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An exoplanet in orbit around τ^1 Gruis

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ABSTRACT

We report the detection of a new candidate exoplanet around the metal-rich star τ^1 Gruis. With M sin i = 1.23±0.18 M_{JUP}, a period of 1326±300 d and an orbit with an eccentricity of 0.14±0.14 it adds to the growing population of long period exoplanets with near-circular orbits. This population now comprises more than 20% of known exoplanets.

When the companion to τ^1 Gruis is plotted together with all exoplanets found by the Anglo-Australian Planet Search and other radial velocity searches we find evidence for a peak in the number of short-period exoplanets, followed by a minimum of planets between around 7 and 50 days and then an apparent rise in the number of planets per unit radius that seems to set in by a hundred days, indicating more planets farther from the host star. This is very different from the gaussian-like period distribution found for stellar companions. This lends support to the idea that once a clearing in the inner protoplanetary disk develops, it halts the inward migration of planets. In particular, the smooth distribution of exoplanets arising from planetary migration through a disk is altered by an accumulation of exoplanets at the point where the disk has been cleared out.

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Key words: planetary systems - stars: individual (HD216435), brown dwarfs

1 INTRODUCTION

The Anglo-Australian Planet Search (AAPS) is a long-term planet detection programme which aims to perform exoplanet detection and measurement at the highest possible precision. Together with programmes using similar techniques on the Lick 3 m and Keck I 10 m telescopes (Fischer et al. 2001; Vogt et al. 2000), it provides all-sky planet search coverage for inactive F, G, K and M dwarfs down to a magnitude limit of V=7.5. So far the AAPS has has published data for 17 exoplanets. (Tinney et al. 2001; Butler et al. 2001; Butler et al. 2002a; Jones et al. 2002a,b; Tinney et al. 2002a,b).

The AAPS is carried out on the 3.9m Anglo-Australian Telescope (AAT) 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. 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. 2002a).

Our target sample, which we have observed since 1998, is given in Jones et al. (2002b). It includes 178 late (IV-V) F, G and K stars with declinations below $\sim -20°$ 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 $\sim -20°$. The sample is being increased to around 300 solar-type stars to be complete to a magnitude limit of V=8. Where age/activity information is available from log R'(HK) indices (Henry et al. 1996; Tinney et al. 2002c) 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 get an uncontaminated spectrum of a star with a nearby companion. Spectroscopic binaries discovered during the programme have also been removed and will be reported elsewhere (Blundell et al., in preparation). 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).

2 STELLAR CHARACTERISTICS OF τ^1 GRUIS

The Bright Star Catalog assigns τ^1 Gruis a spectral type of G0V, compared to the Hipparcos spectral type of G3IV. Its parallax of 30.0±0.7 mas (ESA 1997) together with a V magnitude of 6.03 imples an absolute magnitude of M_V = 3.42±0.03 and $M_{\rm bol}$=3.20±0.05 (Cayrel et al. 1997). This absolute magntidue puts τ^1 Gruis a magnitude above the main sequence and explains the discrepancy between the literature assigned spectral types G0V and G3IV.

Figure 1 shows the Ca II H line for τ^1 Gruis (HD 216435, HIP113044, HR8700) and indicates it is chromospherically inactive, confirming the activity index log R'(HK) = –5.00 found by Henry et al. (1996). Furthermore there is no evidence for significant photometric variability in the 121 measurements made by the Hipparcos satellite. Combining Hipparcos astrometry of τ^1 Gruis with its SIMBAD radial velocity yields a space velocity with respect to the local standard of rest: U, V, W = –27.5, –21.7, –10.5. Its inferred age is 5 Gyr(Gonalez 1999). Favata, Micela & Sciortino (1996) report an equivalent width Li detection of 70 mÅ equating to an abundance of lithium N(Li) = 2.44, consistent with other similar metal-rich sub-giants (Randich et al. 1999). di Benedetto (1998) has calculated the effective temperature of τ^1 Gruis to be 5943±60 K as part of a substantial programme to apply the infrared flux method and angular diameters from interferometry experiments to ISO standard stars with V-K measurements. Like many of the stars found to have extra-solar planets, τ^1 Gruis is metal rich with [Fe/H] derived from high resolution spectroscopic analysis of Fe lines is +0.15±0.04 (Favata, Micela & Sciortino 1997). Interpolation between the tracks of Fuhrmann, Pfeiffer & Bernkopf (1998) and Girardi et al. (2000) indicates a mass of 1.25±0.10 $M_\odot$.

