The Pan-Pacific Planet Search III: Five companions orbiting giant stars

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ABSTRACT

We report a new giant planet orbiting the K giant HD 155233, as well as four stellar-mass companions from the Pan-Pacific Planet Search, a southern hemisphere radial velocity survey for planets orbiting nearby giants and subgiants. We also present updated velocities and a refined orbit for HD 47205b (7 CMa b), the first planet discovered by this survey. HD 155233b has a period of 885±63 days, eccentricity $e = 0.03\pm0.20$, and $m \sin i = 2.0\pm0.5 \ M_\text{Jup}$. The stellar-mass companions range in $m \sin i$ from 0.066 $M_\odot$ to 0.33 $M_\odot$. Whilst HD 104358B falls slightly below the traditional hydrogen-burning mass limit, and is hence a brown dwarf candidate, we estimate only a 50\% a priori probability of a truly substellar mass.

Key words: planetary systems, stars: giants, techniques: radial velocity

1 INTRODUCTION

Radial velocity planet search efforts have been underway for more than 20 years, discovering hundreds of new planetary companions. However, brown-dwarf and stellar-mass companions tend to be largely ignored in these surveys: limited telescope time means that targets showing large-amplitude variations ($>500 \text{ m s}^{-1}$) are usually dropped from the observing queue. Only limited results on such massive companions have been published (Patel et al. 2007), with many objects featuring incomplete orbits. However, such objects remain valuable for exploring the lower end of the mass function and the properties of stellar systems in the Solar neighbourhood. The observed deficit of companions between 13-80 $M_{\text{Jup}}$ is known as the “brown dwarf desert” (Marcy & Butler 2000; Mazeh et al. 2003), and became evident in the earliest days of radial velocity planet searches (Campbell et al. 1988; Murdoch et al. 1993). A comprehensive, self-consistent study by Grether & Lineweaver (2006) confirmed the presence of a “valley” in the brown-dwarf mass range at $M = 31^{+18}_{-15} \ M_{\text{Jup}}$. Stellar companions are also not to be ignored, since any binary system with a well-characterised orbit is useful for a range of follow-up science. Most obviously, a precisely-determined binary orbit permits the search for additional Doppler velocity signals due to planets orbiting one or both stars. Binary systems compose ~50\% of nearby star systems (Duquennoy & Mayor 1991; Raghavan et al. 2010), yet are hosts to only ~5\% of known extrasolar planets. The mechanisms and outcomes of planet formation in close binary systems remain significant questions virtually unexplored by observations.

At the 3.9m Anglo-Australian Telescope (AAT), we carried out a 5-year survey for planets orbiting intermediate-mass evolved stars in an effort to characterise the dependence of planetary system properties on stellar mass (Wittenmyer et al. 2011; Reffert et al. 2015). The initial sample was selected according to these criteria: $1.0 < (B - V) < 1.2$, $1.8 < M_V < 3.0$, and $V < 8.0$. Of those stars meeting these criteria, 18 were discarded as binaries by their Hipparcos multiple systems flag. From the 167-star Pan-Pacific Planet Search (PPPS) sample, 17 targets turned out to be double-lined spectroscopic binaries (SB2s – Table I). Since the Doppler velocity technique used here assumes only a single set of spectral lines, we were unable to derive velocities for these binaries and they were dropped from the program as soon as they were identified as

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such. We note that it has recently become possible to modify planet-search Doppler codes to obtain precise velocities for SB2s, by including the secondary star’s spectrum in the modelling process if the flux ratio is known. This novel approach is now being applied to the Alpha Centauri binary system (Bergemann et al. 2013; Endl et al. 2013).

A further 31 stars in the PPPS sample show large-amplitude velocity variations or long-term trends, which indicate stellar-mass companions. This yields a first-order binary fraction of 48/167=29%, for a sample which was initially selected to avoid suspected binaries (Wittenmyer et al. 2011). As is common in planet-search programs, these stars were deprecated in observing priority and so the orbits of these massive companions cannot be constrained. However, four stars host shorter-period companions and received enough observations to reliably determine the orbital solutions. Here, we present the velocity data and orbital solutions for stellar-mass companions orbiting HD 34851, HD 94386, HD 104358, and HD 188981. We also present new data and a refined orbital solution for the giant planet orbiting 7 CMa (HD 47205). Section 2 briefly describes the observational data and gives the stellar parameters. In Section 3, we describe the orbit-fitting process. Section 4 gives the companion parameters and our conclusions.

