Extra-solar planets around HD 196050, HD 216437 and HD 160691

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ABSTRACT

We report precise Doppler measurements of the stars HD 216437, HD 196050 and HD 160691 obtained with the Anglo-Australian Telescope using the UCLES spectrometer together with an iodine cell as part of the Anglo-Australian Planet Search. Our measurements reveal periodic Keplerian velocity variations that we interpret as evidence for planets in orbit around these solar type stars. HD 216437 has a period of 1294±250 d, a semi-amplitude of 38±4 m s\(^{-1}\) and of an eccentricity of 0.33±0.09. The minimum (M sin i) mass of the companion is 2.1±0.3 M\(_{\text{JUP}}\) and the semi-major axis is 2.4±0.5 au. HD 196050 has a period of 1288±230 d, a semi-amplitude of 54±8 m s\(^{-1}\) and an eccentricity of 0.28±0.15. The minimum mass of the companion is 3.0±0.5 M\(_{\text{JUP}}\) and the semi-major axis is 2.3±0.5 au. We also report further observations of the metal rich planet bearing star HD 160691. Our new solution confirms the previously reported planet and shows a trend indicating a second, longer-period companion. These discoveries add to the growing numbers of midly-eccentric, long-period extra-solar planets around Sun-like stars. As seems to be typical of stars with planets, both stars are metal-rich.
1 INTRODUCTION

Radial velocity programmes have now found around 80 extra-solar planets orbiting stars in the solar neighbourhood. As the time baseline and precision of surveys improve new realms of possible planets are being explored. Discoveries include the first system of multiple planets orbiting a Sun-like star (Butler et al. 1999); the first planet seen in transit (Henry et al. 2000, Charbonneau et al. 2000); the first two sub-Saturn-mass planets (Marcy, Butler & Vogt 2000); and the Anglo-Australian Planet Searches’ (AAPS) discovery of the first planet in a circular orbit outside the 0.1 au tidal-circularisation radius (Butler et al. 2001). The AAPS began operation in 1998, its southern hemisphere location completing all-sky coverage of the brightest stars at precisions reaching 3 m s$^{-1}$. The AAPS has already found a number of extra-solar planets (Butler et al. 2001, 2002a; Tinney et al. 2001, 2002a; Jones et al. 2002). In this paper we present further results from this programme.

2 THE ANGLO-AUSTRALIAN PLANET SEARCH

The Anglo-Australian Planet Search (AAPS) is carried out on the 3.9m Anglo-Australian Telescope using the University College London Echelle Spectrograph (UCLES), operated in its 31 lines/mm mode together with an I$_2$ absorption cell. UCLES now uses the AAO’s EEV 2048×4096 13.5µm pixel CCD, which provides excellent quantum efficiency across the 500–620 nm I$_2$ absorption line region.

Doppler shifts are measured by observing through an I$_2$ cell mounted behind the UCLES slit. The resulting superimposed iodine lines provide a fiducial wavelength scale against which to measure radial velocity shifts. The shapes of the iodine lines convey the PSF of the spectrograph, revealing changes in optics and illumination on all time scales. Following the procedure of Butler et al. (1996) we synthesize the echelle spectrum of each observation on a sub-pixel grid using a high-resolution reference template, and fit for spectrograph characteristics (the wavelength scale, scattered light and the spectrograph PSF) and Doppler shift. This analysis obtains velocities from multiple epoch observations measured against a reference template. This reference template is an observation at the highest available resolution (using a small 0.5 arcsec slit) and high signal-to-noise, without the I$_2$ cell present. Such
measurements can only be efficiently obtained in good seeing and take about 4 times as long to acquire as a standard epoch (I₂ and a 1 arcsec slit) observation. Despite this search taking place on a common-user telescope with frequent changes of instrument, we achieve a 3 m s\(^{-1}\) precision down to the V = 7.5 magnitude limit of the survey (Butler et al. 2001; fig. 1, Jones et al. 2002). The fundamental limit to the precision that can be achieved for our sample is set by a combination of S/N (which is dependent on seeing and weather conditions), and the intrinsic velocity stability of our target stars, rather than our observing technique (Butler et al. 1996). Intrinsic velocity instability in these stars – often called “jitter” – is induced by surface inhomogeneities due to activity (e.g. spots, plages or flares) combined with rotation (Saar et al. 1998; Saar & Fischer 2000). There is currently no way to tell whether a residual scatter of larger than 3 m s\(^{-1}\) is due to a small-amplitude planet, or jitter induced by star spots and/or activity. Only observations over a long enough period to allow the search for long-term periodicities can reveal the presence of such relatively small-amplitude long-period signals such as Jupiter. We intend to monitor all our targets for the lifetime of the survey, not just those that initially appear to be good planet candidates.

Our target sample which we have observed since 1998 is given in Table 1. It includes 178 late (IV-V) F, G and K stars with declinations below \(\sim -20^\circ\) and is complete to \(V < 7.5\). We also observe sub-samples of 16 metal-rich ([Fe/H] > 0.3) stars with \(V < 9.5\) and 7 M dwarfs with \(V < 7.5\) and declinations below \(\sim -20^\circ\). The sample has been increased to around 300 solar-type stars to be complete to a magnitude limit of V=8. Where age/activity information is available from \(R'_{HK}\) indices (Henry et al. 1996; Tinney et al. 2002b) we require target stars to have \(R'_{HK} < -4.5\) corresponding to ages greater than 3 Gyr. Stars with known stellar companions within 2 arcsec are removed from the observing list, as it is operationally difficult to get an uncontaminated spectrum of a star with a nearby companion. Spectroscopic binaries discovered during the programme have also been removed and are reported by Blundell et al. (2002). Otherwise there is no bias against observing multiple stars. The programme is also not expected to have any bias against brown dwarf companions. The observing and data processing procedures follow those described by Butler et al. (1996, 2001). The first observing run for the AAPS was in 1998 January, and the last run for which observations are reported here was in 2002 March.
3 STELLAR CHARACTERISTICS AND ORBITAL SOLUTION FOR HD 216437

HD 216437 (ρ Ind, HR 8701, HIP 113137) is a chromospherically inactive ($R'_{HK} = -5.01$, Tinney et al. 2002b) G4IV-V star (Cayrel et al. 1997). Its Hipparcos parallax of 37.7±0.6 mas together with a V magnitude of 6.04 implies an absolute magnitudes of $M_V = 3.92 ± 0.03$ (ESA 1997) and $M_{bol} = 3.88 ± 0.03$ (Cayrel et al. 1997). There is no evidence for significant photometric variability in the 160 measurements made by the HIPPARCOS satellite. HD 216437 is known to be somewhat metal-enriched relative to the Sun (e.g. $[\text{Fe/H}] = 0.1$, Cayrel de Strobel et al. 1997). Recent high resolution observations by Randich et al. (1999) have found HD 216437 to have a metallicity of $[\text{Fe/H}] = 0.21$ and a lithium abundance of 26 mÅ that is consistent with other similar metal-rich sub-giants. Interpolation between the tracks of Fuhrmann, Pfeiffer & Bernkopf (1997,1998) indicates a mass of 1.15±0.1 for metallicities between solar and $[\text{Fe/H}] = 0.3$.

