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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 a extrasolar planet candidate orbiting the G1 V star HD 39091. The orbital period is 2083 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: planetary systems - stars: individual (HD 39091); brown dwarf

1 INTRODUCTION

Since the discovery of the first extra-solar planet (Mayor & Queloz 1995), planetary detections have been dominated by northern hemisphere search programmes – most prolifically by 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 OHP (Baranne et al. 1996), McDonald Observatory (Cochran et al. 1997), AFOE (Noyes et al. 1997), and programmes at La Silla (Kurster et al. 2000; Queloz et al. 2000). Of these programmes, which achieve precisions of $\sim$ 10 m s^{-1}, only the latter has access to the sky south of ~ -20 deg, and these achieve precisions of $\sim$ 10 m s^{-1}. 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 m s^{-1}. In this paper we present the second set of results from this programme. Two companion papers, Tinney et al. (2002a, 2002b), present results for a further two planets and an initial investigation of the Calcium H and K activity among some of the target stars of the AAPS.

Precision Doppler surveys have found all of the known extrasolar 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 (Henry et al. 2000, Charbonneau et al. 2000); the first two sub-Saturn-mass planets (Marcy, Butler & Vogt 2000); and the AAPS' discovery of the first planet in a circular orbit outside the 0.1 au tidal-circularisation radius (Butler et al. 2001). A number of major surprises have emerged from the sample of extrasolar planets.

- The sub-stellar 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 $M_{\rm JUP}$. And surprisingly, brown dwarf companions to solar type stars are rare (Butler et al. 2000). This is in spite of a strong selection 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 two of the true masses.
- About $\sim$0.75% of nearby solar-type stars stars have been found to have planets orbiting in circularised orbits inward of 0.1 au (the 51 Peg-like "hot Jupiters"). A smaller fraction of stars is now being found to have "eps Ret -like" planets orbiting in circularised orbits at 1 au or so (Tinney et al. 2002). But the dominant class of extra solar planets, (found around some 7 per cent of target stars) show highly eccentric orbits within 3.5 au. None of these classes were predicted *a priori* by planetary formation theories. Such theories have

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

- The majority of extrasolar planets that have been found so far occur around stars which are mildy metal-rich (∼+0.2 dex with considerable scatter) compared to the Sun (Laughlin 2000; Santos, Israelian & Mayor 2002).

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 (AAPS) is carried out on the 3.92m 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 before the slit. UCLES used to be operated with an MIT/LL 2048×4096 15μm pixel CCD. Since August 2001 the AAPS has changed to the AAO's EEV 2048×4096 13.5μm pixel CCD. This CCD provides 30% better quantum efficiency across the 5000–6200 Å region containing I_2 absorption lines. Furthermore, the EEVs smaller pixels result in improved resolution and reduced charge diffusion. This CCD change has not required any significant changes of observational or reduction procedure and has resulted in significantly increased signal-to-noise. In the future we envisage further improvements in observing efficiency and S/N through the use of a (1) an exposure meter, (2) a motorised system for moving the I_2 cell in and out of the beam and (3) a prime focus fibre feed for UCLES.

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 spectrometer for changes in optics and illumination on all time scales. 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, which are measured against this reference template. This reference template is an observation at the highest available resolution (using a small 0.5 arcsec slit) and high S/N = 200 to 300, without the I_2 cell present. Such measurements can only be efficently obtained in good seeing and take about 4 times as long to acquire as a standard epoch (I_2 and a 1 arcsec slit) observation. We show in Fig. 1 the residuals about zero velocity for a sample of apparently stable stars reported by Butler et al. (2001), as well as the residuals about a Keplerian fit for several detected planets. We achieve 3 m s^{-1} precisions down to the V = 7.5 magnitude 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 (which is dependent on good seeing and weather conditions), and the intrinsic velocity stability of our target stars often called "jitter", induced by activity and/or star spots (Saar et al. 1998; Saar & Fischer 2000), rather than our observing technique. 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 (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 periodicites 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 ~ -20 deg and V<7.5, and a further 23 metal-rich stars with V<11.5. Where age/activity information is available from log $R_{\rm HK}$ indices (Henry et al. 1996; Tinney et al. 2002a) we require target stars to have log $R_{\rm HK} < -4.5$ 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 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 follows that described in Butler et al. (1996,2001). Our first observing run was in January 1998, and the last run for which observations are reported here was in October 2001.

