey on astronomy and astrophysics 2020*. The National Academies Press.
National Academy of Sciences, N. A. o. E., and Institute of Medicine. (2007). *Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future*. The National Academies Press. https://doi.org/doi:10.17226/11463
Nielsen, E. L., De Rosa, R. J., Macintosh, B., Wang, J. J., Ruffio, J.-B., Chiang, E., . . . Wolff, S. (2019). The Gemini Planet Imager Exoplanet Survey: Giant Planet and Brown Dwarf Demographics from 10 to 100 au. *The Astronomical Journal*, *158*(1), 13. https://doi.org/10.3847/1538-3881/ab16e9
North, J. (2008). *Cosmos: an illustrated history of astronomy and cosmology*. University of Chicago Press.
O’Donovan, F. T. (2016). *TrES: The Transatlantic Exoplanet Survey*. Retrieved September 7, 2023 from https://proinsias.github.io/portfolio/tres.html
Observatory, L. C. (2023). *Las Cumbres Observatory*. Retrieved September 7, 2023 from https://lco.global/
Osborne, J., Simon, S., & Collins, S. (2003). Attitudes towards science: A review of the literature and its implications. *International Journal of Science Education*, *25*(9), 1049-1079. https://doi.org/10.1080/0950069032000032199
Painter, C., Di Stefano, R., Larner, S., Kashyap, V., Martinez Galarza, J., Kumar, S., . . . Medoff, J. (2023). Searching For and Studying Extragalactic Exoplanets Orbiting X-Ray Binaries. American Astronomical Society Meeting Abstracts,
Pannekoek, A. (1989). *A History of Astronomy*. Dover Publications.
Pearson, K. A., Beichman, C., Fulton, B. J., Esposito, T. M., Zellem, R. T., Ciardi, D. R., . . . Wünsche, A. (2022). Utilizing a global network of telescopes to update the ephemeris for the highly eccentric planet HD 80606 b and to ensure the efficient scheduling of JWST. arXiv:2208.14520. Retrieved August 01, 2022, from https://ui.adsabs.harvard.edu/abs/2022arXiv220814520P
Peluso, D. O. C., Esposito, T. M., Marchis, F., Dalba, P. A., Sgro, L., Megowan-Romanowicz, C., . . . Scientists, U. C. (2023). The Unistellar Exoplanet Campaign: Citizen Science Results and Inherent Education Opportunities. *Publications of the Astronomical*

