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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Received 2022 September 12; accepted 2022 December 8; published 2023 February 6

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 Exoplanet (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 $1.72''\,\mathrm{pixel}^{-1}$. The eVscope 2 detector provides a $34' \times 47'$ FOV and plate scale of $1.33''\,\mathrm{pixel}^{-1}$.

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 $N_{\mathrm{obs}}^{1/2}$).

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.

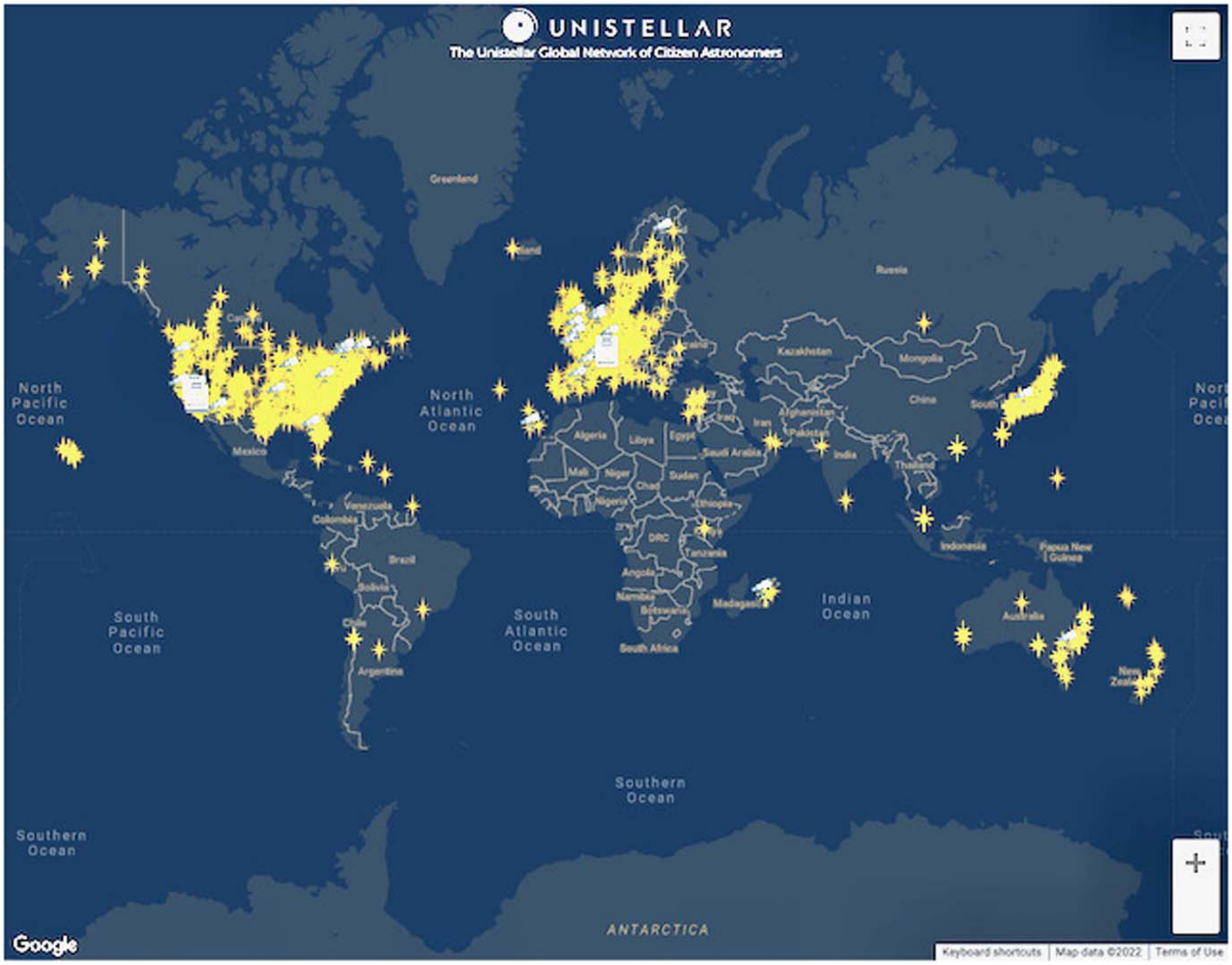


Figure 1. Unistellar Citizen Science network. Yellow dots represent Unistellar eVscope users. Credit: Unistellar.