3 STELLAR CHARACTERISTICS AND ORBITAL SOLUTION FOR HD 39091

A total of 26 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 $M_{\rm V}$ = 4.32. The star is photometrically stable within the HIPPARCOS measurement error, with a photometric scatter of 0.006 magnitudes. 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 $R_{\rm HK}$ = –4.97 (Henry et al. 1996). Based on the spectroscopic analysis of Santos, Israelian & Mayor (2002), [Fe/H] = 0.09 and Mass = 1.1±0.02 $M_\odot$. Decin et al. (2000) find no evidence for a 60 μm excess in deep ISO data for HD 39091. It is interesting to note that Queloz et al. (2000) report HD 39091 as a non-variable star, however, the Queloz et al. survey would not yet have been sensitive to the long period of HD 39091.

The 26 Doppler velocity measurements of HD 39091, obtained between November 1998 and October 2001, are listed in Table 1 and shown graphically in Fig. 2. The third column labelled error 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-fit Keplerian curve yields an orbital period of 2083 d, a velocity amplitude of 196 m s^{-1}, and an eccentricity of 0.62. The minimum (M sin i) mass of the planet is 10.3 $M_{\rm JUP}$, and the semi-major axis is 3.34 au. The RMS to the Keplerian fit is 6.6 m s^{-1}, yielding a reduced chi-squared of 1.1. The properties of the extra-solar planet in orbit around HD 39091 are summarised in Table 2. Whilst we do not yet have a full orbit for HD 39091, we do clearly have a 2nd inflection, which means that the orbit is starting to become clear. However, the parameters of the orbit are relatively poorly constrained and any follow-up observations should take this into account. We are announcing 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 dataset 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 two 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 amplitude (the astrometric semi-major axis of the orbit) corresponding to the spectroscopic period. Once again, the method can not 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_{JUP} places HD 39091's companion rather close to the canonical deuterium fusion limit of around 13 M_{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 (1) the capability to make high resolution and high signal-to-noise infrared spectroscopic measurements of such faint close-in companions and (2) sufficiently high quality molecular line lists of HDO and H_2O, HD 39091's mass and long orbit 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 3m 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.

The star HD 39091 is established as metal-rich star relative to the Sun which is itself metal-rich compared to the average of stars in the solar neighbourhood. The companion to HD 39091 reported here thus further confirms the statistical findings of Santos et al. (2002) that stars with planets are metal rich compared to 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+ year periods where analogues of the gas giants in our own Solar System may become detectable around other stars.