Society of the Pacific, *135*(1043), 015001. https://doi.org/10.1088/1538-3873/acaa58
Pepper, J., Stassun, K. G., & Gaudi, B. S. (2018). KELT: The Kilodegree Extremely Little Telescope, a Survey for Exoplanets Transiting Bright, Hot Stars. In H. J. Deeg & J. A. Belmonte (Eds.), *Handbook of Exoplanets* (pp. 1-12). Springer International Publishing. https://doi.org/10.1007/978-3-319-30648-3_128-1
Perazzo, J., Bass, K., Pennypacker, C., Heredia, J., Stronck, D., Lobo, R., & Ben-Shalom, G. (2015). Persistent and Encouraging Achievement Gains on Common Core-Aligned Items for Middle School English Language Learners. *Science Education & Civic Engagement: An International Journal 7*(2), 121-131. http://new.seceij.net/articletype/research/persistent-and-encouraging-achievement-gains-on-common-core-aligned-items/
Perottoni, H. D., Amarante, J. A. S., Limberg, G., Rocha-Pinto, H. J., Rossi, S., Anders, F., & Borbolato, L. (2021). Searching for Extragalactic Exoplanetary Systems: The Curious Case of BD+20 2457. *The Astrophysical Journal Letters*, *913*(1), L3. https://doi.org/10.3847/2041-8213/abfb06
Perrocheau, A., Esposito, T. M., Dalba, P. A., Marchis, F., Avsar, A. M., Carrera, E., . . . Will, S. (2022). A 16 hr Transit of Kepler-167 e Observed by the Ground-based Unistellar Telescope Network. *The Astrophysical Journal Letters*, *940*(2), L39. https://doi.org/10.3847/2041-8213/aca073
Perryman, M. (2018). *The Exoplanet Handbook* (2 ed.). Cambridge University Press. https://doi.org/DOI: 10.1017/9781108304160
Pollacco, D. L., Skillen, I., Cameron, A. C., Christian, D. J., Hellier, C., Irwin, J., . . . Wilson, D. M. (2006). The WASP Project and the SuperWASP Cameras. *Publications of the Astronomical Society of the Pacific*, *118*(848), 1407-1418. https://doi.org/10.1086/508556
Popescu, M. M. (2023). The impact of citizen scientist observations. *Nature Astronomy*, *7*(5), 516-517. https://doi.org/10.1038/s41550-023-01954-6
Porter, A. M., & Ivie, R. (2019). *Women in Physics and Astronomy, 2019*. https://www.aip.org/statistics/reports/women-physics-and-astronomy-2019
Rees, M. (2009). Pondering Astronomy in 2009. *Science*, *323*(5912), 309-309. https://doi.org/doi:10.1126/science.1170104
Ricker, G., Winn, J., Vanderspek, R., Latham, D., Bakos, G., Bean, J., . . . Villasenor, J. (2014). Transiting Exoplanet Survey Satellite. *Journal of Astronomical Telescopes, Instruments, and Systems*, *1*(1), 014003. https://doi.org/ 10.1117/1.JATIS. 1.1.014003
Rotermund, S., & Burke, A. (2021). *Elementary and Secondary STEM Education* (Science and Engineering Indicators 2022, Issue. https://ncses.nsf.gov/pubs/nsb20211
Sackett, P. D. (1999). Searching for Unseen Planets Via Occultation and Microlensing. In J. M. Mariotti & D. Alloin (Eds.), *Planets Outside the*

Solar System: Theory and Observations (pp. 189-228). Springer Netherlands. https://doi.org/10.1007/978-94-011-4623-4_14
Sagan, C. (1996). *The Demon Haunted World: Science as a Candle in the Dark*. The Random House Publishing Group.
Salimpour, S., & Fitzgerald, M. T. (2022). Astronomy and Culture. *Science & Education*. https://doi.org/10.1007/s11191-022-00389-1
Santerne, A., Hébrard, G., Deleuil, M., Havel, M., Correia, A. C. M., Almenara, J.-M., . . . Verilhac, D. (2014). SOPHIE velocimetry of Kepler transit candidates. *A&A*, *571*, A37. https://doi.org/https://doi.org/10.1051/0004-6361/201424158
Sarva, J., Freed, R., Fitzgerald, M. T., & Salimpour, S. (2020). An Exoplanet Transit Observing Method using LCO Telescopes, ExoRequest and astrosource. *Astronomy Theory, Observations & Methods*, *1*(1), 34-43.
Scharf, C., & Cronin, L. (2016). Quantifying the origins of life on a planetary scale. *Proceedings of the National Academy of Sciences*, *113*(29), 8127-8132.
Scharf, C. A. (2006). The Potential for Tidally Heated Icy and Temperate Moons around Exoplanets. *The Astrophysical Journal*, *648*(2), 1196. https://doi.org/10.1086/505256
Schleicher, A. (2019). PISA 2018: Insights and Interpretations. *OECD Publishing*.
Schneider, D. (2014). DIY exoplanet detector. *IEEE Spectrum*, *51*(12), 27-28. https://doi.org/10.1109/MSPEC.2014.6964922
Seager, S. (2010). *Exoplanets*. The University of Arizona Press.
Seager, S., Bains, W., & Hu, R. (2013). BIOSIGNATURE GASES IN H2-DOMINATED ATMOSPHERES ON ROCKY EXOPLANETS. *The Astrophysical Journal*, *777*(2), 95. https://doi.org/10.1088/0004-637x/777/2/95
Sgro, L. A., Esposito, T. M., Blaclard, G., Gomez, S., Marchis, F., Filippenko, A. V., . . . Arnaud, Y. (2023). Photometry of Type II Supernova SN 2023ixf with a Worldwide Citizen Science Network. *Research Notes of the AAS*, *7*(7), 141. https://doi.org/10.3847/2515-5172/ace41f
Shaw, G. B. (1903). *Man and Superman*. Archibald Constable & Co.
Sheppard, K., & Robbins, D. M. (2002). Lessons from the Committee of Ten. *The Physics Teacher*, *40*(7), 426-431. https://doi.org/10.1119/1.1517887
A Short History of Panspermia from Antiquity Through the Mid-1970s. (2022). *Astrobiology*, *22*(12), 1379-1391. https://doi.org/10.1089/ast.2022.0032
Sibbernsen, K. (2022). Electronic telescopes and their use in astronomy education. *The Physics Teacher*, *60*(5), 394-395. https://doi.org/10.1119/10.0010401
Simon, M., Prather, E., Rosenthal, I., Cassidy, M., Hammerman, J., & Trouille, L. (2022). A New Curriculum Development Model for Improving Undergraduate Students' Data Literacy and Self-Efficacy