2 AAT OBSERVATIONS AND STELLAR PROPERTIES

The PPPS used the UCLES echelle spectrograph (Diego et al. 1991) at the AAT to obtain high-resolution spectra, with an observing procedure identical to that used by the 16-year Anglo-Australian Planet Search (AAPS). UCLES uses a 1-arcsecond slit to deliver a resolving power of $R \sim 45,000$. An iodine absorption cell, temperature-controlled at 60+0.1°C, is placed in the light path. The iodine cell imprints a forest of narrow absorption lines from 5000 to 6200 Å, allowing simultaneous calibration of instrumental drifts as well as a precise wavelength reference (Valenti et al. 1993; Butler et al. 1996). Precise Doppler velocities are derived using the well-established PSF modelling techniques described in Butler et al. (1996). The result is a velocity with a zero-point relative to the stellar template: a high S/N spectrum obtained without the iodine cell at $R \sim 60,000$. The internal uncertainty estimate includes the effects of photon-counting uncertainties, residual errors in the spectrograph PSF model, and variation in the underlying spectrum between the iodine-free template and epoch spectra observed through the iodine cell. A summary of the observations is given in Table 9 and the radial velocities are given in Tables 3–8.

For each new star discussed in this work, we have used our iodine-free template spectrum ($R \sim 60,000$, S/N~150-250) to derive spectroscopic stellar parameters. The same techniques were used in Wittenmyer et al. (2011) and Wittenmyer et al. (2013) for HD 47205 and HD 121056, respectively. In brief, the iron abundance [Fe/H] was determined from the equivalent widths of ~30 unblended Fe lines, and the LTE model atmospheres adopted in this work were interpolated from the ODNEW grid of ATLAS9 (Castelli & Kurucz 2004). The effective temperature ($T_{\text{eff}}$) and bolometric correction (BC) were derived from the colour index $B-V$ and the estimated metallicity using the empirical calibration of Alonso et al. (1999, 2001). Since the colour-$T_{\text{eff}}$ method is not extinction-free, we corrected for reddening using $E(B-V)$ (Schlegel et al. 1998). The stellar mass and age were estimated from the interpolation of Yonsei-Yale ($Y^2$) stellar evolution tracks (Yi et al. 2001). The resulting stellar masses were adopted for calculating the planet masses. Complete stellar parameters from this analysis are given in Table 9.

3 ORBIT FITTING AND COMPANION PARAMETERS

As shown in Table 2 many of the stars considered here received fewer observations than is typical or desired for planet-search efforts. However, the signals in our data are large enough as to be unambiguous, particularly for the stellar-mass companions. We first used a genetic algorithm to search a wide range of orbital periods, running for 10,000 iterations (about $10^6$ possible configurations). This approach has been used in our previous work on systems for which data are sparse and/or poorly sampled (e.g. Tinney et al. 2011; Wittenmyer et al. 2011, 2013). In all cases, convergence occurred rapidly, a hallmark of a genuine signal. Again as in our previous work, we then used the best solution from the genetic algorithm as a starting point for the generalized least-squares program GaussFit (Jefferys et al. 1988), here used to solve a Keplerian radial velocity orbit model. Finally, we estimated the parameter uncertainties using the bootstrap routine within Systemic 2 (Meschiari et al. 2009) on 10,000 synthetic data set realisations. The results are given in Table 10.

4 RESULTS

We have continued to observe HD 47205 in the four years since the discovery of HD 47205b (Wittenmyer et al. 2011). We have added 6 new epochs, extending the baseline by 964 days, a factor of two longer than reported in the discovery work. The updated orbital solution given in Table 10 is significantly more precise, and has an rms of only 6.5 m s$^{-1}$, further strengthening the case for the planet’s presence and apparent solitla. Notably, the orbital period is now slightly longer (796d compared to 763d); other parameters remain within 1σ of their originally-reported values. No residual trends or periodicities are evident, though of course very low-mass planets could remain undetected with our radial velocity precision and cadence (e.g. Wittenmyer et al. 2009; Swift 2015).