The 26 Doppler velocity measurements of HD 216437, obtained between 1998 November and 2002 May, are listed in Table 2 and shown graphically in Fig. 1, along with the best fit Keplerian. The third column labelled uncertainty is the velocity uncertainty produced by our least-squares fitting. This uncertainty includes the effects of photon-counting uncertainties, residual errors in the spectrograph PSF model, and variation in the underlying spectrum between the template and iodine epochs. All velocities are measured relative to the zero-point defined by the template observation. Only observations where the uncertainty is less than twice the median uncertainty are listed. The best-fit Keplerian curve yields an orbital period of 1294±250 d, a velocity amplitude of 38±4 m s$^{-1}$, and an eccentricity of 0.33±0.09. The minimum ($M \sin i$) mass of the planet is 2.1 ± 0.3 M$_{JUP}$, and the semi-major axis is 2.4 ± 0.5 au. The RMS to the Keplerian fit is 6.64 m s$^{-1}$, yielding a reduced chi-squared of 1.5. The properties of the extra-solar planet in orbit around HD 216437 are summarised in Table 2.

4 STELLAR CHARACTERISTICS AND ORBITAL SOLUTION FOR HD 196050

HD 196050 (HIP 101806) is a chromospherically inactive ($R'_{HK} = -5.04$, Henry et al. 1996) G3V star (Houck & Cowley 1975). Its Hipparcos parallax of 21.3±0.9 mas (ESA 1997) implies absolute magnitudes of $M_V = 4.14 ± 0.05$ and $M_{bol} = 3.94 ± 0.05$ (Drilling & Landolt 2000).
The fundamental parameters of HD 196050 have been examined via B–V and Strömgren \( u b v y \) photometry (Olsen 1994). These suggest \( T_{\text{eff}} = 5590 \) K. Based on interpolation between the evolutionary tracks by Fuhrmann et al. (1998) HD 196050 is thus estimated to have a metallicity of \([\text{Fe/H}] = 0.3 \pm 0.2\) and a mass of \(1.13 \pm 0.1 \, M_\odot\). HD 196050 is not detected as variable in the of 144 measurements made by HIPPARCOS. It has recently been used as an infrared spectroscopic standard by the SOFI instrument on the New Technology Telescope at the European Southern Observatory in Chile.

The 30 Doppler velocity measurements of HD 196050, obtained between 1998 November and 2002 May, are listed in Table 3 in the same manner as for HD 216437 and shown graphically in Fig. 2. The best-fit Keplerian curve yields an orbital period of \(1288 \pm 230\) d, a velocity amplitude of \(54 \pm 8 \, \text{m s}^{-1}\) and an eccentricity of \(0.28 \pm 0.15\). The minimum \((M \sin i)\) mass of the planet is \(2.3 \pm 0.5 \, M_{\text{JUP}}\) and the semi-major axis is \(3.0 \pm 0.5\) au. The RMS to the Keplerian fit is \(7.51 \, \text{m s}^{-1}\), yielding a reduced chi-squared of 1.2. The properties of the extra-solar planet in orbit around HD 196050 are summarised in Table 2.

5 A NEW ORBITAL SOLUTION FOR HD 160691

We previously announced a companion to HD 160691 (Butler et al. 2001) based on data taken from 1998 November to 2000 November. Table 3 includes our data up until 2002 May. All the radial velocities presented in Table 3 have been computed using an improved template observation of HD 160691 and supercede those given previously. The best-fit single Keplerian curve yields an orbital period of \(638 \pm 10\) d, a velocity amplitude of \(41 \pm 5 \, \text{m s}^{-1}\) and an eccentricity of \(0.31 \pm 0.08\). The minimum \((M \sin i)\) mass of the planet is \(1.7 \pm 0.2 \, M_{\text{JUP}}\) and the semi-major axis is \(1.5 \pm 0.1\) au. The RMS to the Keplerian fit is \(5.42 \, \text{m s}^{-1}\), yielding a reduced chi-squared of 1.5. The properties of the extra-solar planet in orbit around HD 160691 are summarised in Table 2.

The new velocities confirm the planet presented by Butler et al. (2001), though in addition, Fig. 3 also shows a trend indicating a second companion. The period of such an outer object is poorly constrained. Examination of the parameter space using the sum of two Keplerians indicates that the RMS is currently minimized for the “trend” being due to an eccentric \((0.8)\) outer planet with a period of \(1300\) d and \(M \sin i = 1.0 \, M_{\text{JUP}}\) and an inner planet with an eccentricity of \(0.37\) period of \(603\) d and mass of \(1.6 \, M_{\text{JUP}}\). However, the data are currently inadequate to provide a convincing case for this outer planet. The RMS of the
two-planet fit is 4.9 m/s, lower than the 5.4 m/s from the single planet plus linear trend fit, but not statistically compelling at this time. Thus these parameters for the putative outer planet are speculative pending further velocity measurements. Any follow-up observations should take this into account. We are mentioning the possibility of this object at this very early stage in order that any high precision imaging of HD 160691 may take this trend into account.

6 DISCUSSION

Although many extra-solar planets had been discovered prior to 2000 December it was unclear whether giant planets in circular, or near-circular, orbits outside 0.1 au would be found at all outside the Solar System (e.g. Boss 2001). The AAPS identification of $\epsilon$ Ret (Butler et al. 2001) clearly showed that such planets exist. Since our announcement a further seven “$\epsilon$ Ret-class” (fig. 4, Tinney et al. 2002a) have been announced so clearly such planets are not as unusual as once thought.

