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A probable planetary companion to HD 39091 from the Anglo-Australian Planet Search

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ABSTRACT

We report the detection of an extra-solar planet candidate orbiting the G1 V star HD 39091. The orbital period is 2049 d and the eccentricity is 0.62. With a minimum ($M \sin i$) mass of $10.3 M_{\rm JUP}$ this object falls near the high-mass end of the observed planet mass function, and may plausibly be a brown dwarf. Other characteristics of this system, including orbital eccentricity and metallicity, are typical of the well-populated class of radial velocity planets in eccentric orbits around metal-rich stars.

Key words: stars: individual: HD 39091 – stars: low-mass, brown dwarfs – planetary systems.

1 INTRODUCTION

Since the discovery of the first extra-solar planet (Mayor & Queloz 1995), planetary detections have been dominated by northern-hemisphere search programmes. Major planet searches include the high-precision velocity programmes at Lick (e.g. Butler et al. 1996) and Keck (e.g. Vogt et al. 2000) and lower-precision programmes at Haute-Provence Observatory (Baranne et al. 1996), McDonald Observatory (Cochran et al. 1997), Whipple Observatory (Noyes et al. 1997) and at La Silla Observatory (Kürster et al. 2000; Queloz et al. 2000). Of these, only the La Silla programmes, operating at precisions of $\sim 10\,\mathrm{m\,s^{-1}}$, have access to the sky south of $-20°$. In 1998, the Anglo-Australian Planet Search (AAPS) began in the southern hemisphere, enabling all-sky coverage of the brightest stars at precisions reaching $3\,\mathrm{m\,s^{-1}}$ (Butler et al. 2001; Tinney et al. 2001). In this paper we present further results from this programme. Two companion papers present results for two relatively low-mass planets (Tinney et al. 2002a), and an initial investigation of the Ca H and K activity among some of the target stars of the AAPS (Tinney et al. 2002b).

Precision Doppler surveys have found all of the known extra-solar planets around solar-type stars. Discoveries have included: the first system of multiple planets orbiting a Sun-like star (Butler et al. 1999); the first planet seen in transit (Charbonneau et al. 2000; Henry et al. 2000); the first two sub-Saturn-mass planets (Marcy, Butler & Vogt 2000); and the discovery by the AAPS of the first planet in a circular orbit outside the 0.1-au tidal-circularization radius (Butler et al. 2001). A number of major surprises have emerged from the sample of extra-solar planets.

(i) The substellar companion mass function for F, G, and K dwarfs rises strongly below $10 M_{\rm JUP}$, and shows no signs of flattening toward the detection limit near $1 M_{\rm JUP}$. Surprisingly, brown dwarf companions to solar-type stars are rare (Butler et al. 2002; Jorissen, Mayor & Udry 2001; Zucker & Mazeh 2001). This is in spite of a strong bias in the observations that makes brown dwarfs easier to detect than planets. It should be noted that the mass is only known within the uncertainty of the projection factor represented by the $\sin i$ of the orbit. However, the $\sin i$ statistic is between 1 and 0.5 for 87 per cent of randomly inclined orbits, so 87 per cent of reported $M \sin i$ values will be within a factor of 2 of the true masses.

(ii) Approximately ~ 0.75 per cent of nearby solar-type stars have been found to have planets orbiting in circularized orbits inward of 0.1 au (the 51 Peg-like 'hot Jupiters'). A smaller fraction of stars is now being found to have 'ϵ Ret-like' planets orbiting in circularized orbits at 1 au or so (Tinney et al. 2002a). However, the dominant class of extra-solar planets, seems to be those with highly eccentric orbits within 3.5 au, which are found around some 7 per cent of target stars. None of these classes were predicted a priori by planetary formation theories. Such theories have received

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enormous impetus from these observations, leading to models for planet formation and evolution that now include the effects of dynamical friction, disk–planet and planet–planet interactions (e.g. Rasio & Ford 1996; Weidenschilling & Marzari 1996; Boss 2000; Artymowicz 2000).