4.1 A giant planet orbiting HD 155233

We have obtained 21 radial velocity measurements of HD 155233, indicating a linear trend and a periodic signal, though with significant jitter. A simple linear fit to our data yields a residual rms scatter of 24.2 m s$^{-1}$ and $\chi^2_{\nu} = 5.23$. By comparison, a planet-only model (no trend) gives an rms of 19.1 m s$^{-1}$ and $\chi^2_{\nu} = 3.65$. We
fit a planet+trend model, which indicates a planetary companion with $P=885 \pm 63$ days, $e = 0.03 \pm 0.20$, and $m \sin i = 2.0 \pm 0.5 \, M_{\text{Jup}}$ (Table 10). That model has a residual rms of $11.0 \, \text{m s}^{-1}$ and $\chi^2_\text{nu} = 1.44$, with a linear trend of $15.4 \pm 6.5 \, \text{m s}^{-1} \, \text{yr}^{-1}$. Feng et al. (2012) gave a discussion on estimating minimum companion masses from velocity data with such trends when no curvature is evident. Using their Equation 1, which assumes an “unlucky” seeing an orbital period $P \sim 1.25 T_{\text{obs}}$ (=4.9 yr) and $e \sim 0.5$, we obtain a minimum mass of $2.0 \, M_{\text{Jup}}$ for the distant outer body. The possibility also exists that the velocity signals of the planet and/or the long-term trend originate from a magnetic activity cycle; however, the velocity amplitudes so induced are less than $10 \, \text{m s}^{-1}$ (e.g. Robertson et al. 2013, 2015; Fulton et al. 2013).

There remains substantial uncertainty in the fit due to the best-fit $10.65 \, \text{m s}^{-1}$ velocity jitter for the host star. The residuals to the single planet + trend fit show no coherent periodicity, leading us to conclude that the residual scatter is best explained by stellar noise, as is common for giants (Hekker et al. 2008; Jones et al. 2013). We also note that HD 155233 has a relatively high projected rotational velocity $v \sin i = 4.4 \pm 1.0 \, \text{km s}^{-1}$; this is similar to HD 34851 and HD 104358, which have residual scatters of $34.6 \, \text{m s}^{-1}$ and $15.3 \, \text{m s}^{-1}$, respectively (Table 10). The data and model fit are shown in Figure 1.

To check whether the observed velocity variations could be due to intrinsic stellar processes, we examined the All-Sky Automated Survey (ASAS) V-band photometric data for HD 155233 (Pomimanski & Maciejewski 2004). A total of 222 epochs were obtained from the ASAS All Star Catalog. After removing 52 outliers, 218 points remained, and their generalised Lomb-Scargle periodogram (Zechmeister & Kürster 2009) is shown in Figure 2. No periodicities of interest are evident in data spanning 7.4 years. Furthermore, we can use the projected rotational velocity $v \sin i$ and the radius estimate from Table 9 to estimate a maximum rotation period of 58 days, well away from the planetary orbital period of 885 days.

### 4.2 Four stellar-mass companions

For HD 34851, the rms about the fit is $34.6 \, \text{m s}^{-1}$, which is unusually large given that the typical velocity jitter of evolved stars targeted by the PPPS and other surveys is $5-20 \, \text{m s}^{-1}$ (Sato et al. 2005; Johnson et al. 2010a; Jones et al. 2011). The companion has a minimum mass of $345 \, M_{\text{Jup}}$ or $0.33 \, M_\odot$, corresponding to a mid-M dwarf. The Keplerian orbit fit for HD 34851B and the other three stellar-mass companions are shown in Figure 3.

Nearly two orbital cycles of data result in a well-constrained fit for the massive companion orbiting HD 94386, with an rms of only $5.7 \, \text{m s}^{-1}$ (Figure 4). The companion has $m \sin i = 112.5 \, M_{\text{Jup}}$ ($= 0.11 \, M_\odot$) corresponding to a late M dwarf. HD 104358 hosts a brown dwarf candidate, with $m \sin i = 69.3 \pm 1.9 \, M_{\text{Jup}}$ ($= 0.066 \, M_\odot$). The probability of an inclination small enough to give a stellar-mass companion ($> 80 \, M_{\text{Jup}}$) is then 50%. The rms about the fit is $15.3 \, \text{m s}^{-1}$; removal of the 4σ outlier at BJD 2455757 gives the same parameters for the companion, though with slightly larger bootstrap uncertainties due to the already-limited amount of data available. Hence we have retained all our data for the fitting. The data and model fit are plotted in Figure 4.

