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Optimizing radial velocity detection limits for Southern Habitable Worlds Observatory targets

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ABSTRACT

The planned NASA Habitable Worlds Observatory (HWO) flagship mission aims to image and spectroscopically characterize 25 Earth-sized planets in the habitable zones of their stars. However, one giant planet in the habitable zone can ruin your whole day. Recent work has examined the current state of our knowledge on the presence or absence of such objects in samples of likely HWO targets, and that knowledge has been found wanting; even Saturn-mass planets remain undetectable in many of these systems. In this work, we present simulations assessing the degree to which new campaigns of high-cadence radial velocity (RV) observations can ameliorate this woeful state of affairs. In particular, we highlight the value of moderate-precision but highly flexibly scheduled RV facilities in aiding this necessary HWO precursor science. We find that for a subset of Southern HWO stars, 6 yr of new RVs from the MINERVA-Australis telescope array in Australia can improve the median detection sensitivity in the habitable zones of 13 likely HWO targets to $\sim 50 M_{\oplus}$, an improvement of ∼44 per cent.

Key words: techniques: radial velocities – planets and satellites: dynamical evolution and stability – exoplanets.

1 INTRODUCTION

For generations, humanity has yearned to understand our place in the cosmos. Are we alone? Is the Solar system unique? Could there be planets like our home orbiting distant stars?

Until the past few decades, all we could do was speculate. As recently as the early 1990s, we knew of just a single planetary system – the Solar system – and there remained significant debate over whether planets would one day be found to be common around other stars, or if the Solar system was a peculiar anomaly, alone in a vast, uncaring cosmos.

The first hints that planets might be common in the cosmos came in the early 1980s, with the launch of the Infrared Astronomical Satellite. That spacecraft revealed stars that were brighter than expected at infrared wavelengths (Aumann et al. 1984; Smith & Terrile 1984; Aumann 1985; Backman & Paresce 1993). That excess infrared radiation was the result of vast swathes of debris orbiting those stars – the first detected debris discs – and was clear evidence that the process by which planets form was in action around other stars.

In the latter years of the twentieth century, astronomers finally discovered the first planets orbiting main-sequence stars other than the Sun (e.g. Mayor & Queloz 1995; Butler et al. 1999; Fischer et al. 2001). To the great surprise of the astronomical community, the planetary systems so revealed bore precious little relation to our own home.

The decades since have seen an incredible growth in the number of known exoplanets – led primarily by the great space observatories *Kepler* (e.g. Batalha 2014; Dressing & Charbonneau 2015; Grunblatt et al. 2019; Kunimoto & Matthews 2020) and *Transiting Exoplanet Survey Satellite* (*TESS*; Zhou et al. 2019; Gan et al. 2023; Ment & Charbonneau 2023; Vach et al. 2024). But while the number and variety of planetary systems we have discovered have continued to grow rapidly, there remains a remarkable dearth of systems with architectures like our own (e.g. Wittenmyer et al. 2011, 2014, 2016; Agnew, Maddison & Horner 2018; Bonomo et al. 2023).[1] This poses an obvious question – where are all the Solar system analogues?

The question of whether planetary systems like our own are common, scarce, or incredibly rare is particularly important in the context of humanity's efforts to answer the question 'are we alone?'. In the coming years, the search for life beyond the Solar system will begin in earnest, and significant work has been undertaken in efforts to help direct that search to the most promising targets (e.g. Menou & Tabachnik 2003; Horner & Jones 2008, 2009, 2010a, 2012; Wittenmyer et al. 2009; Horner, Jones & Chambers 2010b; Vervoort et al. 2022; Kane & Wittenmyer 2024).

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[1]For a detailed overview of our understanding of the Solar system in the context of exoplanetary science, we direct the interested reader to Horner et al. (2020), and references therein.

Planned for the 2040s, the Habitable Worlds Observatory (HWO) is recommended (National Academies of Sciences 2021) as a NASA flagship mission to launch a 6–8m ultraviolet/optical/infrared space telescope with the primary mission of directly imaging Earth-sized planets in the habitable zones of their stars. The goal of HWO will be to obtain images and spectra of the scattered light from 25 such exo-Earths. The angular separation constraints of direct imaging impose stringent limits on the distance to candidate target stars. Hence, the likely targets are predominantly nearby bright stars that have, in the main, been extensively studied by long-term radial-velocity exoplanet surveys. Occurrence-rate studies have shown that approximately 10 per cent of Solar-type stars host giant planets beyond 1 au (e.g. Fernandes et al. 2019; Wittenmyer et al. 2020; Fulton et al. 2021; Bonomo et al. 2023). Such objects are of course dynamically incompatible with a terrestrial planet in that region, which coincides with the habitable zone for these types of stars.