3 ORBITAL SOLUTION FOR τ^1 GRUIS

The 40 Doppler velocity measurements of τ^1 Gruis, obtained between 1998 August and 2002 August, are shown graphically in Figure 2 and listed in Table 1. 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 data are well-fit by a Keplerian curve which yields an orbital period of 1326 ± 300 d,

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a velocity amplitude of 20 ± 2 m s^{-1}, and an eccentricity of 0.14 ± 0.14. The minimum (M sin i) mass of the planet is 1.2 ± 0.1 M_{JUP}, and the semi-major axis is 2.6 ± 0.6 au. The RMS to the Keplerian fit is 6.92 m s^{-1}, yielding a reduced chi-squared of 1.24. Since τ^1 Gruis is relatively bright (V=6.03) and inactive, the measured RMS seems a little high. We have investigated our data and find that the internal velocity errors correlate well with the number of photons per pixel. The velocity errors vary nearly as $1/\sqrt{(\text{photons})}$, as one would expect. We consider that there is some constant error of around ~3 m s^{-1}, probably caused by inadequate S/N in our template measurement. We also note that at the spectral type of τ^1 Gruis, G0V, our precision is limited by the smaller equivalent widths of stellar lines relative to later spectral types. Thus with our observing exposures adjusted to give S/N=200 per exposure our precision is probably limited to around 4 rather than 3 m s^{-1}. The lack of any observed chromospheric activity or photometric variations gives us confidence that the radial velocity signature arises from an exoplanet rather than from long-period starspots or chromospherically active regions. The properties of the candidate extra-solar planet in orbit around τ^1 Gruis are summarised in Table 2.

4 DISCUSSION

The companion to τ^1 Gruis announced here serves to further reinforce the predominantly metal-rich nature of stars with exoplanets. It also adds to the growing population of long period exoplanets with near-circular orbits. Now more than 20% of exoplanets have orbital parameters within those of the Solar System. It is notable that as the Anglo-Australian Planet Search becomes sensitive to longer periods, we are continuing to find objects with longer periods, but remain limited by our first epoch observations. τ^1 Gruis is a pleasing example. Within the errors its velocity amplitude is nearly as low as any long-period single exoplanet announced by radial velocity searches and the error on its period is dominated by our first epoch observation. Thus the detection of an exoplanet around τ^1 Gruis together with our long-term stable stars (e.g., Butler et al. 2001) gives us confidence in the stability of our search as we move to longer periods and the possibility of detecting Jupiter analogues.

The radial velocity signal we measure for τ^1 Gruis suggests a planet with a minimum mass around that of Jupiter. τ^1 Gruis b becomes the fifth exoplanet to be found with a mass around that of Jupiter with a period of greater than three years and indicates that radial velocity surveys now have significant sensitivity to Jupiter mass planets out to relatively large periods.

It is thus intriguing to look at the period distribution of exoplanets found by the AAPS and other radial velocity searches. In Butler et al. (2002b), we plotted a histogram of semi-major axes for exoplanets from the Lick, Keck and AAT searches. This showed a relatively large number of exoplanets at very short orbits and a tail of objects with longer orbits. The detection of long period planets and long-term stable stars indicated that the peak at short periods was a real feature. Two years later, with twice as many exoplanets known, Figure 3 shows the exoplanets that have been announced based on exoplanets.org by 2002 August 21. The bulk of known exoplanets now lie at relatively large periods. Although the AAPS has been operating for less time than other successful searches, Figure 3 also shows that the exoplanets published by the AAPS are dominated by companions at longer periods such as τ^1 Gruis b. The top part of Figure 3 shows a peak at shorter periods together with a substantial fraction at longer periods. Interestingly there appears to be a gap in the distribution between periods of around 7 and 50 days. The evidence for this gap is relatively poor when considering the AAT planets alone though striking when all exoplanets are considered.