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.

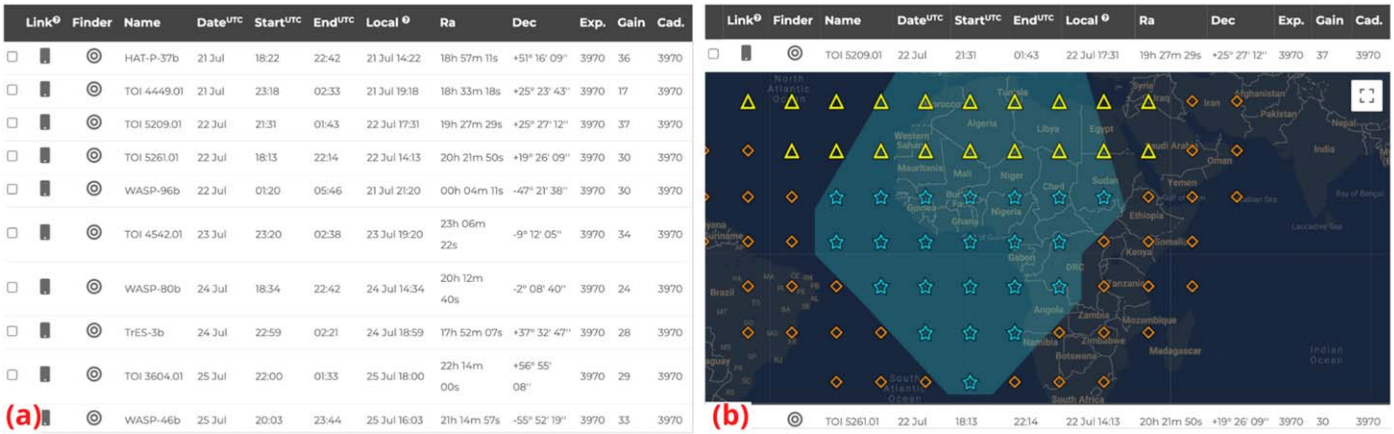
Any Unistellar eVscope user can join the Unistellar Citizen Science channel. As of 2022 August, the Unistellar Slack channel had 1350 members. There are 26 sub-channels on the Unistellar Slack channel for various citizen science missions, such as comet tracking and observation, planetary defense, asteroid 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).