Recent work by Laliotis et al. (2023) (hereafter L23) assessed the detectability of potentially disruptive habitable-zone interlopers in a sample of likely Southern HWO target stars. Since candidate HWO targets are preferentially nearby, bright, Solar-type stars, many are well studied from legacy radial velocity (RV) surveys going back decades. L23 gathered all available RV data on these stars, analysed them for signals from planets and stellar activity, then performed extensive injection-recovery tests to determine the current detection sensitivity at the 'Earth Equivalent Insolation Distance' (EEID). The results included this damning statement: 'for many of these stars we are not yet sensitive to even Saturn-mass planets in the habitable zone, let alone smaller planets, highlighting the need for future extreme precision RV (EPRV) vetting efforts.' Moreover, the dynamical simulations for the HWO known exoplanet systems by Kane et al. (2024), and subsequent RV assessment by Kane & Burt (2024), demonstrated the critical importance of detecting planets as small as Neptune that can serve as sources of dynamical instability in the habitable zone.

In this paper, we explore observing strategies with the aim of improving the detection sensitivities derived in L23. In particular, we seek to quantify the degree to which small, flexibly scheduled telescopes can contribute to this effort. It is obvious that intensive RV campaigns observing the HWO target stars with the world's most precise RV instruments would handily resolve the distressing state of affairs revealed by L23. But such an approach is inefficient; we seek to identify those stars that would benefit most from attention with 1–2m class 'regular RV' facilities in an effort to inform better allocation of limited EPRV resources. We examine the benefit to sensitivity achieved by campaigns at various levels of intensity (observing cadence). Section 2 describes the simulated RV data properties, Section 3 gives our results and discussion, and we conclude in Section 4.

2 SIMULATION SET-UP

We choose 36 Southern stars from L23 that are also included in the most recent NASA Exoplanet Exploration Program Mission Star List given in Mamajek & Stapelfeldt (2024). Those stars are listed in Table 1 along with their EEID and the current RV detection sensitivity, as given in table 12 of L23. Those detection limits are given here and throughout this work as the mass for which 50 per cent of injected planets were successfully recovered. Shown in Fig. 1 is a Hertzsprung–Russell diagram for our stellar sample, where the colour of the data points represents the stellar metallicity. Those data points shown as circles are stars presently known to harbour planets. Such visualization of the stellar sample summarizes the breadth of the stellar properties, and the metallicity may be indicative of the likelihood for additional planets being present in those systems (Fischer & Valenti 2005; Buchhave et al. 2014, 2018; Brewer et al. 2018).

We consider three values of observing cadence C: 5, 10, and 20 d. We then generate the simulated observation times as follows: Starting at an arbitrary date JD = 2460000.0, the time until the next observation is drawn from a Gaussian distribution with a mean of C and width $\sigma = C/3$, where C is the desired cadence in days and has values of 5, 10, and 20. This arrangement simulates a one-third weather loss by imposing the stochasticity expected from real observing conditions. Seasonality is simulated by forbidding observations during a 4-month period each year.

This set-up ensures that all the simulations share a similar temporal baseline (i.e. 3 or 6 yr of new observations) as well as the number of new observations within each test case of observing cadence. However, such a set-up creates a scenario where the time difference between the last real observation and the new data will vary for each star. As mentioned in Li et al. (submitted), such a time difference (temporal gap) between the last observation and future data does have a significant effect on the orbital ephemerides of planets and therefore the derived RV sensitivity as well. In particular, simulations with a larger temporal gap typically exhibit better orbital constraints and may consequently produce a higher sensitivity towards the low planetary mass regime. However, the effect such a variable has on our simulation is beyond the scope of this work and we leave that to interested readers.