The newly discovered companions to HD 216437 and HD 196050 announced here have masses at least several times that of Jupiter and have mildly eccentric orbits with periods roughly twice that of Mars or one-third of Jupiter. These discoveries serve to reinforce the trend that an increasing fraction of the extra-solar planets discovered have orbital parameters closer to those in our Solar System than was typical for earlier announcements of extra-solar planets. In Table 5, we classify the extra-solar planets reported up until 2002 June. Around 15% of extra-solar planetary systems have orbital parameters within the range of the planets of our Solar System. It should be noted that this is probably a lower bound as we expect that typical orbital parameters and detection frequencies will evolve considerably as survey baselines and precisions improve. Furthermore eccentricity solutions tend to decrease with time (Marcy et al. 2002).

7 CONCLUSIONS

We report extra-solar planets in orbit around the stars HD 216437 and HD 196050, and further observations of HD 160691, which give the preliminary indication of a second planet. These detections serve to further emphasize that planetary systems with orbital parameters

* 47 Uma was discovered by Butler & Marcy (1996) but was only realised to have a long-period circular orbit when it was discovered to have two planets in orbit (Fischer et al. 2002)
similar to those of our own Solar System are not as rare as suggested by the early extrasolar planet discoveries (e.g., Boss 2001). These discoveries confirm the preponderance (1) of relatively low-mass $M \sin i$ planets and (2) planets around metal-rich objects. The detection of these relatively long-period planets gives us confidence in the stability of our search and gives added impetus for the continuation of the AAPS to longer periods. We now must endeavour to continue to improve the precision and stability of the AAPS to be sensitive to the 10+ year periods where analogues of the gas giants in our own Solar System may become detectable around other stars (e.g. Marcy et al. 2002).

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Figure 1. AAT Doppler velocities for HD 216437 from 1998 August to 2001 October. The solid line is a best fit Keplerian orbit with the parameters shown in Table 2. The RMS of the velocities about the fit is 6.64 m s$^{-1}$ consistent with our errors. Assuming 1.15$\pm$0.10 M$_{\odot}$ for the primary, the minimum (M sin i) mass of the companion is 2.1$\pm$0.3 M$_{\text{Jup}}$ and the semi-major axis is 2.4$\pm$0.5 au.
Figure 2. AAT Doppler velocities for HD 196050 from 1998 July to 2002 March. The solid line is a best fit Keplerian orbit with the parameters shown in Table 2. The RMS of the velocities about the fit is 7.51 m s\(^{-1}\) consistent with our errors. Assuming 1.13\(\pm\)0.1 \(M_\odot\) for the primary, the minimum (M sin i) mass of the companion is 3.0\(\pm\)0.5 \(M_{\text{Jup}}\) and the semi-major axis is 2.3\(\pm\)0.5 au.
Figure 3. AAT Doppler velocities for HD 160691 from 1998 November to 2002 March. The solid line is a best fit Keplerian orbit with the parameters shown in Table 2. The RMS of the velocities about the fit is $5.42 \text{ m s}^{-1}$ consistent with our errors. Assuming $1.08 \pm 0.05 \, M_\odot$ for the primary, the minimum ($M \sin i$) mass of the companion is $1.7 \pm 0.2 \, M_{\text{JUP}}$ and the semi-major axis is $1.5 \pm 0.1 \, \text{au}$. 

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Table 1. Anglo-Australian planet search target list 1998 January to 2002 March. Doppler companions discovered so far are indicated in the final column.