(iii) The majority of extra-solar planets that have been found so far occur around stars that are metal-rich ($\sim +0.2$ dex with considerable scatter) compared with the Sun (Laughlin 2000; Santos, Israelian & Mayor 2001).

This paper reports the discovery of a new planet candidate from the AAPS. Section 2 describes this precision programme. The stellar properties and Keplerian orbital fits for the new planet candidate are presented in Section 3. Section 4 provides a discussion of the new object.

2 THE ANGLO-AUSTRALIAN PLANET SEARCH

The Anglo-Australian Planet Search is being carried out on the 3.92-m Anglo-Australian Telescope using the University College London Echelle Spectrograph (UCLES), operated in its 31 line mm^{-1} mode together with an I_2 absorption cell. UCLES used to be operated with an MIT/LL 2048×4096 15-μm pixel charge-coupled device (CCD). Since 2001 August the AAPS has changed to the EEV CCD of the Anglo-Australian Observatory (AAO) 2048×4096 13.5-μm pixel CCD. This CCD provides 30 per cent better quantum efficiency across the 5000–6200 Å I_2 absorption-line region. Furthermore, the smaller pixels of the EEV result in improved spectral sampling, and it suffers reduced charge diffusion compared with the MIT/LL, producing improved spectral resolution. This CCD change has not required any significant changes of observational or reduction procedure and has resulted in significantly increased signal-to-noise (S/N) ratio. In the future we envisage further improvements in observing efficiency and signal-to-noise ratio through the use of (i) an exposure meter, (ii) a motorized system for moving the I_2 cell in and out of the beam and (iii) a prime focus fibre feed for UCLES.

Doppler shifts are measured by observing through the 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 point spread function (PSF) of the spectrograph for changes in optics and illumination on all time-scales. We synthesize the echelle spectrum of each observation on a subpixel 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 S/N ratio of 200–300, without the I_2 cell present. Such measurements can only be obtained efficiently with good seeing conditions and take approximately 4 times as long to acquire as a standard *epoch* (I_2 and a 1-arcsec slit) observation. In Fig. 1 we show the mean of the residuals about zero velocity for a sample of apparently stable stars reported by Butler et al. (2001), and the residuals about a Keplerian fit for several detected planets. We achieve a precision of 3 m s^{-1} down to the $V = 7.5$ mag limit of the survey. The fundamental limit to the precision that can be achieved for our sample is set by a combination of S/N ratio (which is dependent on seeing and weather conditions), and the intrinsic velocity stability of our target stars, rather than our observing technique. Intrinsic velocity instability in these stars – often called 'jitter' – is induced by surface inhomogeneities (e.g. spots, plages or flares) combined with the rotation (Saar, Butler & Marcy 1998; Saar & Fischer 2000). There is currently no way to tell whether a residual scatter of greater than 3 m s^{-1} is caused by a small-amplitude planet (either short- or long-period – the detection of the latter is one of our primary goals, as these are Jupiter-like signals), 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. It is therefore vital to monitor all our targets for the lifetime of the survey not just those that appear to be good planet candidates.

Our target sample includes 178 FGK stars with declinations below $\sim -20°$ and $V < 7.5$, and a subsample of a further 23 metal-rich stars with $V < 11.5$. Where age–activity information is available from $\log R'_{HK}$ indices (Henry et al. 1996; Tinney et al.