Next, the simulated RV is derived as follows: for each of the 36 stars, we have the real RV from archival data as compiled for the sensitivity simulations of L23. For stars that host planets, the known planet orbits and any trends are fitted and removed, and the residual planet-free data are used for this step. The simulated RV data point is then drawn at random (with replacement) from the real RV for each star. In this way, we capture the intrinsic differences in the noise level between stars; not all stars are equally well-behaved. Often the legacy RV data come from very precise instruments such as Keck/HIRES, HARPS, or Magellan/PFS. To properly account for the fact that here we are simulating future observations with a less-precise instrument, we add scatter to the simulated RV observation. The RV value is 'bumped' by an amount drawn from a Gaussian distribution with zero mean and $\sigma = 4\,\mathrm{m\,s^{-1}}$. The RV uncertainty on each simulated point is then drawn from a Gaussian distribution with a mean of $4\,\mathrm{m\,s^{-1}}$ and width of $1\,\mathrm{m\,s^{-1}}$. This is chosen as representative of the RV precision delivered by MINERVA-Australis for typical bright Solar-type stars like those in the HWO target list. MINERVA-Australis (Addison et al. 2019) is used here as an exemplar 'regular RV' facility with flexible scheduling. It is comprised of four 0.7m Planewave CDK-700 telescopes fibre feeding a single environmentally stabilized Kiwistar R4-100 spectrograph (Barnes et al. 2012). It has been wholly dedicated to RV follow-up and mass measurement of candidate planets from the *TESS* mission since 2019, contributing data to the confirmation of nearly 40 *TESS* planets to date (e.g. Brahm et al. 2020; Addison et al. 2021; Wittenmyer et al. 2022; Clark et al. 2023).

3 RESULTS AND DISCUSSION

With simulated data in hand – three cadence scenarios for each target – we determined detection sensitivities using `RVSearch` (Rosenthal et al. 2021). First we test the effect of adding a further 3 yr of new observations to the existing legacy RV data that were analysed in L23. Table 1 shows the detection sensitivity results for the three cadences.

Table 1. Target list with EEID and RV sensitivity results reprised from table 12 of L23, the gap in time between the last real observation and the start of our simulated observations, and the resulting sensitivities after adding a further 3 yr of new data at three different values of observing cadence.

Star HD	RMS m s^{-1}	EEID (au)	L23 sensitivity ($M_\oplus$)	Time gap (d)	5d	10d	20d
					Detection limit at EEID ($M_\oplus$)		
693	3.08	1.731	403.8	4236	92.5	162.9	227.6
1581	4.60	1.123	9.7	2028	22.1	24.5	26.6
2151	2.75	1.864	44.8	2654	89.6	68.6	81.8
4628	2.74	0.548	13.4	2034	16.7	17.2	19.5
7570	6.30	1.415	88	2652	94.0	122.9	94.6
14412	4.31	0.668	24.5	1296	35.6	33.6	46.9
20766	10.28	0.891	81	2651	113.3	163.0	154.4
20794	1.62	0.809	7.4	787	35.5	42.9	36.5
20807	4.82	1.008	21.4	1229	42.9	49.7	43.1
23249	4.22	1.778	27.6	1921	56.1	50.0	59.1
26965	1.92	0.658	11.8	1078	18.6	18.4	18.6
30495	14.02	0.983	393.6	1951	256.4	574.0	823.5
32147	2.38	0.539	9.1	786	11.7	10.6	11.2
38858	3.75	0.909	17.2	1983	40.8	37.8	40.2
39091	4.35	1.238	51.1	1115	33.9	38.5	30.5
50281	7.03	0.469	55.9	818	44.1	56.6	82.9
69830	1.29	0.779	7.4	1887	10.1	10.0	8.8
72673	3.75	0.635	9.6	1851	17.9	19.1	18.3
75732	4.62	0.797	35	1971	38.4	47.2	37.7
76151	9.53	0.985	17394	3744	135.5	219.9	374.0
100623	7.05	0.608	19.2	1111	32.9	26.6	36.9
102365	3.20	0.919	13.6	1473	15.0	17.0	13.5
102870	5.00	1.941	201.6	1396	782.0	4103	4113
114613	5.14	2.055	53.6	640	95.9	97.3	103.4
115617	3.27	0.914	15.2	2027	21.8	18.9	20.6
131977	6.24	0.472	171.2	5108	76.6	129.6	218.3
136352	3.86	1.014	9.7	2031	15.2	16.9	18.9
140901	11.88	0.904	95.3	1078	134.5	203.8	177.3
146233	9.16	1.046	17.8	1790	132.1	162.7	159.6
149661	8.51	0.680	110	2768	136.8	155.0	244.0
156026	3.96	0.397	13.5	668	20.4	23.7	25.2
160691	3.82	1.378	27.7	2743	40.6	45.9	46.4
190248	3.83	1.118	10.9	2338	17.0	17.6	16.1
192310	2.78	0.636	7.8	1901	10.8	9.5	10.2
207129	5.63	1.099	35.8	1256	54.2	59.6	61.0
216803	14.00	0.443	176.5	2438	106.5	85.9	133.1