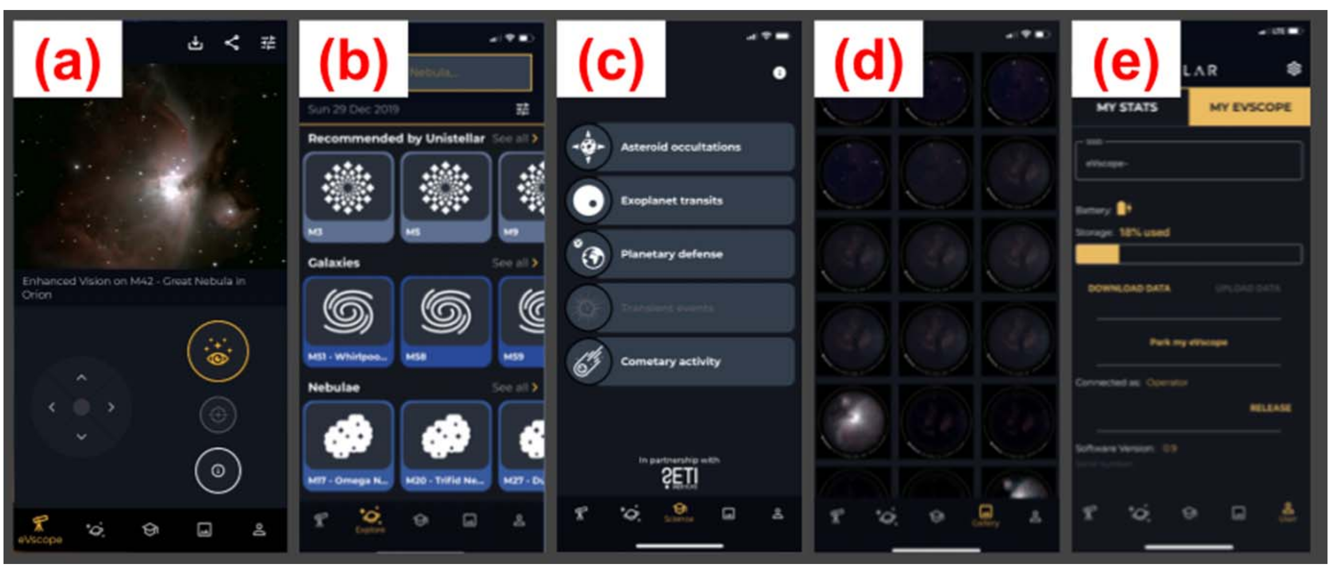


Figure 3. Screen captures of the V.1 of the Unistellar app. (a) Main controls and image viewing, (b) target selection, (c) citizen science mode, (d) saved images, and (e) user settings menu.

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

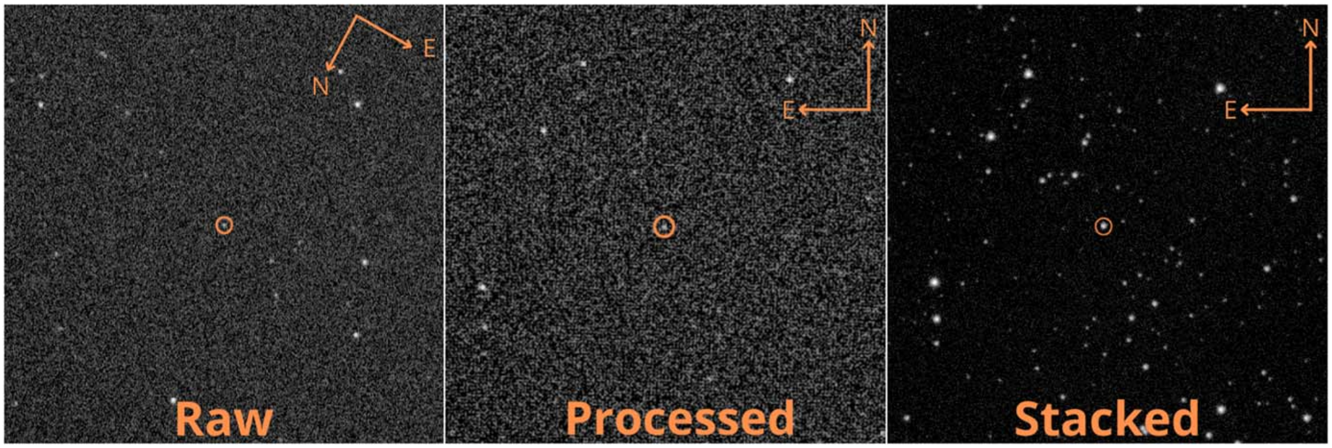


Figure 4. The observation was done in a Bortle 7 sky in a small city near Caen, France with a relatively high air mass between 2.4 and 1.9. The raw FITS file had an exposure of 3.970 s and gain of 0.0640 e–/ADU (31 dB). The processed image was dark subtracted, and the stacked image is of 30 frames with 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% ($\sim 1\sigma$) 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.)