| HD   | RA      | Dec      | Equinox | V   | Sp   | Doppler Companion?   |
|------|---------|----------|---------|-----|------|----------------------|
| 225213 | 00 05 24.2 | -37 21 31 | 2000.0  | 8.56 | M2V  |
| 142    | 00 06 19.0 | -49 04 30 | 2000.0  | 5.70 | G1IV | planet (Tinney et al. 2002a) |
| 1581   | 00 20 02.0 | -64 52 39 | 2000.0  | 4.23 | G0V  |
| 2039   | 00 24 20.0 | -56 39 00 | 2000.0  | 9.00 | G4V  |
| 2151   | 00 25 45.1 | -77 15 15 | 2000.0  | 2.80 | G2IV |
| 2587   | 00 29 10.0 | -50 36 42 | 2000.0  | 8.46 | G7V  |
| 3277   | 00 35 34.0 | -39 44 47 | 2000.0  | 7.45 | G6V  | star (Blundell et al. 2002) |
| 3823   | 00 40 26.4 | -59 27 16 | 2000.0  | 5.89 | G1V  |
| 4308   | 00 44 39.0 | -65 38 52 | 2000.0  | 6.55 | G4V  |
| 6735   | 01 07 32.0 | -41 44 50 | 2000.0  | 7.01 | F9V  |
| 7199   | 01 10 47.0 | -66 11 16 | 2000.0  | 8.06 | K0V  |
| 7570   | 01 15 11.0 | -45 31 56 | 2000.0  | 4.97 | G0V  | star (Blundell et al. 2002) |
| 9280   | 01 31 14.0 | -10 53 48 | 2000.0  | 8.03 | G8V  |
| 10180  | 01 37 54.0 | -60 30 41 | 2000.0  | 7.33 | G2V  |
| 10360  | 01 39 47.4 | -56 11 53 | 2000.0  | 5.87 | K0V  |
| 10361  | 01 39 47.8 | -56 11 41 | 2000.0  | 5.76 | K5V  |
| 10647  | 01 42 29.0 | -53 44 26 | 2000.0  | 5.52 | F9V  |
| 10700  | 01 44 04.0 | -15 56 15 | 2000.0  | 3.50 | G8V  |
| 11112  | 01 48 20.0 | -41 29 43 | 2000.0  | 7.13 | G3V  |
| 12387  | 02 00 32.0 | -40 43 51 | 2000.0  | 7.37 | G4V  |
| 13445  | 02 10 25.6 | -50 49 28 | 2000.0  | 6.12 | K1V  | planet (Butler et al. 2001) |
| 16417  | 02 36 58.6 | -34 34 42 | 2000.0  | 5.79 | G5IV |
| 17051  | 02 42 33.2 | -50 48 03 | 2000.0  | 5.40 | G3IV | planet (Butler et al. 2001) |
| 18709  | 02 58 59.0 | -43 44 53 | 2000.0  | 7.39 | G1V  |
| 18907  | 03 01 37.7 | -28 05 30 | 2000.0  | 5.89 | G5IV | star (Blundell et al. 2002) |
| 19632  | 03 08 52.0 | -24 53 17 | 2000.0  | 7.29 | G5V  |
| 20029  | 03 11 53.0 | -39 01 23 | 2000.0  | 7.05 | F9V  |
| 20201  | 03 12 55.0 | -47 09 20 | 2000.0  | 7.27 | G0V  |
| HD   | RA       | Dec      | Equinox | V mag | Sp   | Doppler Companion? |
|------|----------|----------|---------|-------|------|-------------------|
| 20766| 03 17 45.0| -62 34 37| 2000.0  | 5.53  | G3V  |                   |
| 20794| 03 19 55.7| -43 04 11| 2000.0  | 4.27  | G8V  |                   |
| 20807| 03 18 12.9| -62 30 23| 2000.0  | 5.24  | G1V  |                   |
| 20782| 03 20 04.0| -28 51 13| 2000.0  | 7.36  | G3V  |                   |
| 22104| 03 27 37.0| -73 26 24| 2000.0  | 8.32  | G5V  |                   |
| 23127| 03 39 24.0| -60 04 42| 2000.0  | 8.58  | G5V  |                   |
| 23079| 03 39 43.0| -52 54 57| 2000.0  | 7.12  | G0V  | planet (Tinney et al. 2002a) |
| 23484| 03 44 09.0| -38 16 54| 2000.0  | 6.99  | K1V  |                   |
| 24112| 03 48 47.0| -40 23 58| 2000.0  | 7.24  | F9V  |                   |
| 25874| 04 02 27.0| -61 21 26| 2000.0  | 6.74  | G4V  |                   |
| 25587| 04 02 43.0| -27 29 00| 2000.0  | 7.40  | F8V  |                   |
| 26491| 04 07 21.6| -64 13 21| 2000.0  | 6.38  | G3V  | star (Blundell et al. 2002) |
| 26754| 04 10 07.0| -61 35 56| 2000.0  | 7.16  | F9V  |                   |
| 27442| 04 16 28.9| -59 18 07| 2000.0  | 4.44  | K2IV | planet (Butler et al. 2001) |
| 28255A| 04 24 12.2| -57 04 17| 2000.0  | 6.29  | G4V  |                   |
| 28255B| 04 24 12.2| -57 04 17| 2000.0  | 6.60  | G6V  |                   |
| 30177| 04 41 54.0| -58 01 15| 2000.0  | 8.41  | G8V  | planet (Tinney et al. 2002c) |
| 30295| 04 42 20.0| -61 37 17| 2000.0  | 8.86  | G9V  |                   |
| 30876| 04 49 53.0| -35 06 29| 2000.0  | 7.49  | K2V  |                   |
| 31527| 04 55 38.0| -23 14 31| 2000.0  | 7.49  | G1V  |                   |
| 31827| 04 56 18.0| -51 02 50| 2000.0  | 8.26  | G8V  |                   |
| 33811| 05 10 43.0| -44 34 20| 2000.0  | 8.71  | G8V  |                   |
| 36108| 05 28 21.0| -22 26 04| 2000.0  | 6.78  | G1V  |                   |
| 38283| 05 37 02.0| -73 41 58| 2000.0  | 6.69  | G0V  |                   |
| 39091| 05 37 09.8| -80 28 09| 2000.0  | 5.65  | G1V  | planet (Jones et al. 2002) |
| 38110| 05 42 59.0| -07 28 51| 2000.0  | 8.18  | G5V  |                   |
| 38382| 05 44 28.0| -20 07 35| 2000.0  | 6.34  | G0V  |                   |
| 38973| 05 46 28.0| -53 13 09| 2000.0  | 6.63  | G1V  |                   |
| 39213| 05 49 16.0| -37 30 48| 2000.0  | 8.96  | G9V  | star (Blundell et al. 2002) |
| 40307| 05 54 04.0| -60 01 24| 2000.0  | 7.17  | K2V  |                   |
| HD   | RA       | Dec      | Equinox | V mag | Sp  | Doppler Companion?                        |
|------|----------|----------|---------|-------|-----|-------------------------------------------|
| 42024 | 06 06 12.0 | -45 48 58 | 2000.0  | 7.24  | F9V | star (Blundell et al. 2002)              |
| 43834 | 06 10 14.4 | -74 45 11 | 2000.0  | 5.09  | G6V |                                          |
| 42902 | 06 11 14.0 | -44 13 28 | 2000.0  | 8.92  | G2V |                                          |
| 44447 | 06 15 06.0 | -71 42 10 | 2000.0  | 6.62  | F9V |                                          |
| 44120 | 06 16 18.5 | -59 12 49 | 2000.0  | 6.43  | G0V |                                          |
| 44594 | 06 20 06.0 | -48 44 26 | 2000.0  | 6.61  | G4V |                                          |
| 45289 | 06 24 24.0 | -42 50 28 | 2000.0  | 6.67  | G5V |                                          |
| 45701 | 06 24 26.0 | -63 25 44 | 2000.0  | 6.45  | G4V |                                          |
| 52447 | 06 57 26.0 | -60 51 05 | 2000.0  | 8.38  | G1V |                                          |
| 53705 | 07 03 57.3 | -43 36 29 | 2000.0  | 5.54  | G3V |                                          |
| 53706 | 07 03 59.0 | -43 36 44 | 2000.0  | 6.83  | G8V |                                          |
| 55720 | 07 11 32.0 | -49 25 29 | 2000.0  | 7.50  | G6V |                                          |
| 55693 | 07 13 03.0 | -24 13 33 | 2000.0  | 7.17  | G4V |                                          |
| 59468 | 07 27 26.0 | -51 24 09 | 2000.0  | 6.72  | G5V |                                          |
| 61686 | 07 39 35.0 | -26 28 28 | 2000.0  | 8.54  | G5V |                                          |
| 64184 | 07 49 27.0 | -59 22 52 | 2000.0  | 7.49  | G5V | star (Blundell et al. 2002)              |
| 65907A| 07 57 46.9 | -60 18 12 | 2000.0  | 5.60  | G0V |                                          |
| 67199 | 08 02 31.0 | -66 01 18 | 2000.0  | 7.18  | K1V |                                          |
| 67556 | 08 07 09.0 | -36 22 54 | 2000.0  | 7.30  | F8V |                                          |
| 69655 | 08 15 26.0 | -52 03 37 | 2000.0  | 6.63  | G0V |                                          |
| 70642 | 08 21 28.0 | -39 42 21 | 2000.0  | 7.17  | G5V |                                          |
| 70889 | 08 23 32.0 | -27 49 21 | 2000.0  | 7.09  | G1V |                                          |
| 72769 | 08 33 46.0 | -23 21 18 | 2000.0  | 7.22  | G7V |                                          |
| 73121 | 08 35 12.6 | -39 58 12 | 2000.0  | 6.47  | G1V |                                          |
| 73526 | 08 37 17.0 | -41 19 10 | 2000.0  | 8.99  | G7V | planet (Tinney et al. 2002c)             |
| 73524 | 08 37 20.0 | -40 08 51 | 2000.0  | 6.53  | G1V |                                          |
| 74868 | 08 44 51.0 | -44 32 34 | 2000.0  | 6.56  | F9V |                                          |
| 75289 | 08 47 41.0 | -41 44 14 | 2000.0  | 6.35  | G0V | planet (Butler et al. 2001)              |
| 76700 | 08 53 54.0 | -66 48 05 | 2000.0  | 8.16  | G7V |                                          |
| 78429 | 09 06 39.0 | -43 29 32 | 2000.0  | 7.31  | G4V |                                          |
### Anglo-Australian Planet Search