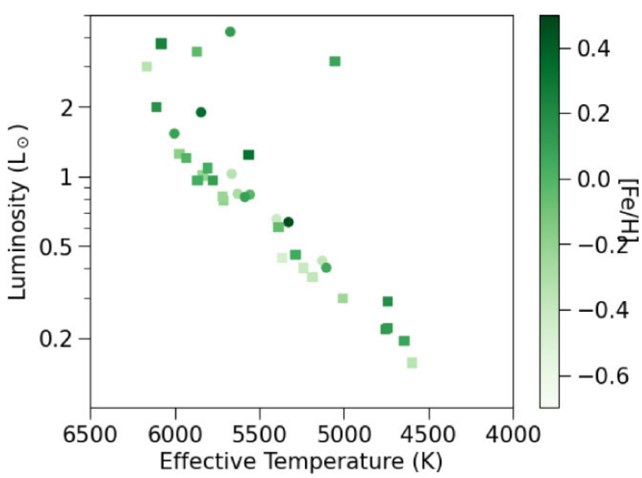

Figure 1. Hertzsprung–Russell diagram for the 36 stars in our sample. Stellar metallicity is represented by the colour bar, and the circular points indicate those stars that are currently known to harbour planets.

Intuitively, one would expect a faster cadence (5 d) to deliver better sensitivities than slower (20 d). This is generally true, but we also see some stars where the detection limit is relatively insensitive to the observing cadence. We interpret this as a ‘floor’: new data at the moderate (4 m s^{-1}) single-measurement precision in the presence of stellar noise do little to improve the overall sensitivity to lower mass planets. These are stars for which the existing data are already quite good, so further improvement must be obtained by other means, e.g. with higher precision instruments and/or a detailed treatment of stellar activity noise.

Table 1 also features some targets where, perversely, adding 3 yr of new data delivers a worse sensitivity result than that of L23. We attribute this counterintuitive outcome to some pathologies of data sampling; in particular, the long time gap between the old and new observations can introduce strong aliases in the log-likelihood periodograms that `RVSearch` uses to identify injected periodicities. We thus next performed the same tests with 3 and 6 yr of only new simulated data, in an effort to mitigate the deleterious effects of haphazard sampling and data inhomogeneities. Those results are given in Table 2. Here we see that the 3-yr results are again

Table 2. RV detection limit at the EEID considering *only* 3 and 6 yr of new data at three different values of observing cadence. The 13 stars in boldface are those for which this strategy improves on the results of L23.