in Online Astronomy Classrooms. Astronomy Education Journal, 2(1).
Simpson, R., Page, K. R., & De Roure, D. (2014, 2014). *Zooniverse: Observing the World's Largest Citizen Science Platform* Proceedings of the 23rd International Conference on World Wide Web, Seoul, Korea. https://dx.doi.org/10.1145/2567948.2579215
Simpson, R., Page, K. R., & Roure, D. D. (2014). *Zooniverse: observing the world's largest citizen science platform* Proceedings of the 23rd International Conference on World Wide Web, Seoul, Korea. https://doi.org/10.1145/2567948.2579215
Sincell, M. (1999). Shadow and Shine Offer Glimpses of Otherworldly Jupiters. *Science*, *286*(5446), 1822-1823. https://doi.org/10.1126/science.286.5446.1822
Statista. (2023). *Number of smartphone mobile network subscriptions worldwide from 2016 to 2022, with forecasts from 2023 to 2028*. https://www.statista.com/statistics/330695/number-of-smartphone-users-worldwide/
Statistics, N. C. f. E. (2022). *Private School Enrollment. Condition of Education.* . https://nces.ed.gov/programs/coe/indicator/cgc
Struve, O. (1952). Proposal for a project of high-precision stellar radial velocity work. *The Observatory*, *72*, 199-200.
Technology, P. s. C. o. A. o. S. (2010). *Prepare and Inspire: K-12 Education in Science, Technology, Engineering, and Math (STEM) for America's Future*.
Timms, M. J., Moyle, K., Weldon, P. R., & Mitchell, P. (2018). Challenges in STEM learning in Australian schools: Literature and policy review.
Tröbst, S., Kleickmann, T., Lange-Schubert, K., Rothkopf, A., & Möller, K. (2016). Instruction and Students' Declining Interest in Science:An Analysis of German Fourth- and Sixth-Grade Classrooms. *American Educational Research Journal*, *53*(1), 162-193. https://doi.org/10.3102/0002831215618662
Tsiganis, K., Gomes, R., Morbidelli, A., & Levison, H. F. (2005). Origin of the orbital architecture of the giant planets of the Solar System. *Nature*, *435*(7041), 459-461. https://doi.org/10.1038/nature03539
Twenge, J. M., & Campbell, W. K. (2018). Associations between screen time and lower psychological well-being among children and adolescents: Evidence from a population-based study. *Prev Med Rep*, *12*, 271-283. https://doi.org/10.1016/j.pmedr.2018.10.003
U.S. Department of Education, Institute of Education Sciences, & Statistics, N. C. f. E. (2019). *NAEP Report Card: 2019 NAEP Science Assessment*. https://www.nationsreportcard.gov/highlights/science/2019/
University, T. T. o. P. (2023). *The HATNet Exoplanet Survey*. Retrieved September 7, 2023 from https://hatnet.org/
Villanueva, S., Dragomir, D., & Gaudi, B. S. (2019). An Estimate of the Yield of Single-transit Planetary Events from the Transiting