HD 188981 is a known spectroscopic binary (Salzer & Beavers 1985; Pourbaix et al. 2004) that escaped the elimination of binaries in our initial target selection process. Our iodine-cell velocity data have resulted in an extremely precise orbital solution for this system (Table 10 and Figure 4). We obtain $m \sin i = 220.9 \, M_{\text{Jup}}$ ($= 0.211 \, M_\odot$). Salzer & Beavers (1985) remarked that the host star is ~0.1 mag bluer than expected for a solitary K1 giant, and postulated that the stellar companion was an F-type dwarf. An F dwarf companion of $1.2 \, M_\odot$ would require a binary orbital inclination of only $i \sim 10^\circ$. While the spectral lines from such a star would have remained hidden in the data of Salzer & Beavers (1983), the higher resolution and S/N of the AAT data should have produced a double-lined spectrum, which would have caused the planet-search Doppler analysis to fail as for those stars in Table 4. We simulated the effect of a second light at various levels of contamination. These tests revealed that for a 10% flux contribution from a secondary set of stellar lines, the Doppler code still produces reasonable though somewhat less precise velocities. From Table 9 the luminosity of the primary is $12.3 \pm 0.9 \, L_\odot$, and hence a 10% contamination from the secondary would give $L \lesssim 1.2 \, L_\odot$, corresponding to $\sim 0.5 \, M_\odot$ by the main-sequence mass-luminosity relation. In other words, the lack of a detectable second set of stellar lines at best disfavours very high-mass companions.

### 5 DISCUSSION AND CONCLUSIONS

Radial velocity observations of binaries are important in order to determine the masses, arguably the most fundamental parameter of stars. When combined with astrometric observations and parallax measurements, the true masses of the stars can be determined. With the highly anticipated results from the GAIA mission (Perryman et al. 2001), it is important to have radial velocity observations of binary stars in hand as well.

Raghavan et al. (2010) presented a comprehensive study of stellar multiplicity for Sun-like stars in the solar neighbourhood, but their sample did not include evolved stars, and it remains unclear how the orbital parameters of a binary system are affected by a component’s post-main-sequence evolution (but see Vera et al. 2011 and Mustill et al. 2012 for discussion of the effect on planets in such systems). The stellar mass-ratio distribution prefers equal-mass pairs (Raghavan et al. 2010), but none of the four systems presented here has a mass ratio close to unity. However, this is a selection effect, as stars with a mass ratio close to unity would fall into the category of SB2s, which were dropped from this survey. Because suspected binaries were initially avoided in the sample selection (Wittenmyer et al. 2011).
any newly discovered binaries will help estimate the number of binaries that have been missed in past estimations of the binary fraction (Duquennoy & Mayor 1991, Raghavan et al. 2010), or verify their incompleteness corrections, respectively. The aforementioned selection biases also make it difficult to compare the binary fraction for evolved stars to that of main sequence stars.

The planet HD 155233b has been independently detected by the EXPRESS survey of M. Jones et al. (2015, in prep). This planet joins the ranks of “typical” planets found to orbit intermediate-mass stars. Such planets are characterised by super-Jupiter masses and semimajor axes beyond ~1 AU (Bowler et al. 2010, Johnson et al. 2010b). For intermediate-mass giants such as HD 155233, giant planet occurrence has been shown to correlate positively with host-star mass (Johnson et al. 2010a). HD 155233 is slightly metallic in (Fe/H) = 0.10 ± 0.07, again consistent with the overall trend of increasing giant planet occurrence rate with host-star metallicity (Reffert et al. 2015).

Hipparcos astrometry has been used for some massive companions to place limits on the system inclination, and hence the true masses (e.g. Kürster et al. 2005, Reffert & Quirrenbach 2011, Wittenmyer et al. 2009a). However, for the stars considered here, the distances are simply too large to make this approach useful at present. Using the distances and the semimajor axes (Table 10), we estimate maximum angular separations as follows: HD 34851B – 0.044 mas; HD 94386B – 0.48 mas; HD 104358B – 0.11 mas; HD 155233B – 0.48 mas; HD 188981B – 0.11 mas. The greater astrometric precision of GAIA, of order 10 microarcsec for these bright targets (Perryman et al. 2014), will shed more light on these binary systems.