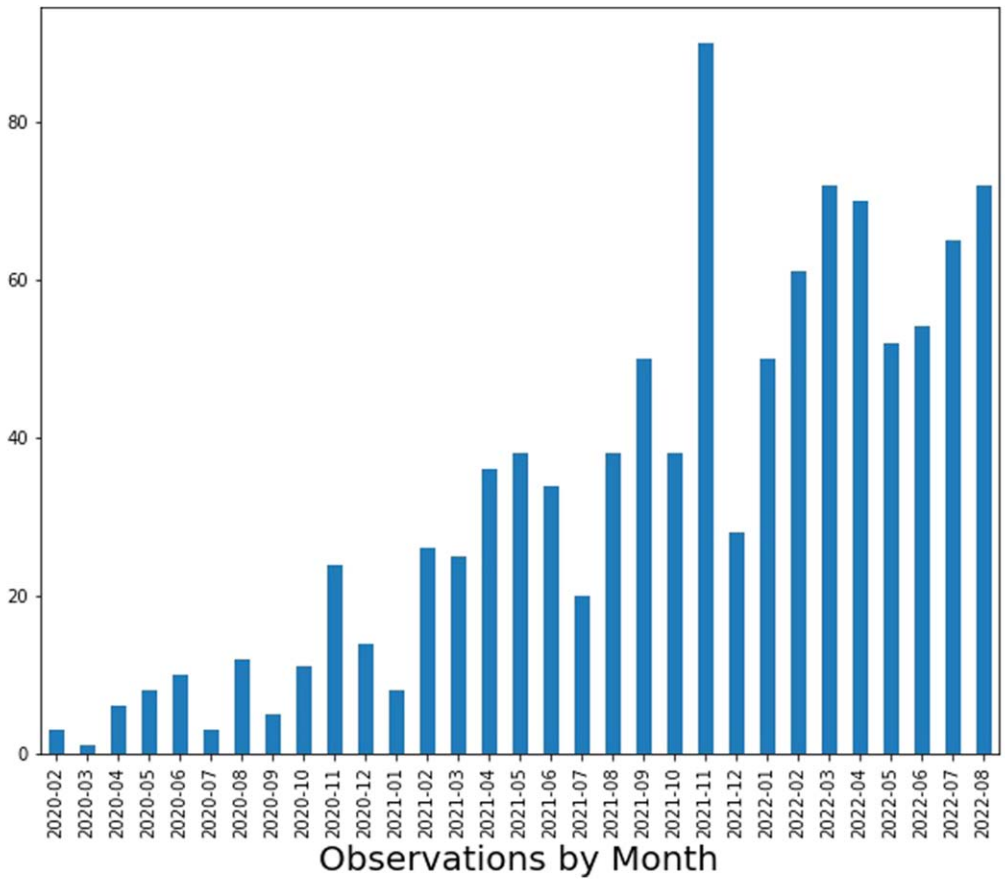


Figure 5. Distribution of all exoplanet observations of UE by observation date (YYYY-MM).

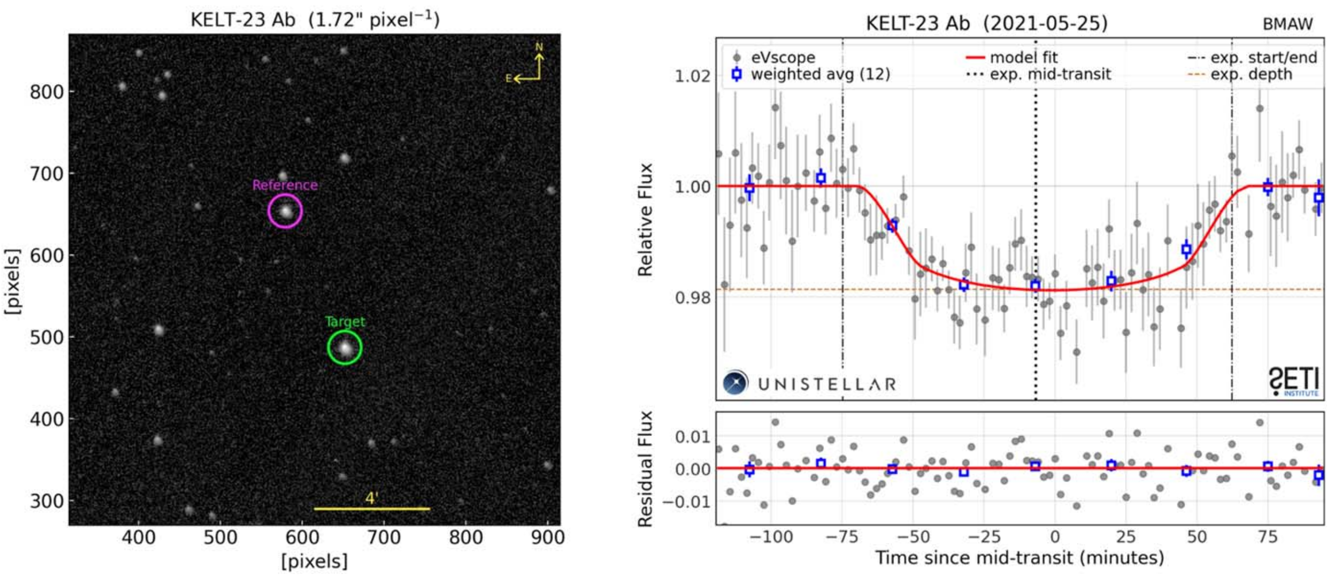


Figure 6. Example of data uploaded to AAVSO Exoplanet Database. Pertinent FITS header information is also included in these uploads. FOV for KELT-23 Ab (left). Light curve for KELT-23 Ab (right).