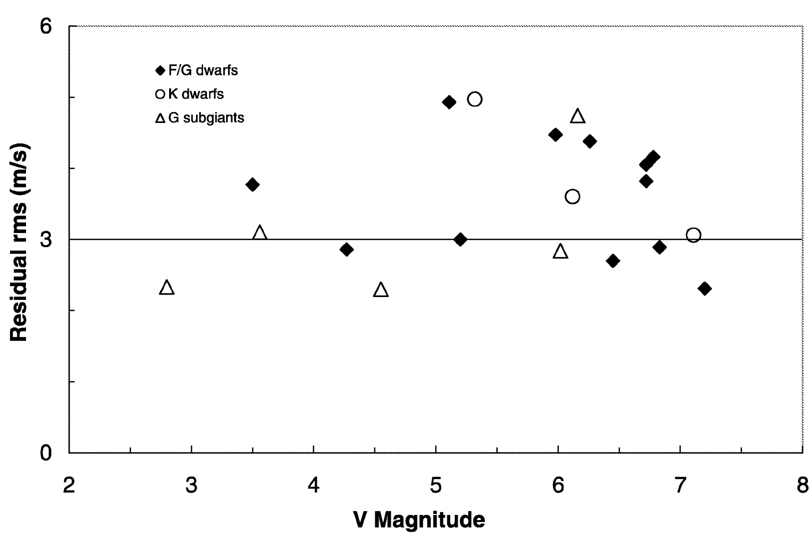

Figure 1. Velocity precision as a function of V magnitude for targets reported in Butler et al. (2001) and Tinney et al. (2001). The solid line at 3 m s^{-1} represents our target precision. Only the surveys at Lick and Keck have demonstrated comparable precision.

2002b) we require target stars to have log $R'_{HK} < -4.5$, 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 obtain an uncontaminated spectrum of a star with a nearby companion. Spectroscopic binaries discovered during the programme have also been removed and will be the subject of a separate paper (Blundell et al. 2002, in preparation). Otherwise there is no bias against observing multiple stars. The programme is not expected to have any bias against brown dwarf companions. The observing and data processing procedures follow those described in 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 April.

3 STELLAR CHARACTERISTICS AND ORBITAL SOLUTION FOR HD 39091

A total of 132 observations of HD 39091 (GJ 9189, HIP 26394, HR 2022) have been made by *Hipparcos*, yielding a distance of 18.2 pc and a *V* magnitude of 5.65 (ESA 1997). The resulting absolute magnitude is $M_V = 4.32$. The star is photometrically stable within the *Hipparcos* measurement error, with a photometric scatter of 0.006 mag. The Bright Star Catalogue (Hoffleit 1982) assigns a spectral type of G1V, in reasonable agreement with the *Hipparcos* spectral type of G3IV. The star is chromospherically inactive with $\log R'_{HK} = -4.97$ (Henry et al. 1996). Based on the spectroscopic analysis of Santos et al. (2001), [Fe/H] = 0.09 and mass = $1.1 \pm 0.02\,M_\odot$. Decin et al. (2000) find no evidence for a 60-μm excess in deep *ISO* data for HD 39091.

Table 1. Radial velocities (RV) for HD 39091 are referenced to the solar system barycentre but have an arbitrary zero-point determined by the radial velocity of the template.

HJD-2450 000	RV (m s^{-1})	Uncertainty (m s^{-1})
829.9930	−139.4	6.5
1119.2504	−186.4	10.1
1236.0329	−184.7	7.6
1411.3249	−198.3	6.7
1473.2670	−187.4	5.0
1526.0804	−203.6	6.8
1527.0821	−191.0	6.1
1530.1280	−195.6	6.4
1629.9116	−197.4	6.4
1683.8422	−203.1	6.2
1828.1875	−180.7	5.3
1919.0989	−146.8	9.3
1921.1383	−142.3	6.3
1983.9191	−119.3	6.7
2060.8396	28.2	6.2
2092.3366	106.5	5.8
2093.3515	100.7	5.5
2127.3278	175.8	7.1
2128.3357	171.1	5.8
2130.3383	166.9	7.4
2151.2917	193.5	5.5
2154.3043	195.1	10.8
2187.1959	179.0	4.8
2188.2359	176.9	4.4
2189.2212	175.8	4.4
2190.1464	178.1	4.4
2387.8706	−2.7	5.8
2389.8513	−8.0	5.4