| HD     | RA      | Dec      | Equinox | V mag | Sp    | Doppler Companion? |
|--------|---------|----------|---------|-------|-------|--------------------|
| 80913  | 09 12 26.0 | -81 46 08 | 2000.0  | 7.49  | F9V   |                    |
| 80635  | 09 20 27.0 | -17 25 29 | 2000.0  | 8.80  | G6V   |                    |
| 82082  | 09 27 32.0 | -58 05 40 | 2000.0  | 7.20  | G1V   |                    |
| 83443  | 09 37 12.0 | -43 16 19 | 2000.0  | 8.23  | G9V   | planet (Butler et al. 2002a) |
| 83529A | 09 37 29.0 | -49 59 27 | 2000.0  | 6.97  | G0V   |                    |
| 84117  | 09 42 15.0 | -23 54 58 | 2000.0  | 4.93  | F8V   |                    |
| 85683  | 09 51 41.0 | -54 39 35 | 2000.0  | 7.34  | F8V   |                    |
| 86819  | 10 00 06.0 | -36 02 36 | 2000.0  | 7.38  | G0V   |                    |
| 88742  | 10 13 25.0 | -33 01 55 | 2000.0  | 6.38  | G1V   |                    |
| 92987  | 10 43 36.0 | -39 03 31 | 2000.0  | 7.03  | G3V   |                    |
| 93385  | 10 46 15.0 | -41 27 52 | 2000.0  | 7.49  | G1V   |                    |
| 96423  | 11 06 20.0 | -44 22 24 | 2000.0  | 7.23  | G5V   |                    |
| 101614 | 11 41 27.0 | -41 01 06 | 2000.0  | 6.86  | G1V   |                    |
| 101959 | 11 43 57.0 | -29 44 51 | 2000.0  | 6.97  | F9V   |                    |
| 102117 | 11 44 50.0 | -58 42 12 | 2000.0  | 7.47  | G6V   |                    |
| 102365 | 11 46 31.1 | -40 30 02 | 2000.0  | 4.91  | G3V   |                    |
| 102438 | 11 47 15.7 | -30 17 13 | 2000.0  | 6.48  | G5V   |                    |
| 105328 | 12 07 39.0 | -23 58 33 | 2000.0  | 6.72  | G2V   |                    |
| 106453 | 12 14 42.0 | -24 46 34 | 2000.0  | 7.47  | G6V   |                    |
| 107692 | 12 22 45.0 | -39 10 38 | 2000.0  | 6.70  | G3V   |                    |
| 108147 | 12 25 46.0 | -64 01 22 | 2000.0  | 6.99  | F8V   | planet (Pepe et al. 2002) |
| 108309 | 12 26 48.2 | -48 54 48 | 2000.0  | 6.26  | G3-5V |                    |
| 109200 | 12 33 32.0 | -68 45 20 | 2000.0  | 7.13  | K0V   |                    |
| 114613 | 13 12 03.2 | -37 48 11 | 2000.0  | 4.85  | G3V   |                    |
| 114853 | 13 13 52.0 | -45 11 10 | 2000.0  | 6.93  | G3V   |                    |
| 117618 | 13 32 26.0 | -47 16 18 | 2000.0  | 7.17  | G1V   |                    |
| 118972 | 13 41 04.0 | -34 27 50 | 2000.0  | 6.92  | K0V   |                    |
| 120237 | 13 48 55.0 | -35 42 14 | 2000.0  | 6.56  | F9V   |                    |
| 120690 | 13 51 20.0 | -24 23 27 | 2000.0  | 6.43  | G6V   | star (Blundell et al. 2002) |
| 121384 | 13 56 33.0 | -54 42 16 | 2000.0  | 6.00  | G6IV-V| star (Blundell et al. 2002) |