Since the host stars are old, we are able to investigate whether our newly found large companions are detectable via direct imaging with the latest generation of instruments (GPI & SPHERE) by assuming their luminosities to be similar to that of field main sequence dwarfs. Assuming that the system is edge on (i.e. taking the minimum mass) we could use observed absolute magnitudes as a function of spectral type (collated and plotted in Kirkpatrick et al. 2012) to estimate the contrast ratio of each of our companions and their hosts. By also assuming we are able to observe at the optimal time (maximum projected separation) we use the known distance to the systems to calculate their maximum on-sky separation. We find that although the contrast ratios of these systems are not very large, the very small angular separations cause most of these systems to be inaccessible via direct imaging. Only HD 94386B is potentially detectable via observations using Non-Redundant Masking in conjunction with either SPHERE or GPI. Although HD 155233B’s projected separation is possibly feasible with Non-Redundant Masking, it is a giant planet in an old system, and therefore too faint to be detected with these types of observations (Table 11).

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Table 1. Double-lined spectroscopic binaries in the PPPS sample

| HD    | HIP   |
|-------|-------|
| 749   | 944   |
| 5873  | 4696  |
| 5877  | 4618  |
| 20035 | 14868 |
| 31860 | 23061 |
| 46122 | 46159 |
| 98579 | 55374 |
| 136905| 73525 |
| 137164| 75689 |
| 142384| 78027 |
| 153438| 83224 |
| 176650| 93383 |
| 176794| 94208 |
| 204203| 105953|

Table 2. Summary of observations

| Star   | N_{obs} | Span (days) | Mean uncertainty (m s^{-1}) |
|--------|---------|-------------|-----------------------------|
| HD 34851 | 9       | 1278        | 6.0                         |
| HD 47205 | 27      | 1881        | 1.1                         |
| HD 94386 | 14      | 1512        | 1.8                         |
| HD 104358 | 21     | 1426        | 2.1                         |
| HD 155233 | 21     | 1426        | 2.1                         |
| HD 188981 | 16     | 1453        | 2.3                         |

Table 3. AAT radial velocities for HD 34851

| BJD-2400000 | Velocity (m s^{-1}) | Uncertainty (m s^{-1}) |
|-------------|---------------------|------------------------|
| 55251.94376 | 1418.0              | 3.6                    |
| 55525.13661 | -15566.3            | 7.3                    |
| 55580.07072 | -12641.7            | 6.8                    |
| 55602.00949 | 334.7               | 3.5                    |
| 55879.17147 | -1270.4             | 6.7                    |
| 55906.06875 | -8285.2             | 6.2                    |
| 55969.98892 | -6099.1             | 6.8                    |
| 56375.89323 | 0.0                 | 6.4                    |
| 56529.27818 | -8020.4             | 6.4                    |
Table 4. AAT radial velocities for HD 47205

| BJD-2400000 | Velocity (m s\(^{-1}\)) | Uncertainty (m s\(^{-1}\)) |
|-------------|--------------------------|-----------------------------|
| 54866.09965 | 28.1                     | 0.8                         |
| 54866.94000 | 18.4                     | 1.3                         |
| 54867.91576 | 26.6                     | 1.3                         |
| 54869.08575 | 20.8                     | 1.0                         |
| 54871.03478 | 30.4                     | 1.3                         |
| 55140.18899 | -29.1                    | 0.9                         |
| 55227.06602 | -18.4                    | 1.3                         |
| 55317.85835 | 0.8                      | 0.6                         |
| 55525.22369 | 34.4                     | 1.4                         |
| 55526.21028 | 38.8                     | 0.9                         |
| 55581.09317 | 43.3                     | 1.1                         |
| 55601.00002 | 36.9                     | 0.9                         |
| 55706.84304 | -5.3                     | 1.0                         |
| 55783.30462 | -25.6                    | 1.0                         |
| 55879.26442 | -46.9                    | 1.1                         |
| 55880.21953 | -38.9                    | 0.9                         |
| 55906.04456 | -38.4                    | 1.1                         |
| 55969.96686 | -37.2                    | 0.8                         |
| 55994.95994 | -20.4                    | 0.9                         |
| 56051.84618 | 1.6                      | 1.4                         |
| 56059.86471 | -4.0                     | 1.6                         |
| 56343.99185 | 47.7                     | 0.9                         |
| 56374.88203 | 55.7                     | 1.2                         |
| 56377.97935 | 54.8                     | 0.9                         |
| 56526.27125 | -4.2                     | 1.0                         |
| 56685.97593 | -27.9                    | 0.9                         |
| 56747.92127 | -22.7                    | 1.3                         |