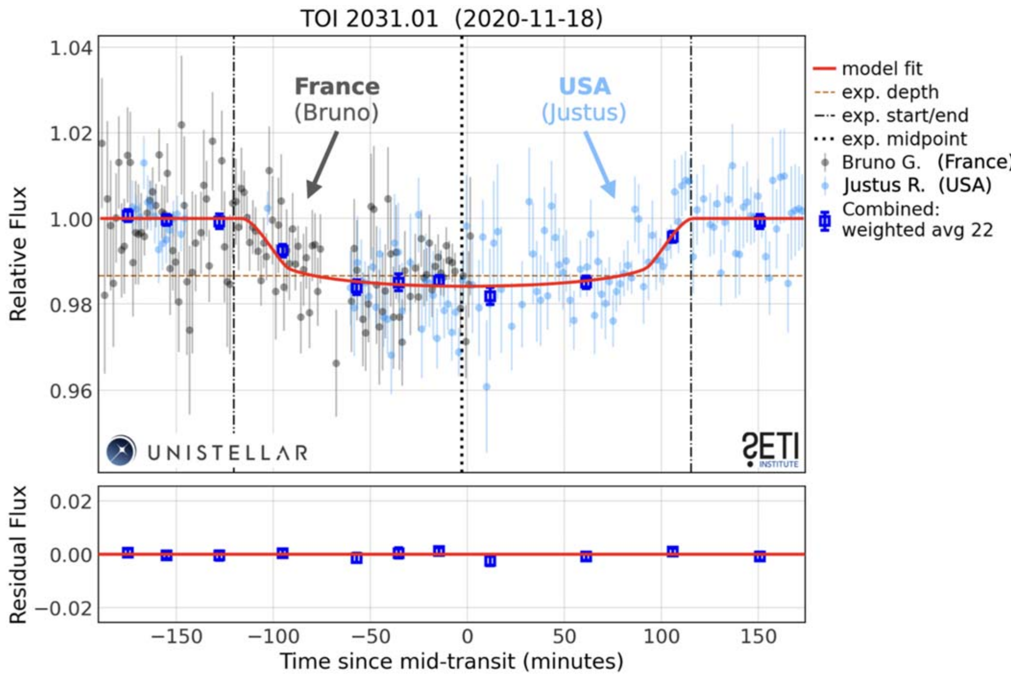


Figure 7. Transit light curve of TOI 2031.01 combines eVscope data taken by two citizen scientists located over 6700 km apart. Broken lines are the predicted transit times (black) and depth (orange).

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 $\mathrm{BJD_{TDB}}$ 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