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| HD     | RA      | Dec     | Equinox | V mag | Sp     | Doppler Companion?        |
|--------|---------|---------|---------|-------|--------|--------------------------|
| 122862 | 14 08   | -74 51  | 2000.0  | 6.02  | G2-3IV |                          |
| 125072 | 14 19   | -59 22  | 2000.0  | 6.66  | K4V    |                          |
| GL551  | 14 29   | -62 40  | 2000.0  | 11.01 | M5V    |                          |
| 128620 | 14 39   | -60 50  | 2000.0  | -0.01 | G2V    |                          |
| 128621 | 14 39   | -60 50  | 2000.0  | 1.33  | K1V    |                          |
| 129060 | 14 44   | -69 40  | 2000.0  | 6.99  | F9V    |                          |
| 131923 | 14 58   | -48 51  | 2000.0  | 6.35  | G3-5V  | star (Blundell et al. 2002) |
| 134331 | 15 10   | -43 43  | 2000.0  | 7.01  | G2V    |                          |
| 134330 | 15 10   | -43 42  | 2000.0  | 7.60  | G6V    |                          |
| 134060 | 15 10   | -61 25  | 2000.0  | 6.30  | G2V    |                          |
| 134987 | 15 13   | -25 18  | 2000.0  | 6.45  | G4V    | planet (Butler et al. 2001) |
| 134606 | 15 15   | -70 31  | 2000.0  | 6.86  | G7V    |                          |
| 136352 | 15 21   | -48 19  | 2000.0  | 5.65  | G3-5V  |                          |
| 140901 | 15 47   | -37 54  | 2000.0  | 6.01  | G6V    |                          |
| 143114 | 15 59   | -29 37  | 2000.0  | 7.34  | G1V    |                          |
| 144628 | 16 09   | -56 26  | 2000.0  | 7.11  | K0V    |                          |
| 145825 | 16 14   | -31 39  | 2000.0  | 6.55  | G3V    | star (Blundell et al. 2002) |
| 147722 | 16 24   | -29 42  | 2000.0  | 6.50  | G0IV   |                          |
| 147723 | 16 24   | -29 42  | 2000.0  | 5.84  | G0IV   |                          |
| 150248 | 16 41   | -45 22  | 2000.0  | 7.03  | G4V    | star (Blundell et al. 2002) |
| 154577 | 17 10   | -60 43  | 2000.0  | 7.38  | K1V    |                          |
| 155974 | 17 16   | -35 44  | 2000.0  | 6.12  | G0IV-V |                          |
| 156274A| 17 19   | -46 38  | 2000.0  | 7.0   | M0V    | star (Blundell et al. 2002) |
| 156274B| 17 19   | -46 38  | 2000.0  | 5.52  | K0V    |                          |
| 158783 | 17 34   | -54 53  | 2000.0  | 7.09  | G4V    | star (Blundell et al. 2002) |
| 160691 | 17 44   | -51 50  | 2000.0  | 5.15  | G3IV-V | planet (Butler et al. 2001; this paper) |
| 161050 | 17 47   | -63 33  | 2000.0  | 7.16  | G1V    |                          |
| 161612 | 17 47   | -34 01  | 2000.0  | 7.20  | G7V    |                          |
| 162255 | 17 51   | -22 55  | 2000.0  | 7.15  | G3V    | star (Blundell et al. 2002) |
| 164427 | 18 04   | -59 12  | 2000.0  | 6.88  | G2V    | brown dwarf (Tinney et al. 2001) |
| HD    | RA     | Dec    | Equinox | V mag | Sp   | Doppler Companion? |
|-------|--------|--------|---------|-------|------|-------------------|
| 168871| 18 24 33.0 | -49 39 10 | 2000.0 | 6.45  | G1V  |                   |
| 169586| 18 26 41.0 | -30 23 37 | 2000.0 | 6.75  | F8V  | star (Blundell et al. 2002) |
| GL729 | 18 49 49.0 | -23 50 10 | 2000.0 | 10.46 | M4V  |                   |
| 175345| 18 56 00.0 | -25 02 48 | 2000.0 | 7.37  | F9V  | star (Blundell et al. 2002) |
| 177565| 19 06 52.5 | -37 48 37 | 2000.0 | 6.16  | G5IV |                   |
| 179949| 19 15 33.0 | -24 10 45 | 2000.0 | 6.25  | F8V  | planet (Tinney et al. 2001) |
| 181428| 19 21 39.0 | -29 36 19 | 2000.0 | 7.10  | F9V  |                   |
| 183877| 19 32 40.0 | -28 01 11 | 2000.0 | 7.14  | G5V  |                   |
| 187085| 19 49 34.0 | -37 46 50 | 2000.0 | 7.22  | G0V  |                   |
| 189567| 20 05 32.8 | -67 19 15 | 2000.0 | 6.07  | G3V  |                   |
| 190248| 20 08 43.6 | -66 10 55 | 2000.0 | 3.56  | G6-8IV |                   |
| 191408| 20 11 11.9 | -36 06 04 | 2000.0 | 5.32  | K3V  |                   |
| 192310| 20 15 17.4 | -27 01 58 | 2000.0 | 5.73  | K0V  |                   |
| 193193| 20 19 45.0 | -25 13 43 | 2000.0 | 7.20  | G1V  |                   |
| 192865| 20 21 36.0 | -67 18 46 | 2000.0 | 6.91  | F9V  |                   |
| 193307| 20 21 41.0 | -49 59 58 | 2000.0 | 6.27  | G0V  |                   |
| 194640| 20 27 44.0 | -30 52 00 | 2000.0 | 6.61  | G6V  |                   |
| 196050| 20 37 52.0 | -60 38 03 | 2000.0 | 7.50  | G4V  | planet (this paper) |
| 196800| 20 40 22.0 | -24 07 04 | 2000.0 | 7.21  | G2V  |                   |
| 196068| 20 41 45.0 | -75 20 46 | 2000.0 | 7.18  | G3V  |                   |
| 196378| 20 40 02.3 | -60 32 51 | 2000.0 | 5.11  | F8V  |                   |
| 199288| 20 57 40.0 | -44 07 37 | 2000.0 | 6.52  | G0V  |                   |
| 199190| 21 00 06.0 | -69 34 45 | 2000.0 | 6.86  | G3V  |                   |
| 199509| 21 09 22.0 | -82 01 37 | 2000.0 | 6.98  | G2V  |                   |
| 202560| 21 17 15.0 | -38 52 04 | 2000.0 | 6.69  | M0V  |                   |
| 202628| 21 18 27.0 | -43 20 05 | 2000.0 | 6.75  | G3V  |                   |
| 204385| 21 30 48.0 | -62 10 06 | 2000.0 | 7.14  | G1V  |                   |
| 204961| 21 33 34.0 | -49 00 25 | 2000.0 | 8.66  | G1V  |                   |
| 205390| 21 36 41.0 | -50 50 46 | 2000.0 | 7.15  | K1V  |                   |
| 205536| 21 40 31.0 | -74 04 28 | 2000.0 | 7.07  | G7V  |                   |
| HD     | RA     | Dec      | Equinox | V mag | Sp  | Doppler Companion? |
|--------|--------|----------|---------|-------|-----|-------------------|
| 206395 | 21 43 02.0 | -43 29 46 | 2000.0  | 6.67  | F9V |                   |
| 207129 | 21 48 15.8 | -47 18 13 | 2000.0  | 5.58  | G0V |                   |
| 207700 | 21 54 46.0 | -73 26 17 | 2000.0  | 7.43  | G5V |                   |
| 208487 | 21 57 20.0 | -37 45 52 | 2000.0  | 7.47  | F9V |                   |
| 208998 | 22 01 37.0 | -53 05 36 | 2000.0  | 7.12  | G0V |                   |
| 209268 | 22 03 35.0 | -55 58 38 | 2000.0  | 6.88  | F9V |                   |
| 209653 | 22 07 31.0 | -68 01 23 | 2000.0  | 6.99  | G0V |                   |
| 210918 | 22 14 38.6 | -41 22 54 | 2000.0  | 6.23  | G5V | star (Blundell et al. 2002) |
| 211317 | 22 18 50.0 | -68 18 47 | 2000.0  | 7.26  | G4V |                   |
| 212330 | 22 24 56.4 | -57 47 50 | 2000.0  | 5.32  | G3IV|                   |
| 212168 | 22 25 51.0 | -75 00 56 | 2000.0  | 6.04  | G3V |                   |
| 212708 | 22 27 25.0 | -49 21 58 | 2000.0  | 7.48  | G7V |                   |
| 213240 | 22 31 00.0 | -49 26 00 | 2000.0  | 6.81  | G1V | planet (Santos et al. 2001) |
| 214759 | 22 40 55.0 | -31 59 23 | 2000.0  | 7.41  | G8V |                   |
| 214953 | 22 42 36.9 | -47 12 38 | 2000.0  | 5.98  | G0V |                   |
| 216435 | 22 53 37.9 | -48 35 53 | 2000.0  | 6.04  | G0V |                   |
| 216437 | 22 54 39.4 | -70 04 25 | 2000.0  | 6.05  | G2-3IV| planet (this paper) |
| 217958 | 23 04 33.0 | -25 41 27 | 2000.0  | 8.05  | G4V |                   |
| 217987 | 23 05 51.2 | -35 51 11 | 2000.0  | 7.35  | M2V |                   |
| 219077 | 23 14 06.6 | -62 42 00 | 2000.0  | 6.12  | G8V |                   |
| 220507 | 23 24 42.0 | -52 42 08 | 2000.0  | 7.59  | G5V |                   |
| 221420 | 23 33 19.5 | -77 23 07 | 2000.0  | 5.81  | G2V |                   |
| 222237 | 23 39 37.0 | -72 43 19 | 2000.0  | 7.09  | K3V |                   |
| 222335 | 23 39 51.0 | -32 44 34 | 2000.0  | 7.18  | G9V |                   |
| 222480 | 23 41 08.0 | -32 04 14 | 2000.0  | 7.11  | G4V |                   |
| 223171 | 23 47 21.0 | -48 16 33 | 2000.0  | 6.89  | G4V |                   |
Table 2. Radial Velocities (RV) for HD 216437 are referenced to the Solar System barycentre but have an arbitrary zero-point determined by the radial velocity of the template. The JDs are topocentric.