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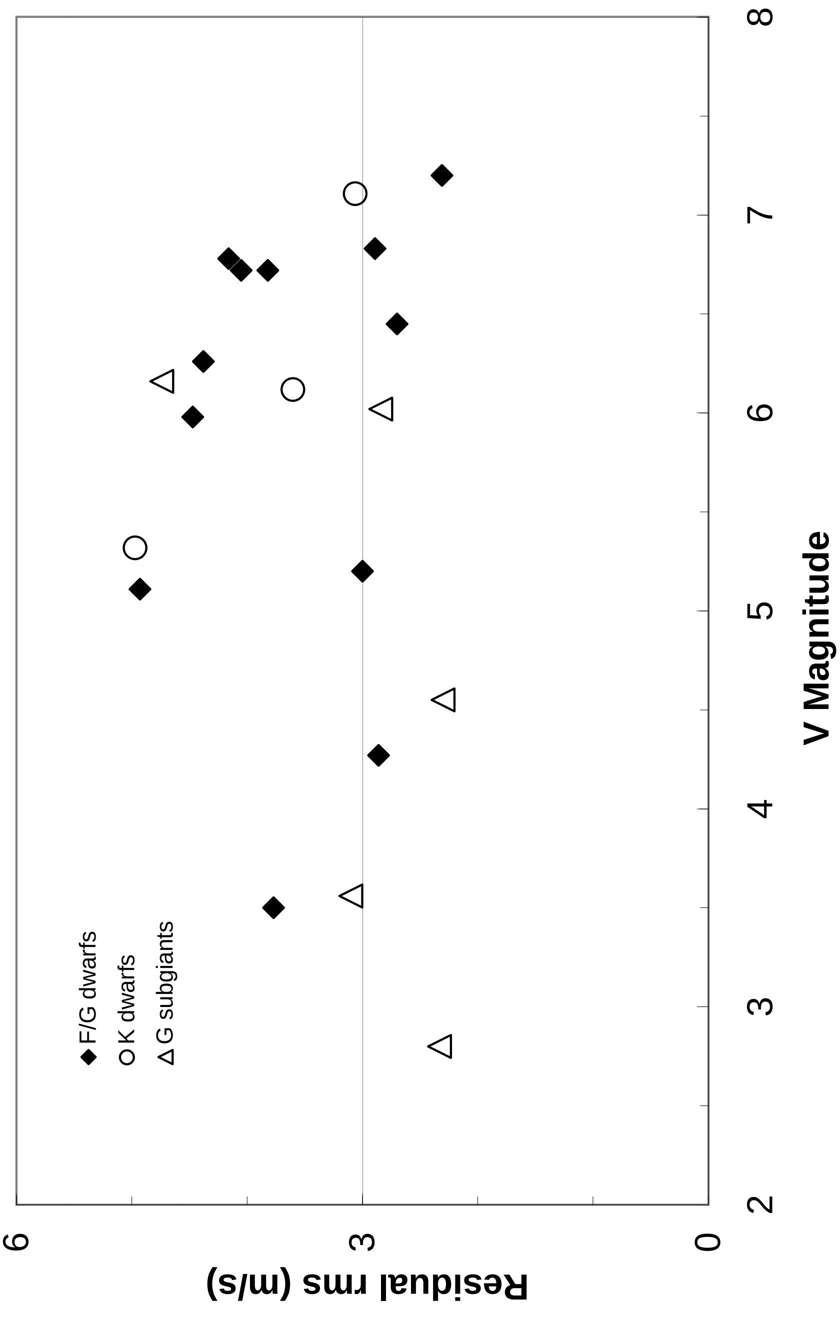

Figure 1. Velocity precision as a function of V magnitude for targets reported in Butler et al. (2001) and Tinney et al. (2001). The solid line at 3 m s^{-1} represents our target precision. Only the surveys at Lick and Keck have demonstrated comparable precision.