		Detection limit at EEID ($M_\oplus$)						
Star	EEID	L23 sensitivity		3 yr			6 yr	
HD	au	$M_\oplus$	5d	10d	20d	5d	10d	20d
693	1.731	403.8	148.0	138.2	521.1	61.1	70.6	150.5
2151	1.864	44.8	190.5	285.8	578.6	24.2	58.7	171.1
7570	1.415	88.0	136.3	202.6	265.6	49.8	104.7	172.1
14412	0.668	24.5	26.4	59.8	133.0	20.5	44.9	71.9
20766	0.891	81.0	148.6	206.0	335.3	61.6	170.2	205.4
30495	0.983	393.6	156.4	324.2	623.1	60.6	120.9	295.6
39091	1.238	51.1	69.4	101.2	122.4	45.7	66.7	135.1
50281	0.469	55.9	35.3	64.3	178.0	34.0	51.8	89.2
76151	0.985	17394	83.9	172.0	393.8	60.6	78.6	180.5
102870	1.941	201.6	249.7	258.8	894.9	55.0	74.7	180.2
131977	0.472	171.2	42.9	109.8	96.0	19.7	34.1	66.4
140901	0.904	95.3	83.4	198.4	446.6	72.0	76.5	219.1
149661	0.680	110.0	66.9	118.4	222.0	41.1	94.5	135.8
1581	1.123	9.7	49.7	150.5	176.7	27.7	55.2	128.2
4628	0.548	13.4	40.9	67.8	114.5	18.0	27.1	59.5
20794	0.809	7.4	26.8	84.2	173.7	18.8	50.0	97.7
20807	1.008	21.4	40.6	127.9	330.1	27.4	66.6	99.6
23249	1.778	27.6	157.2	470.7	280.0	50.1	98.4	93.6
26965	0.658	11.8	44.7	74.6	148.0	22.9	30.4	44.9
32147	0.539	9.1	20.2	60.8	86.8	25.0	24.0	45.4
38858	0.909	17.2	54.5	84.0	192.5	28.3	74.6	86.4
69830	0.779	7.4	37.8	58.4	85.8	28.1	40.8	89.1
72673	0.635	9.6	38.2	35.3	120.6	20.8	40.1	78.4
75732	0.797	35.0	36.1	78.7	144.1	45.2	50.0	74.3
100623	0.608	19.2	65.3	68.4	196.2	44.3	61.8	96.7
102365	0.919	13.6	53.9	78.7	236.9	25.6	42.2	81.0
114613	2.055	53.6	479.5	77.8	692.8	176.1	426.8	526.8
115617	0.914	15.2	40.5	58.9	160.0	32.1	44.8	81.0
136352	1.014	9.7	49.9	72.2	121.9	29.6	49.4	20.3
146233	1.046	17.8	40.9	69.5	201.9	38.7	45.4	120.7
156026	0.397	13.5	20.2	31.0	79.9	17.6	28.7	56.2
160691	1.378	27.7	33.5	101.6	229.3	49.4	58.8	111.5
190248	1.118	10.9	51.8	130.1	209.0	35.9	80.7	99.0
192310	0.636	7.8	38.1	66.1	116.7	24.6	37.8	58.2
207129	1.099	35.8	62.3	131.5	232.2	55.2	66.6	122.9
216803	0.443	176.5	86.2	81.0	265.1	60.3	89.5	158.5

sometimes worse than L23 when the EEID is at a distance such that 3 yr of observations cover not much more than a single orbital period. For those situations, we would expect the sensitivity to fall off dramatically as the orbital period of interest approaches the data span. Hence, we hereafter consider and discuss only the 6-yr simulations to obviate this artefact. A cumulative distribution plot of the 6-yr simulations is shown in Fig. 2, comparing these results to those of L23 over the entire sample.

We next identify a subset, 13 of these 36 stars marked in bold in Table 2, where the advantage of cadence outweighs the shortcoming of only moderate single-measurement precision: those for which small, flexibly scheduled telescopes can make an improvement in detection sensitivity. While the ultimate goal is to clear these systems of disruptive giants, to Neptune mass and below, we recognize the intrinsic limitation of the moderate-precision facilities considered herein. As a figure of merit, a Neptune-mass planet ($15 M_\oplus$) at 1 au imposes a radial-velocity signal of amplitude $K \sim 1.5\,\mathrm{m\,s^{-1}}$ for a Solar-mass star. Simply put, this is not possible for the MINERVA-like data we have simulated here. A Saturn-mass planet ($95 M_\oplus$) would produce an RV signal of $K \sim 9\,\mathrm{m\,s^{-1}}$. Fig. 3 shows the results

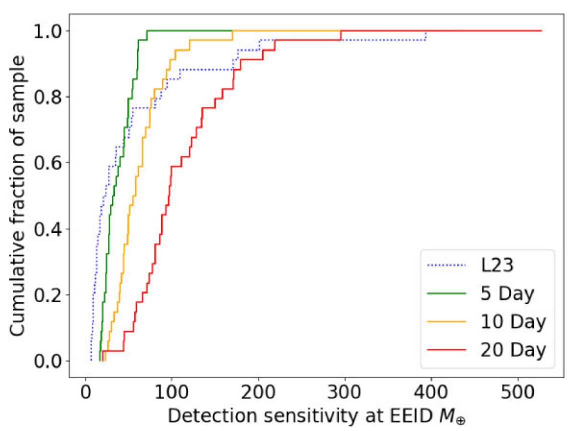

Figure 2. Cumulative distribution function of all simulation results, considering 6 yr of new RV data only. Since these results only used new RV data and not the legacy data analysed in L23, the lower cadence (20 and 10 d) scenarios sometimes performed worse than in L23.