The 28 Doppler velocity measurements of HD 39091, obtained between 1998 November and 2002 April are listed in Table 1 and shown graphically in Fig. 2. The third column labelled 'uncertainty' is the velocity uncertainty produced by our least-squares fitting. This fit simultaneously determines the Doppler shift and the spectrograph point spread function for each observation made through the iodine cell, given an iodine absorption spectrum and an iodine-free template of the object (Butler et al. 1996). 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-fitting Keplerian curve yields an orbital period of 2049 ± 150 d, a velocity amplitude of 196 ± 4 m s^{-1}, and an eccentricity of 0.62 ± 0.03. The minimum ($M \sin i$) mass of the planet is $10.3 M_{JUP}$, and the semimajor axis is 3.28 au. The rms to the Keplerian fit is 6.6 m s^{-1}, yielding a reduced chi-squared of 1.0. The properties of the extra-solar planet in orbit around HD 39091 are summarized in Table 2. It is interesting to note that Queloz et al. (2000) report HD39091 as having a constant radial velocity. However, Fig. 2 shows that in mid-2000 Queloz et al. would not have been sensitive to the long-period, eccentric companion reported here. Whilst we do not yet have a full orbit for HD 39091, we do clearly have a second inflection, which means that the orbit is starting to become clear. None the less, the parameters of the orbit are relatively poorly constrained and any follow-up observations should take this into account. We are announcing

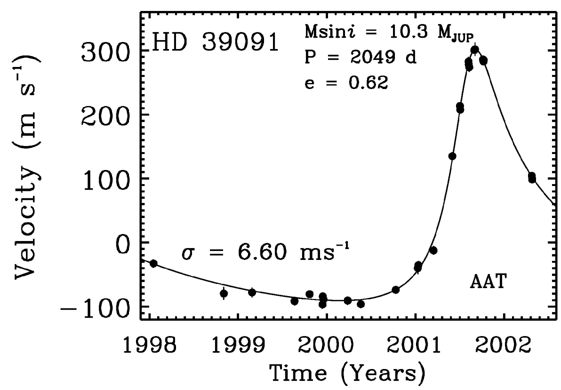

Figure 2. AAT Doppler velocities for HD 39091 from 1998 January to 2002 April. The solid line is a best-fitting Keplerian orbit with the parameters shown in Table 2. The rms of the velocities about the fit is 6.6 m s^{-1} consistent with our errors. Assuming $1.1 \pm 0.02\,M_\odot$ (Santos et al. 2001) for the primary, the minimum ($M \sin i$) mass of the companion is $10.3 M_{JUP}$ and the semimajor axis is 3.28 au.

Table 2. Orbital parameters for the companion to HD 39091. Uncertainties for measured parameters are shown in parentheses.

Orbital period (d)	2049 (150)
Eccentricity	0.61 (0.03)
ω (deg)	330 (20)
Radial velocity semi-amplitude K (m s^{-1})	196 (4)
Periastron time (HJD)	50 073 (150)
$M \sin i$ (M_{JUP})	10.3
a (au)	3.28
rms residuals to fit (m s^{-1})	6.60

this object at this somewhat early stage in order that adaptive optics and astrometric follow-up on this relative long-period object can be started as soon as possible.

We investigated the *Hipparcos* data set for HD 39091 using the set of tests devised by Pourbaix–Arenou (2001). These tests combine radial velocity measurements with those from *Hipparcos* to derive upper mass limits for companions. HD 39091 fails all the Pourbaix & Arenou tests apart from one. The Thiele–Innes orbit does improve the fit. However, the derived elements are not significantly different from zero and thus no constraint can be placed on the orbit. The reason for this is the long period. It exceeds the mission duration by a factor of 2, so the size of the orbit is not constrained at all. Neither does *Hipparcos* give a lower limit for the inclination. Such a limit is based on the size of the semimajor axis of the astrometric orbit when the period, eccentricity and periastron time are adopted from the spectroscopic solution. Once again, the method cannot be applied to HD 39091 since the period exceeds the mission duration. Hence, unfortunately, *Hipparcos* cannot provide any additional information.