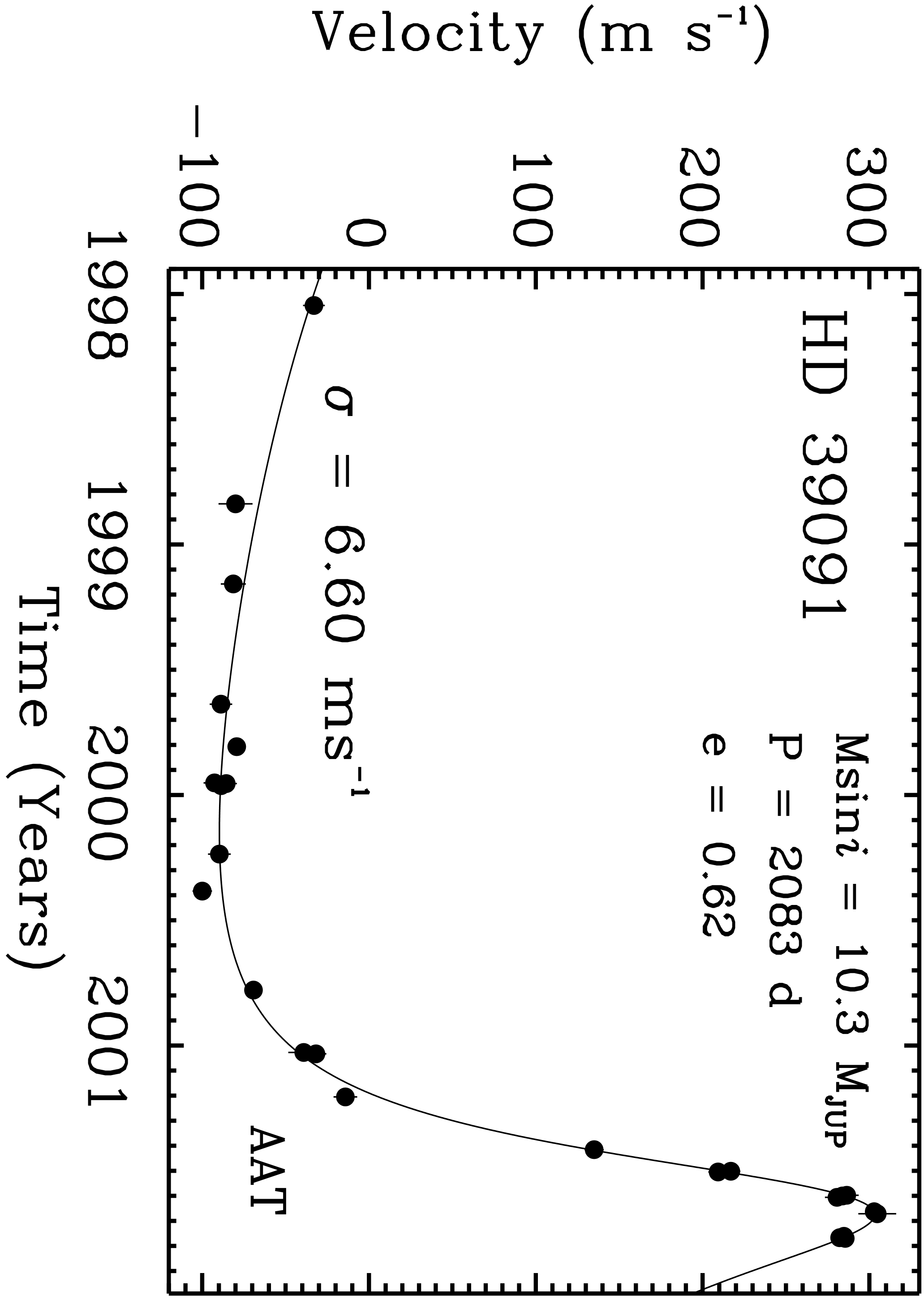

Figure 2. AAT Doppler velocities for HD 39091 from January 1998 to October 2001. The solid line is a best fit Keplerian with the parameters shown in Table 2. The RMS of the velocities about the fit is 6.7 m s^{-1} consistent with our errors. Assuming 1.1±0.02 $M_\odot$ (Santos et al. 2002) for the primary, the minimum (M sin *i*) mass of the companion is 10.3 M_{JUP} and the semi-major axis is 3.34 au.