Table 5. AAT radial velocities for HD 94386

| BJD-2400000 | Velocity (m s\(^{-1}\)) | Uncertainty (m s\(^{-1}\)) |
|-------------|--------------------------|-----------------------------|
| 54866.16823 | -1122.3                  | 1.5                         |
| 55227.08417 | -386.9                   | 1.2                         |
| 55380.81884 | 2145.4                   | 1.2                         |
| 55580.16602 | 490.7                    | 2.0                         |
| 55601.19789 | 15.7                     | 1.8                         |
| 55602.15229 | -4.4                     | 1.6                         |
| 55706.90383 | -1032.6                  | 1.3                         |
| 55970.13115 | -664.4                   | 1.1                         |
| 55994.09656 | -556.4                   | 2.6                         |
| 56059.90490 | -237.2                   | 2.5                         |
| 56088.91084 | -69.2                    | 1.9                         |
| 56345.09758 | 2755.5                   | 2.6                         |
| 56375.98219 | 3125.8                   | 1.6                         |
| 56378.02772 | 3162.6                   | 1.6                         |

Table 6. AAT radial velocities for HD 104358

| BJD-2400000 | Velocity (m s\(^{-1}\)) | Uncertainty (m s\(^{-1}\)) |
|-------------|--------------------------|-----------------------------|
| 54867.22642 | -2349.3                  | 2.0                         |
| 55706.89202 | -2436.0                  | 1.9                         |
| 55757.87488 | -745.0                   | 5.4                         |
| 55970.17721 | -2479.1                  | 1.9                         |
| 55994.10810 | -2265.1                  | 4.2                         |
| 56059.94668 | -66.3                    | 2.9                         |
| 56086.95956 | 543.4                    | 2.2                         |
| 56088.92816 | 596.7                    | 2.2                         |
| 56344.12214 | 0.0                      | 3.7                         |
| 56377.03081 | 683.3                    | 2.4                         |
| 56378.03502 | 708.8                    | 2.3                         |
| 56747.00059 | 609.4                    | 2.0                         |
Table 7. AAT radial velocities for HD 155233

| BJD-2400000 | Velocity (m s\(^{-1}\)) | Uncertainty (m s\(^{-1}\)) |
|-------------|--------------------------|----------------------------|
| 55319.20751 | -76.0                    | 2.1                        |
| 55382.09355 | -68.9                    | 1.6                        |
| 55602.27053 | -10.5                    | 2.8                        |
| 55707.20272 | 12.8                     | 1.8                        |
| 55757.95688 | 3.4                      | 2.5                        |
| 55760.09094 | 24.8                     | 2.0                        |
| 55841.92832 | 11.7                     | 2.9                        |
| 55970.27601 | -12.2                    | 1.4                        |
| 55994.24764 | 9.4                      | 2.1                        |
| 56052.14878 | -48.3                    | 2.4                        |
| 56089.07966 | -16.1                    | 1.8                        |
| 56134.99850 | -29.0                    | 1.9                        |
| 56344.27771 | -12.7                    | 1.6                        |
| 56375.25095 | -0.2                     | 2.4                        |
| 56376.23958 | 11.5                     | 1.6                        |
| 56400.13922 | -3.8                     | 1.6                        |
| 56470.07735 | 2.9                      | 3.8                        |
| 56494.98115 | 22.1                     | 1.6                        |
| 56525.93237 | 37.0                     | 1.8                        |
| 56529.98008 | 18.1                     | 2.3                        |
| 56745.23184 | 47.2                     | 1.2                        |