The relative lack of exoplanet candidates from around 0.2 to 0.6 AU was noted by Cummings, Marcy & Butler (1999) and Butler et al. (2002b) and is also evident in fig. 2 of Heacox et al.(1999), fig. 5 of Rabachnik & Tremaine 2001, fig. 4 of Lineweaver & Grether (2002) and fig. 7 of Armitage et al. (2002). Armitage et al. interpret this feature as a slight excess of exoplanets at the shortest periods and attribute it to the completeness of radial velocity surveys falling off toward longer periods. However, the observed period distribution actually appears to rise toward longer periods where the incompleteness of the radial velocity surveys falls rapidly. To allow for this incompleteness introduced by including lots of low-mass short-period exoplanets we follow Armitage et al. (2002) and consider planets in a restricted mass and period range where the surveys can be judged to be more complete. Following the analysis of Cummings et al. (1999), Armitage et al. consider the known exoplanets to be complete in the mass range 0.6–10 M_{JUP} sin i for periods of less than 3 AU. In the middle plot of Figure 3 we show the period distribution for a 0.6–10 M_{JUP} mass cut off as well as all announced planets. The removal of the lowest mass exoplanets reduces the peak of very short period planets, however, the peak at short periods remains an order of magnitude higher than would be expected from an extension of counts at longer periods. We have also looked at the CORALIE, Keck and Lick surveys in the same manner as for the AAPS. Despite different radial velocity surveys operating with different samples, sensitivities, instruments, scheduling, strategies and techniques we do find evidence for the gap in each of the major surveys. As mentioned above, this gap is evident in a number of works by other authors though is relatively less pronounced because of the substantially smaller number of exoplanets announced when those plots were made. The pronounced nature of this peak leads us to consider Fig. 4 to show evidence for two (or more) populations of exoplanets. That is, a population of exoplanets spanning a small range of short periods (3-7 days) and an separate population increasing with number towards larger periods.

From the lower part of Figure 3, it can be seen that there is no evidence for such a gap in the stellar binary distribution. The stellar companion period distribution plotted was determined by Duquennoy & Mayor (1991) using the same general radial velocity method to discover binary stars as used to discover the exoplanets. Duquennoy & Mayor find it necessary to make corrections to the stellar binary period distribution for incompleteness at longer periods, however, no such corrections are necessary for shorter periods and they find no gap in short-period stellar binaries. Overall Duquennoy & Mayor find that the period distribution of stellar binaries is well fit by a gaussian. Since stellar companions are expected to form via large-scale gravitational instabilities in collapsing cloud fragments or massive disks, whereas planets are expected to form by accretion in dissipative circumstellar disks it is not surprising that stellar and planetary companions should have different period distributions.

The period distribution for exoplanets has been investigated a number of times as the number of radial velocity exoplanets has grown. The existence of a peak at very short periods has been an important motivation in the development of migration theories for exoplanets (Lin et al. 1999; Murray et al. 1998; Trilling et al. 1998; Ward 1997; Armitage et al. 2002; Trilling, Lunine & Benz 2002). The trend toward finding an increasing number of exoplanets with large orbital separation runs counter to the selection effects inherent in radial velocity searches and has been well reproduced by migration theories (Armitage et al. 2002; Trilling et al. 2002). Whilst selection effects start to play an increasingly important role beyond around few hundred days (e.g. Duquennoy & Mayor 1991; Cummings et al. 1999; Butler et al. 2002b), we do not consider them to be significant between 7 and 50 days and thus consider the 'gap' in exoplanet periods to be a feature of the period distribution not currently predicted by migration theories. It is interesting to speculate on the origin of the possible gap in the exoplanet period distribution.

The onset of the stellar wind in young stars and the magnetic clearing of a hole at the centre of the disk will lead to the evacuation of the circumstellar disk and prevent migration of planets. This is expected to happen sooner in stars of higher mass and suggests the exoplanets of stars with higher mass will lie at greater radii. So far the range of stellar masses yielding significant numbers of exoplanets is rather small and we find no clear difference in exoplanet properties for stars of different mass. Even without such evidence, migration theory does provide an attractive explanation for a range of exoplanet properties. Migration theory can already reasonably explain the progressively larger number of exoplanets at larger radii and with the inclusion of appropriate stopping mechanisms (e.g. Lin, Bodenheimer & Richardson 1996; Kuchner & Lecar 2002) may also be able to consistently produce the peak in the period distribution of short period planets.