Exoplanet Survey Satellite. *The Astronomical Journal*, *157*(2), 84. https://doi.org/10.3847/1538-3881/aaf85e
Wang, X.-Y., Rice, M., Wang, S., Pu, B., Stefánsson, G., Mahadevan, S., . . . Laughlin, G. (2022). The Aligned Orbit of WASP-148b, the Only Known Hot Jupiter with a nearby Warm Jupiter Companion, from NEID and HIRES. *The Astrophysical Journal Letters*, *926*(2), L8. https://doi.org/10.3847/2041-8213/ac4f44
Wang, Z. (2023). Extrasolar Planet Candidates Identified by Single Transit from TESS. *Journal of Physics: Conference Series*, *2441*(1), 012030. https://doi.org/10.1088/1742-6596/2441/1/012030
Weiss, L. M., Marcy, G. W., Petigura, E. A., Fulton, B. J., Howard, A. W., Winn, J. N., . . . Cargile, P. A. (2018). The California-KeplerSurvey. V. Peas in a Pod: Planets in aKeplerMulti-planet System Are Similar in Size and Regularly Spaced. *The Astronomical Journal*, *155*(1), 48. https://doi.org/10.3847/1538-3881/aa9ff6
Wells, M., Hestenes, D., & Swackhamer, G. (1995). A modeling method for high school physics instruction. *American Journal of Physics*, *63*(7), 606-619. https://doi.org/10.1119/1.17849
Williams, T. R. (2001). Reconsidering the History of the AAVSO-Part I. *The Journal of the American Association of Variable Star Observers, vol. 29, no. 2, p. 132, 29*, 132.
Windschitl, M., Thompson, J., & Braaten, M. (2008). Beyond the scientific method: Model-based inquiry as a new paradigm of preference for school science investigations. *Science Education*, *92*(5), 941-967. https://doi.org/https://doi.org/10.1002/sce.20259
Wissehr, C., Concannon, J., & Barrow, L. H. (2011). Looking Back at the Sputnik Era and Its Impact on Science Education. *School Science and Mathematics*, *111*(7), 368-375. https://doi.org/https://doi.org/10.1111/j.1949-8594.2011.00099.x
Witze, A. (2018). NASA retires Kepler spacecraft after planet-hunter runs out of fuel. *Nature*. https://doi.org/10.1038/d41586-018-07247-7
Wolszczan, A., & Frail, D. A. (1992). A planetary system around the millisecond pulsar PSR1257 + 12. *Nature*, *355*(6356), 145-147. https://doi.org/10.1038/355145a0
Yee, J. C., & Gaudi, B. S. (2008). Characterizing Long-Period Transiting Planets Observed by Kepler. *The Astrophysical Journal*, *688*(1), 616-627. https://doi.org/10.1086/592038
Yoshida, F., Hayamizu, T., Miyashita, K., Watanabe, H., Yamamura, H., Akitaya, H., . . . Higuchi, A. (2022). Multi-chord observation of stellar occultation by the near-Earth asteroid (3200) Phaethon on 2021 October 3 (UTC) with very high accuracy. *Publications of the Astronomical Society of Japan*, *75*(1), 153-168. https://doi.org/10.1093/pasj/psac096
Zahnle, K., & Sleep, N. H. (2006). Impacts and the early evolution of life. In *Comets and the Origin and Evolution of Life* (pp. 207-251). Springer.

Zellem, R. T., Biferno, A., Ciardi, D. R., Dussault, M., Peticolas, L., Fowler, M., . . . Smith, D. (2019). Engaging Citizen Scientists to Keep Transit Times Fresh and Ensure the Efficient Use of Transiting Exoplanet Characterization Missions. *arXiv preprint arXiv:1903.07716*. https://arxiv.org/abs/1903.07716

Zellem, R. T., Pearson, K. A., Blaser, E., Fowler, M., Ciardi, D. R., Biferno, A., . . . Malvache, A. (2020). Utilizing Small Telescopes Operated by Citizen Scientists for Transiting Exoplanet Follow-up. *Publications of the Astronomical Society of the Pacific*, *132*(1011), 054401. https://doi.org/10.1088/1538-3873/ab7ee7

Zhao, Y. (2012). *World class learners: Educating creative and entrepreneurial students*. Corwin Press.

APPENDIX

Appendix A

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