| JD (-2450000) | RV (m s\(^{-1}\)) | Uncertainty (m s\(^{-1}\)) |
|---------------|-------------------|--------------------------|
| 830.9420      | -38.8             | 4.6                      |
| 1034.2251     | -35.6             | 4.9                      |
| 1386.3051     | -3.4              | 5.7                      |
| 1472.9552     | 4.5               | 4.1                      |
| 1683.3146     | 36.2              | 4.8                      |
| 1684.3276     | 34.5              | 4.2                      |
| 1743.2343     | 50.9              | 6.1                      |
| 1767.2046     | 37.9              | 4.3                      |
| 1768.2248     | 33.5              | 5.3                      |
| 1828.0427     | 42.8              | 5.2                      |
| 1828.9634     | 40.9              | 5.1                      |
| 1829.9568     | 43.7              | 5.7                      |
| 1856.0478     | 30.6              | 7.4                      |
| 1919.9294     | 28.9              | 5.3                      |
| 1920.9255     | 29.2              | 6.6                      |
| 2061.2882     | -21.1             | 4.9                      |
| 2092.2206     | -15.1             | 5.2                      |
| 2127.1081     | -24.9             | 5.5                      |
| 2154.1065     | -29.9             | 4.5                      |
| 2188.0807     | -44.0             | 4.0                      |
| 2387.3194     | -22.0             | 4.2                      |
| 2388.3068     | -17.3             | 2.2                      |
| 2389.2962     | -22.7             | 6.6                      |
| 2390.3183     | -27.2             | 4.5                      |
| 2422.3086     | -27.9             | 4.0                      |
| 2425.3260     | -23.3             | 3.7                      |
Table 3. Radial Velocities (RV) for HD 196050 are referenced to the Solar System barycentre but have an arbitrary zero-point determined by the radial velocity of the template. The JDs are topocentric.

| JD (-2451000) | RV (m s\(^{-1}\)) | Uncertainty (m s\(^{-1}\)) |
|---------------|-------------------|-----------------------------|
| 118.9450      | 10.9              | 10.7                        |
| 411.0456      | 52.3              | 7.9                         |
| 472.9298      | 57.6              | 5.5                         |
| 683.1958      | 56.6              | 6.4                         |
| 706.1291      | 51.7              | 7.3                         |
| 743.0754      | 49.5              | 6.0                         |
| 745.1895      | 46.7              | 5.3                         |
| 767.0285      | 37.3              | 5.5                         |
| 770.1480      | 43.3              | 6.6                         |
| 827.9868      | 17.5              | 6.9                         |
| 855.9770      | 24.0              | 9.3                         |
| 1010.2975     | -18.9             | 6.6                         |
| 1061.1955     | -21.9             | 5.7                         |
| 1092.1221     | -15.4             | 6.6                         |
| 1127.1045     | -27.7             | 6.0                         |
| 1128.6595     | -30.4             | 7.9                         |
| 1130.6415     | -22.1             | 5.7                         |
| 1151.9802     | -25.5             | 5.9                         |
| 1153.8857     | -36.6             | 4.7                         |
| 1186.9195     | -39.6             | 4.1                         |
| 1187.9809     | -45.2             | 3.5                         |
| 1188.9390     | -41.8             | 11.4                        |
| 1189.9371     | -32.9             | 5.3                         |
| 1360.2972     | -11.2             | 6.0                         |
| 1387.3049     | -2.1              | 4.7                         |
| 1388.2519     | -6.8              | 4.8                         |
| 1389.2115     | -6.3              | 5.3                         |
| 1390.2928     | -7.4              | 5.3                         |
| 1421.2467     | 23.5              | 5.6                         |
| 1425.2942     | 19.4              | 4.8                         |
Table 4. Radial Velocities (RV) for HD 160691 are referenced to the Solar System barycentre but have an arbitrary zero-point determined by the radial velocity of the template. The JDs are topocentric.