Table 8. AAT radial velocities for HD 188981

| BJD-2400000 | Velocity (m s\(^{-1}\)) | Uncertainty (m s\(^{-1}\)) |
|-------------|--------------------------|----------------------------|
| 55074.06452 | -399.2                   | 1.9                        |
| 55318.32115 | -8926.5                  | 2.5                        |
| 55455.97154 | 7190.8                   | 1.9                        |
| 55670.31992 | 0.0                      | 1.4                        |
| 55707.29018 | 6601.1                   | 1.5                        |
| 55760.04921 | -8824.9                  | 6.1                        |
| 55842.90819 | 6847.6                   | 2.0                        |
| 55994.29530 | -3545.9                  | 2.2                        |
| 56052.20653 | -1600.1                  | 1.7                        |
| 56060.24069 | -4710.4                  | 3.0                        |
| 56089.16329 | 8535.9                   | 1.6                        |
| 56469.14010 | 8110.5                   | 2.7                        |
| 56470.23672 | 7760.3                   | 2.0                        |
| 56494.06543 | -2017.2                  | 1.7                        |
| 56495.07148 | -2425.4                  | 1.8                        |
| 56527.06483 | 7795.5                   | 2.1                        |
Table 9. Stellar Parameters for Host Stars

| Parameter       | HD 34851   | HD 94386   | HD 104358  | HD 155233  | HD 188981  |
|-----------------|-----------|-----------|-----------|-----------|-----------|
| Spec. Type      | K2 III    | K3 IV     | K0 III    | K1 III    | K1 III    |
|                 | 2         | 7         | 8         | 8         | 10        |
| \((B-V)\)       | 1.095     | 1.176     | 1.136     | 1.630±0.008 | 4.051     |
|                 | 3         | 3         | 3         | 4         | 3         |
| \(E(B-V)\)     | 0.0436    | 0.0189    | 0.0367    | 0.0338    | 0.0232    |
|                 | 0.1359    | 0.0590    | 0.1146    | 0.106     | 0.0724    |
| \(A_V\)        | 2.00±0.22 | 1.19±0.19 | 1.27±0.21 | 1.50±0.20 | 1.49±0.20 |
|                 | 7         | 7         | 1         | 1         | 1         |
| Mass (\(M_\odot\)) | 2.00     | 1.19±0.19 | 1.27±0.21 | 1.50±0.20 | 1.49±0.20 |
|                 | 1         | 1         | 1         | 1         | 1         |
| Distance (pc)   | 161.6±12.5| 73.8±4.7  | 150.2±15.8| 75.1±3.3  | 58.9±2.2  |
|                 | 4         | 4         | 4         | 4         | 4         |
| \(V\sin i\) (km s\(^{-1}\)) | 4.6±0.9  | <1        | 4.1±0.5   | 4.4±1.0   | <1        |
|                 | 7         | 7         | 1         | 1         | 1         |
| \([Fe/H]\)     | 0.29±0.14 | 0.19±0.10 | 0.06±0.08 | 0.10±0.07 | 0.18±0.07 |
|                 | 0.08±0.09 | 0.08±0.09 | 0.08±0.09 | 0.08±0.09 | 0.08±0.09 |
| \(T_{\text{eff}}\) (K) | 4787±100  | 4558±100  | 4631±100  | 4845±100  | 4802±100  |
|                 | 4815      | 4436±13   | 4400      | 4436±13   | 4436±13   |
|                 | 5         | 6         | 7         | 7         | 7         |
| \(\log g\)     | 3.05±0.09 | 2.80±0.10 | 2.80±0.12 | 3.21±0.08 | 3.20±0.08 |
|                 | 2.7       | 2.7       | 2.7       | 9         | 9         |
| Luminosity (\(L_\odot\)) | 23.1±3.6 | 20.1±2.6  | 22.7±4.8  | 12.5±1.1  | 12.3±0.9  |
|                 | 7         | 7         | 7         | 7         | 7         |
| Radius (\(R_\odot\)) | 7.0±0.6  | 7.2±0.6  | 7.4±0.8  | 5.03±0.22 | 5.0±0.3   |

References: 1 - This work, 2 - Houk & Cowley (1975), 3 - Perryma et al. (1997), 4 - van Leeuwen (2007), 5 - McDonald et al. (2012), 6 - Bailer-Jones (2011), 7 - Randich et al. (1999), 8 - Houk & Smith-Moore (1988), 9 - Massarotti et al. (2008), 10 - Houk (1982).
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Figure 1. Top panel: AAT data and Keplerian fit for a 2M$_{\text{Jup}}$ planet orbiting HD 155233. A linear trend of 15.4 ± 6.5 m s$^{-1}$ yr$^{-1}$ is included in the fit as a free parameter and is shown. Error bars include 10.65 m s$^{-1}$ of jitter added in quadrature. The rms about this fit is 10.9 m s$^{-1}$; residuals are shown in the bottom panel.