4 DISCUSSION

It is interesting to note the mass of $10.3 M_{\rm JUP}$ places the companion of HD 39091 rather close to the canonical deuterium fusion limit of around $13 M_{\rm JUP}$. Most definitions of a planet posit that they should not be undergoing any nuclear fusion. Unfortunately, distinguishing the presence of deuterium and thus the lack of fusion is still beyond our current observational capabilities. Once we have (i) the capability to make high-resolution and high signal-to-noise ratio infrared spectroscopic measurements of such faint close-in companions and (ii) sufficiently high-quality molecular-line lists of HDO and H_2O, the mass and long orbit of HD 39091 make it a prime target.

The AAT, Keck and Lick precision velocity surveys are currently surveying a total of 1200 stars. All three of these programmes use the iodine cell technique, and all three have demonstrated long-term precision of $3\,{\rm m\,s^{-1}}$ (Marcy & Butler 1998; Vogt et al. 2000; Butler et al. 2001). The ellipticities for the substellar candidates from these surveys are shown in Fig. 3. The extra-solar planets show a wide range of eccentricity similar to the eccentricity distribution of binary systems with stellar companions (e.g. Duquennoy & Mayor 1991). This is not understood in terms of a global planetary formation model that also allows for the almost circular orbits in our Solar system. Given that we have only just started to explore the potential parameter space for extra-solar planets, history should remind us not to envisage the Solar system as a special case. It is important to note that our studies have not yet run for long enough to be sensitive to a true Solar system analogue.

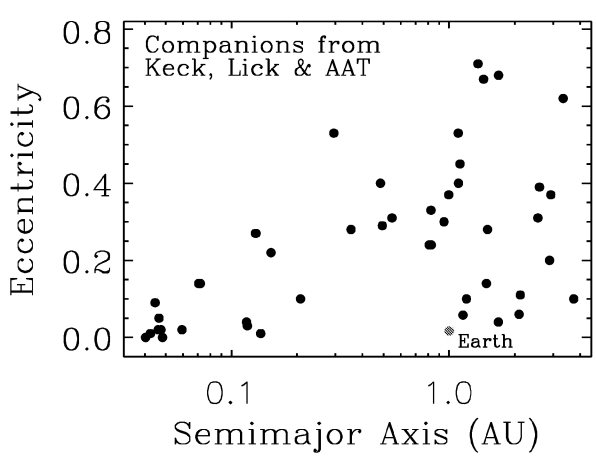

Figure 3. Eccentricity versus semimajor axis with the Earth shown for comparison. The circularity of the smallest planetary orbits (≈ 0.05 au) is expected caused by the strong tidal effects of the host stars. For planets orbiting between 0.15 and 3 au, eccentric orbits are the rule, not the exception. This plot is an update of that shown in Butler et al. (2000) and complements the plot in fig. 13 of Vogt et al. (2002).

The star HD 39091 is established as a metal-rich star relative to the Sun, which is itself metal-rich compared with the average of stars in the solar neighbourhood. The companion to HD 39091 reported here is thus consistent with the statistical findings of Santos et al. (2001) that stars with planets are metal-rich compared with stars without planet detections. There are two general classes of explanation for this: intrinsic metallicity bias and accretion of metal-rich material. After a variety of different spectral analyses and claims a straightforward explanation remains: the higher metallicity of planet-harbouring stars arises because high-metallicity environments have a higher probability of planet formation.

5 CONCLUSIONS

We present data showing evidence for an eccentric-orbit extra-solar planet around the metal-rich star HD 39091. The detection of this long-period object gives added impetus for the continuation of these searches to longer periods. We now must endeavour to continue to improve the precision and stability of the AAPS to be sensitive to the 10+ yr periods where analogues of the gas giants in our own Solar system may become detectable around other stars.

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