| JD    | RV  | Uncertainty |
|-------|-----|-------------|
| (-2450000) | (m s\(^{-1}\)) | (m s\(^{-1}\)) |
| 915.2911 | -11.4 | 6.3 |
| 1118.8874 | -10.2 | 3.4 |
| 1119.9022 | -10.9 | 2.8 |
| 1120.8870 | -11.2 | 3.0 |
| 1121.8928 | -10.3 | 2.9 |
| 1236.2864 | -26.5 | 4.0 |
| 1410.8977 | -47.8 | 2.9 |
| 1412.9780 | -47.7 | 5.6 |
| 1413.8981 | -41.0 | 2.7 |
| 1630.3042 | 39.8 | 3.0 |
| 1683.0926 | 43.9 | 3.7 |
| 1684.1320 | 41.0 | 4.1 |
| 1718.1184 | 28.5 | 3.6 |
| 1742.9096 | 15.7 | 3.1 |
| 1743.9240 | 25.7 | 3.8 |
| 1745.0440 | 13.8 | 3.3 |
| 1766.9330 | 5.8 | 3.2 |
| 1767.9689 | 7.5 | 3.3 |
| 1827.8973 | -5.9 | 2.9 |
| 1828.8866 | -0.4 | 3.6 |
| 1829.8890 | -6.8 | 3.4 |
| 1855.9058 | -7.0 | 4.9 |
| 1984.2618 | -20.5 | 3.5 |
| 2010.2829 | -15.6 | 6.1 |
| 2061.1132 | -27.7 | 3.1 |
| 2091.9807 | -30.3 | 3.6 |
| 2126.9766 | -12.0 | 3.7 |
| 2151.9693 | -7.0 | 3.3 |
| 2152.9493 | 4.3 | 2.4 |
| 2153.8620 | -9.9 | 2.8 |
| 2186.9095 | 20.9 | 2.6 |
| 2187.8879 | 16.7 | 2.7 |
| 2360.3245 | 34.6 | 2.3 |
| 2387.1722 | 34.6 | 2.7 |
| 2388.2097 | 31.0 | 2.9 |
| 2421.1696 | 15.8 | 2.7 |
| 2425.1226 | 20.3 | 3.1 |

Table 5. Orbital parameters for the companions to HD 216437, HD 196050 and HD 160691. The solution for HD 160691b is for the case of a single Keplerian fit to the data whereas the fit for HD 160691c is based on a two Keplerian fit. HD 160691c is uncertain so its best fit values are shown in parentheses.

|                | HD 216437b | HD 196050b | HD 160691b | HD 160691c |
|----------------|------------|------------|------------|------------|
| Orbital Period (d) | 1294±250 | 1288±230 | 638±10 | (1300) |
| eccentricity     | 0.33±0.09 | 0.28±0.15 | 0.31±0.08 | (0.8) |
| ω (degrees)      | 79±30 | 223±30 | 320±30 | (99) |
| Radial velocity semi-amplitude $K$ (m s\(^{-1}\)) | 38±4 | 41±5 | 40±5 | (34.2) |
| Periastron Time (HJD) | 5068±200 | 51033±180 | 50958±30 | (51613) |
| $M \sin i$ ($M_{\text{JUP}}$) | 2.1±0.3 | 3.0±0.5 | 1.7±0.2 | (1) |
| $a$ (au)         | 2.4±0.5 | 2.3±0.5 | 1.5±0.1 | (2.3) |
| RMS residuals to fit (m s\(^{-1}\)) | 6.64 | 7.51 | 5.42 | (5) |
Table 6. Extra-solar planetary systems classified by orbital parameters of period and eccentricity (from http://exoplanets.org). The boundaries for classification are chosen in terms of the Solar System, so eccentricity is chosen as 0.25 (cf. Pluto) and period as 88 d (cf. Mercury). Where there is more than one planet present around a star the classification is made in terms of the inner planet. Outer planets in the system are recorded in the appropriate section though their entry is in italics to indicate that they are not included in the count.

| Class | Number | Objects |
|-------|--------|---------|
| 51 Peg b – like | 24 | HD 83443b, HD 46375b, HD 179949b, HD 187123b, Tau Boo b, BD -103166b, HD 75289b, HD 209458b, 51 Peg b, Ups And b, HD 49674b, HD 68988b, HD 168746b, HD 217107b, HD 130322b, HD 38529b, 55 Cnc b, GJ 86b, HD 195019b, Rho Cr Bb, GJ 876b, HD 121504b, HD 1789111b, HD 16141b |
| HD 114762 – like | 6 | HD 162020b, HD 108147b, HD 6434b, GJ 876c, HD 74156b, HD 168443b, HD 114762b |
| 70 vir b – like | 37 | HD 80606b, 70 Vir b, HD 52265b, HD 1237b, HD 37124b, HD 73526b, HD 82943c, HD 8574b, HD 169830b, HD 12661b, HD 89744b, HD 40979b, HD 202206b, HD 134987b, HD 92788b, HD 142b, HD 177800b, HD 4203b, HD 210277b, HD 82943b, HIP 75458b, HD 222582b, HD 141937b, HD 160691b, HD 213240b, 16 Cyg B b, HD 196050b, HD 114729b, HD 190228b, HD 136118b, HD 50554b, HD216437b, Ups And d, HD 12661c, HD 33636b, HD 106252b, HD 145675b, HD 72659b, HD 39091b, HD 38529c, HD 74156c, Eps Eri b |
| Solar System – like | 13 | HD 37124b, Ups And c, HD 17051b, HD 28185b, HD 108874b, HD 128311b, HD 27442b, HD 19994b, HD 114783b, HD 23079b, HD 4208b, HD 10697b, 47 Uma b, HD 30177b, 47 Uma c, HD 168443c, 55 Cnc c |