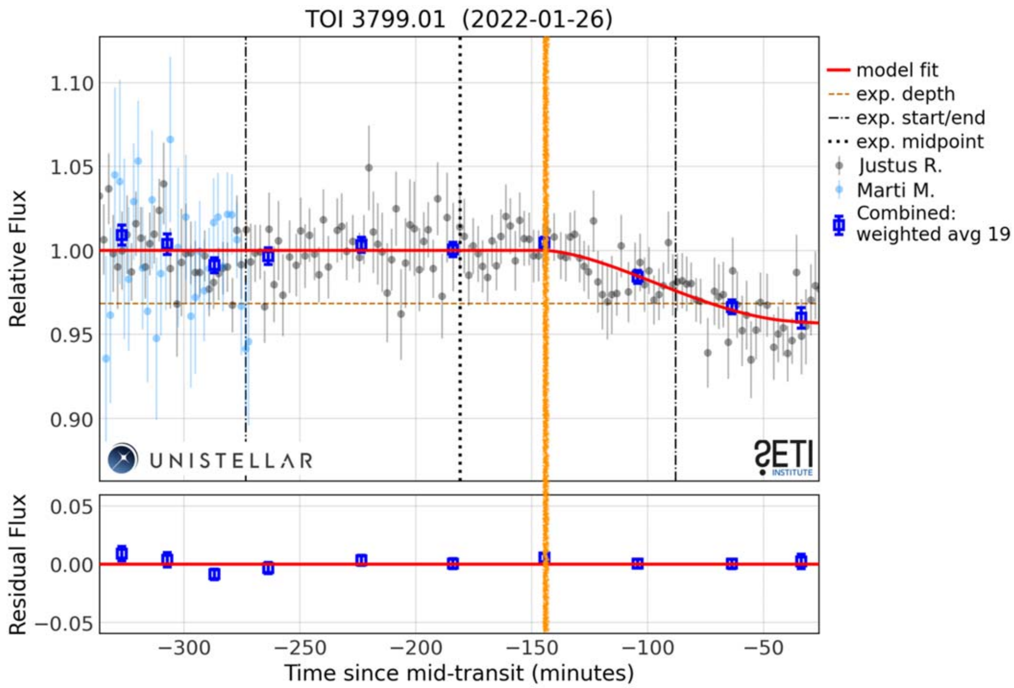


Figure 8. Ingress of TOI 3799.01 by two UE campaign citizen scientists in 2022 January showing a transit start time ∼154 minutes later than the predicted TESS data. The bold orange stylized line highlights the beginning of the ingress captured from this observation.

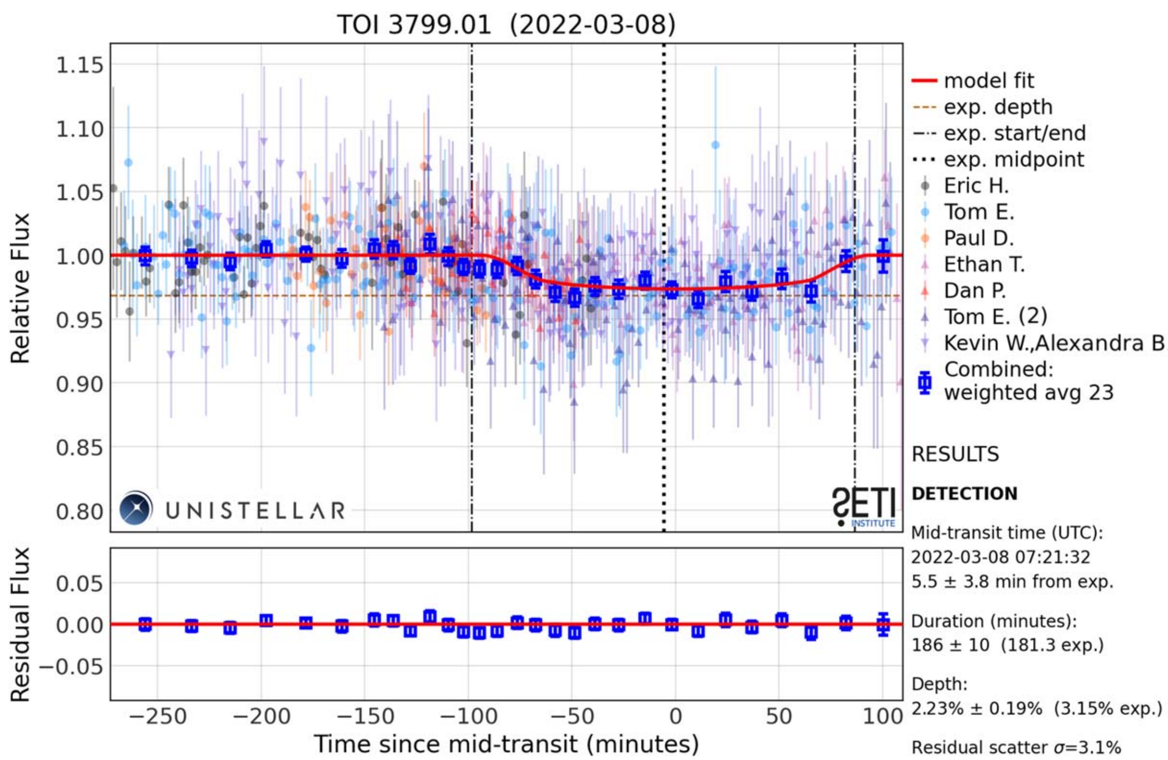


Figure 9. Transit of TOI 3799.01 by seven eVscopes (five citizen scientists and two science team astronomers) on 2022 March 8. This follow-up measurement confirmed our initial timing from 2022 January and the revised ephemeris computed from the TESS data.