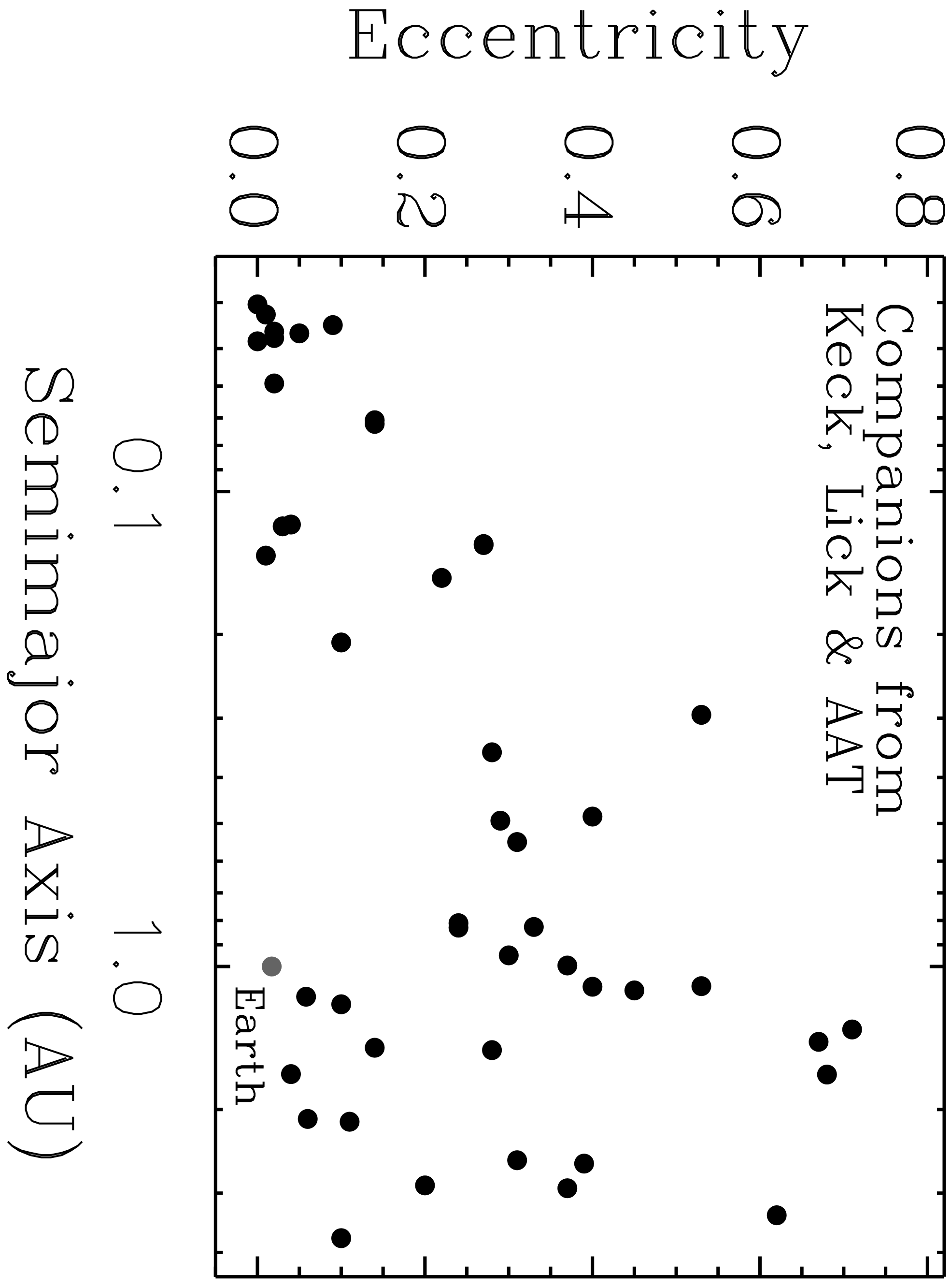

Figure 3. Eccentricity vs Semi-major axis with the Earth shown for comparison. The circularity of the smallest planetary orbits (≈ 0.05 au) is expected due to the strong tidal effects of the host stars. For planets orbiting between 0.15 and 3 au, eccentric orbits are the rule, not the exception. This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

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

JD -2450000	RV m s^{-1}	Error m s^{-1}
829.9930	-133.0	5.1
1236.0329	-191.4	6.0
1411.3249	-188.0	7.0
1473.2670	-173.1	5.2
1526.0804	-184.1	5.2
1527.0821	-175.7	4.7
1530.1280	-175.7	5.2
1629.9116	-181.0	6.0
1683.8422	-192.2	4.7
1828.1875	-167.9	4.5
1919.0989	-158.0	8.6
1921.1383	-143.0	5.2
1983.9191	-103.0	5.6
2060.8396	34.0	4.8
2092.3366	125.3	5.1
2093.3515	125.0	4.4
2127.3278	196.3	6.8
2128.3357	194.5	5.0
2130.3383	190.4	7.2
2151.2917	206.3	5.0
2154.3043	203.1	9.6
2187.1959	179.5	4.2
2188.2359	181.7	3.9
2189.2216	178.7	4.0
2190.1445	176.8	4.1

Table 2. Orbital parameters for the companion to HD 39091.

Orbital Period	2083 (637)
eccentricity	0.62 (0.05)
ω	330 (8)
Velocity amplitude K (m s^{-1})	196 (18)
Periastron Time (JD)	52122.1 (9.5)
M sin i ($M_{\rm JUP}$)	10.3
a (au)	3.34
RMS to Fit	6.60