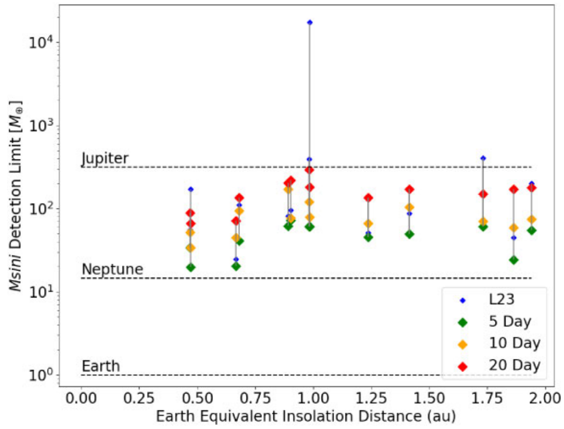

Figure 3. Detailed results for the 13 stars where 6 yr of moderate-precision monitoring significantly improves the detection sensitivity at the EEID.

of our 6-yr simulations compared with those of L23 for these 13 stars where this sort of higher cadence, lower precision data can fill a valuable niche. The median EEID sensitivity for these stars in L23 was 95.3 $M_\oplus$, improving to 74.7$M_\oplus$(i.e. a 22 per cent improvement) after a 6-yr MINERVA-Australis observing campaign with 10-d cadence. Increasing to a 5-d cadence gets us 49.8$M_\oplus$, a 48 per cent improvement. For these stars, then, moderate-precision facilities can make a valuable contribution to HWO precursor science by bringing down the sensitivity limits for the least well-characterized stars on the likely target list.

4 CONCLUSIONS

In this work, we have shown that small, flexibly scheduled, moderate-precision RV facilities can make important contributions to the necessary precursor science for HWO target optimization. These facilities include MINERVA-Australis (as detailed in this work), MINERVA-North (Swift et al. 2015; Wilson et al. 2019), and the 1m Stellar Observations Network Group telescopes (Grundahl et al. 2007, 2017). We have also demonstrated that for some stars, significant improvement in the detection sensitivity is possible with e.g. a 5 to 10 d observing cadence; this is eminently feasible for these facilities. We also note that such observations on time-scales of order 3–6 yr would detect, 'for free,' RV trends attributed to giant planets moving on orbits $a \gtrsim 3$ au. Such cold giants may not in and of themselves disqualify potential HWO targets (except those on problematically eccentric orbits), but their presence (or absence) is a key data point in terms of understanding the overall system architecture, dynamical history, and volatile delivery regime experienced by any inner planets (e.g. Horner et al. 2020; Childs, Martin & Livio 2022; Ogihara, Genda & Sekine 2023; Kane & Wittenmyer 2024).

Recent work by Harada et al. (2024b) performed a similar analysis as L23, focusing on 90 potential HWO target stars including Northern targets (Harada et al. 2024a; Mamajek & Stapelfeldt 2024) observed with HIRES and/or HARPS. They found a median sensitivity of $M_\mathrm{p} \sin i \simeq 66\,\mathrm{M}_\oplus$ in the middle habitable zones, with a similarly large dispersion as L23. They also found that the legacy HARPS and HIRES data were biased towards cooler GKM stars, motivating the continued importance of moderate-precision RV facilities in studying hotter stars that are less amenable to EPRV observations. That work again highlights the need for further concentrated observational efforts for some heretofore neglected stars.

This work and that of L23 and Harada et al. (2024b) all point to the necessity to better understand the cohort of nearby Solar-type stars that will be the best targets for future imaging missions. Given that the occurrence rate of giant planets ($M > 0.3M_\mathrm{Jup}$) steeply increases near 1 au, from ∼1 per cent to ∼10 per cent (Wittenmyer et al. 2020), it is wise to characterize the potential entourage of planets that may be accompanying these stars. The best time to start was 20 yr ago; the second best time is now.

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We respectfully acknowledge the traditional custodians of all lands throughout Australia, and recognize their continued cultural and spiritual connection to the land, waterways, cosmos, and community. We pay our deepest respects to all Elders, ancestors, and descendants of the Giabal, Jarowair, and Kambuwal nations, upon whose lands the MINERVA-Australis facility at Mt Kent is situated.

DATA AVAILABILITY

The data underlying this article are available on request to the corresponding author.

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