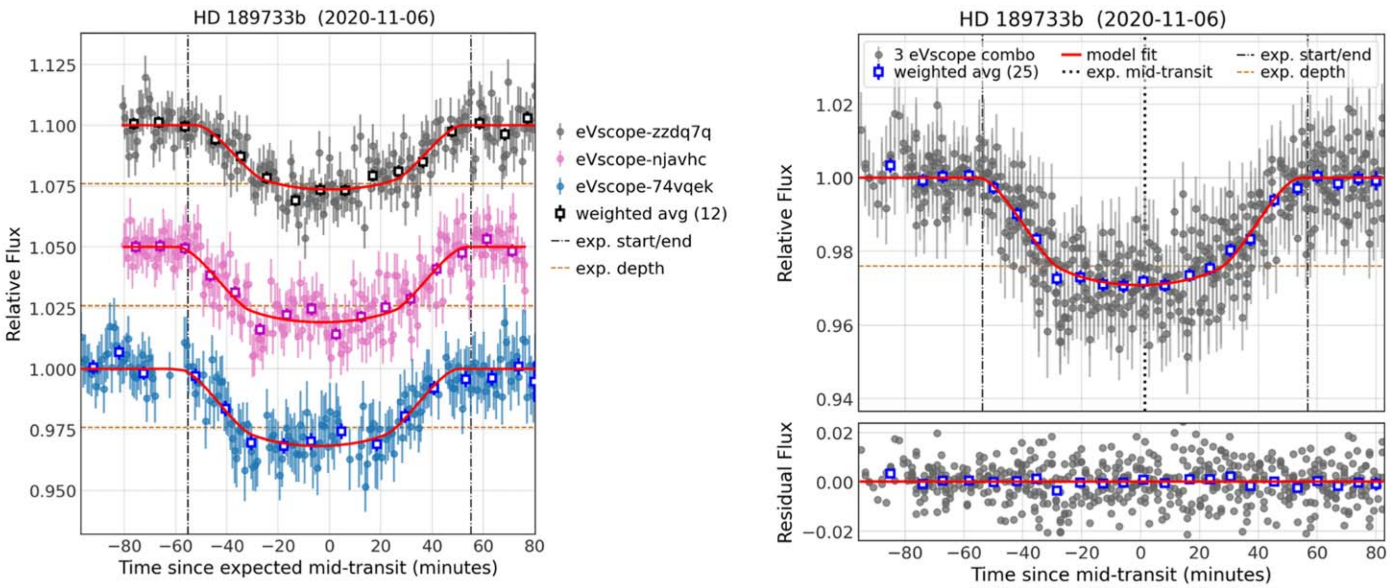


Figure 10. Photometric transit observations of HD 189733b by three Unistellar eVscopes in Europe (left). The alphanumeric strings after each "eVscope-" are the identifiers for each eVscope used. Photometric transit observation of HD 189733b with the data from three combined eVscope observations (right). 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 $\sim$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.

This research was supported with a generous donation by the Gordon and Betty Moore Foundation. Thanks to Frédéric Gastaldo who participated in the financing of the initial project of Unistellar Citizen Science. The scientific data presented herein were obtained using the Unistellar Network, which is managed jointly by Unistellar and the SETI Institute. The authors thank all the citizen astronomers who participated in these observations and contributed their precious data.

This research has made use of the NASA Exoplanet Archive, which is operated by the California Institute of Technology, under contract with the National Aeronautics and Space Administration under the Exoplanet Exploration Program. The authors gratefully acknowledge the variable star observations from the AAVSO International Database contributed by observers worldwide and used in this research. T.E.'s contributions are partially supported by the NASA Citizen Science Seed Funding Program grant number 80NSSC22K1130. P.D. acknowledges support from a National Science Foundation Astronomy and Astrophysics Postdoctoral Fellowship under award AST-1903811 and a 51 Pegasi b Postdoctoral Fellowship from the Heising–Simons Foundation.

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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