Figure 2. Generalised Lomb-Scargle periodogram of ASAS photometry for HD 155233. A total of 218 epochs spanning 7.4 years yield no significant periodicities. The ±1σ range of the planet’s orbital period is shown as vertical dashed lines (885 ± 63 d).
Table 10. New and updated Keplerian orbital solutions

| Parameter       | HD 34851B       | HD 47205 b | HD 94386 B | HD 104358 B | HD 155233 b | HD 188981 B |
|-----------------|-----------------|------------|------------|-------------|-------------|-------------|
| Period (days)   | 62.30±0.005     | 796.0±7.4  | 925.0±1.0  | 281.1±0.3   | 885±63      | 62.96±0.0008|
| $T_0$ (BJD-2400000) | 55214.7±0.4    | 54093±34   | 54582.1±1.2| 54836.8±4.2 | 55112±412   | 55011.487±0.008|
| Eccentricity    | 0.21±0.01       | 0.22±0.07  | 0.422±0.004| 0.24±0.02   | 0.03±0.20   | 0.4218±0.0007|
| $\omega$ (degrees) | 203±2           | 77±14      | 37.8±0.2   | 146±7       | 95±90       | 274.60±0.06 |
| $K$ (m s$^{-1}$) | 10296±144       | 41.8±2.4   | 2176±12    | 1828±42     | 32.2±8.7    | 8735.6±2.2 |
| $m \sin i$ (M$_{\text{Jup}}$) | 345.4±5.4   | 2.46±0.14  | 112.5±0.5  | 69.3±1.9    | 2.0±0.5     | 220.90±0.08 |
| $a$ (AU)        | 0.4078±0.0003   | 1.93±0.01  | 2.0266±0.0015| 0.9251±0.0007| 2.07±0.10   | 0.369753±0.000005|
| RMS about fit (m s$^{-1}$) | 34.6           | 6.5        | 5.7        | 15.3        | 10.9        | 5.3         |
Figure 3. AAT radial velocity data and Keplerian orbit fit for HD 34851B (top) and residuals to the fit (bottom). The data are phase-folded and two cycles are shown for clarity.

Figure 4. AAT radial velocity data and Keplerian orbit fit for HD 94386B (top) and residuals to the fit (bottom).
Figure 5. AAT radial velocity data and Keplerian orbit fit for HD 104358B (top) and residuals to the fit (bottom).

Figure 6. AAT radial velocity data and Keplerian orbit fit for HD 188981B (top) and residuals to the fit (bottom). The data are phase-folded and two cycles are shown for clarity.
Table 11. Estimated contrast ratios. Companion masses are assumed to be the minimum \( m \sin i \) as given in Table 10 and separations are taken to be the maximum for each object modulo its orbital eccentricity and semimajor axis.

| Host     | SpT  | Companion mass (\( M_\odot \)) | SpT-companion | Separation (AU) | Distance (pc) | Contrast (mag) | On-sky separation (mas) |
|----------|------|---------------------------------|----------------|-----------------|---------------|----------------|-------------------------|
| HD 34851B | K2 III | > 0.33                          | <M4            | < 0.49          | 161.6         | < 3.9          | < 3                     |
| HD 94386B | K3 III | > 0.11                          | <M8/L0         | < 2.88          | 73.8          | < 5.3          | < 39                    |
| HD 104358B | K0 III | > 0.066                         | <L5            | < 1.147         | 150.2         | < 7.4          | < 7.6                   |
| HD 188981B | K1 III | > 0.211                         | <M6            | < 0.52          | 58.9          | < 5.0          | < 8.8                   |
| HD 155233b | K1 III | > 2.13                          | >2.0 \( M_\text{Jup} \) | < 2.13 | 75.1          | ...            | < 28.3                  |