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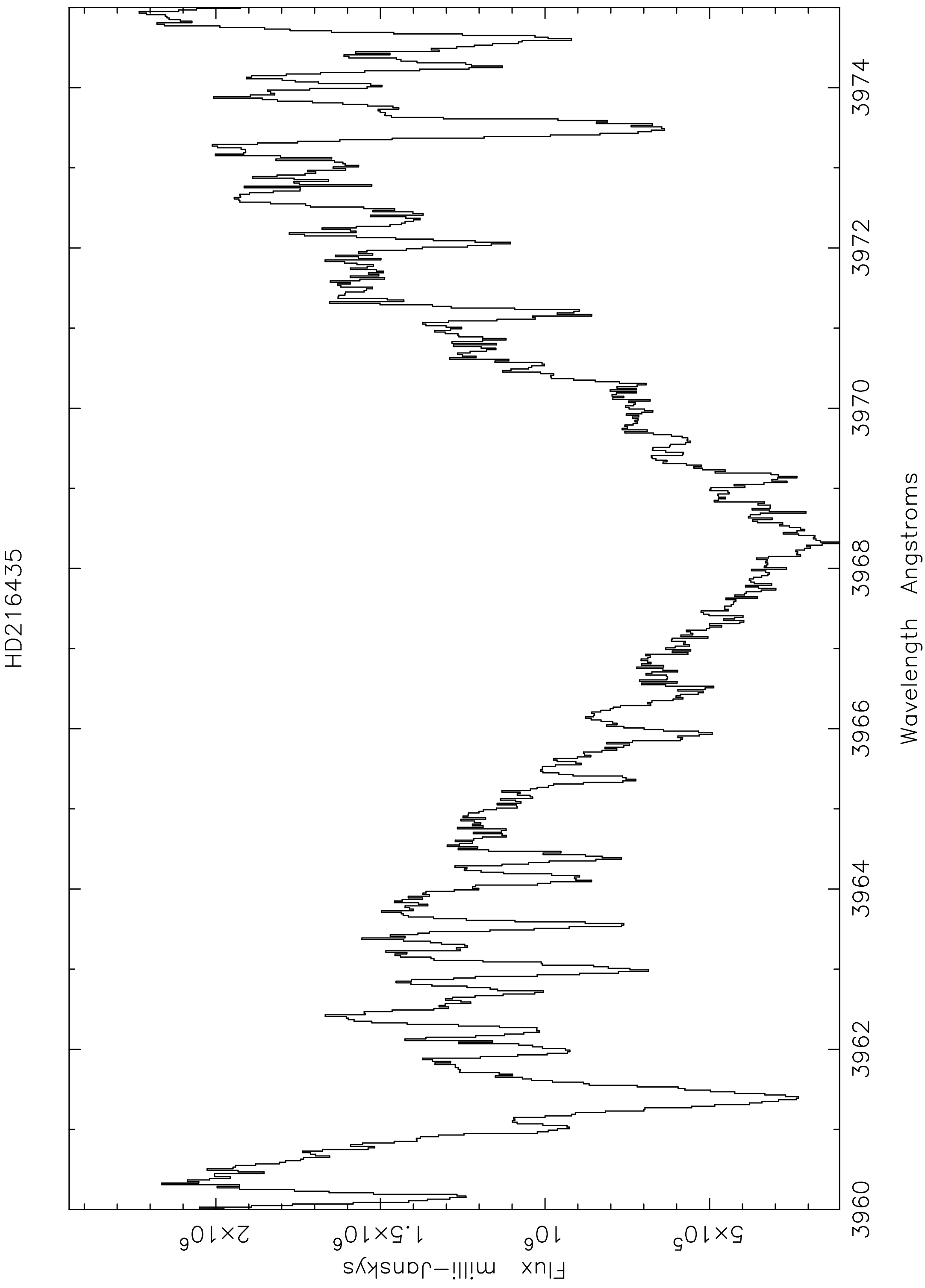

Figure 1. The figure shows the CaII H line core in τ^1 Gruis. No emission is evident confirming the low activity index, log R'(HK) = –5.00, measured by Henry et al. (1996). The activity of the entire AAPS sample will be assessed in forthcoming papers by Tinney et al. (in preparation) and Blundell et al. (in preparation).

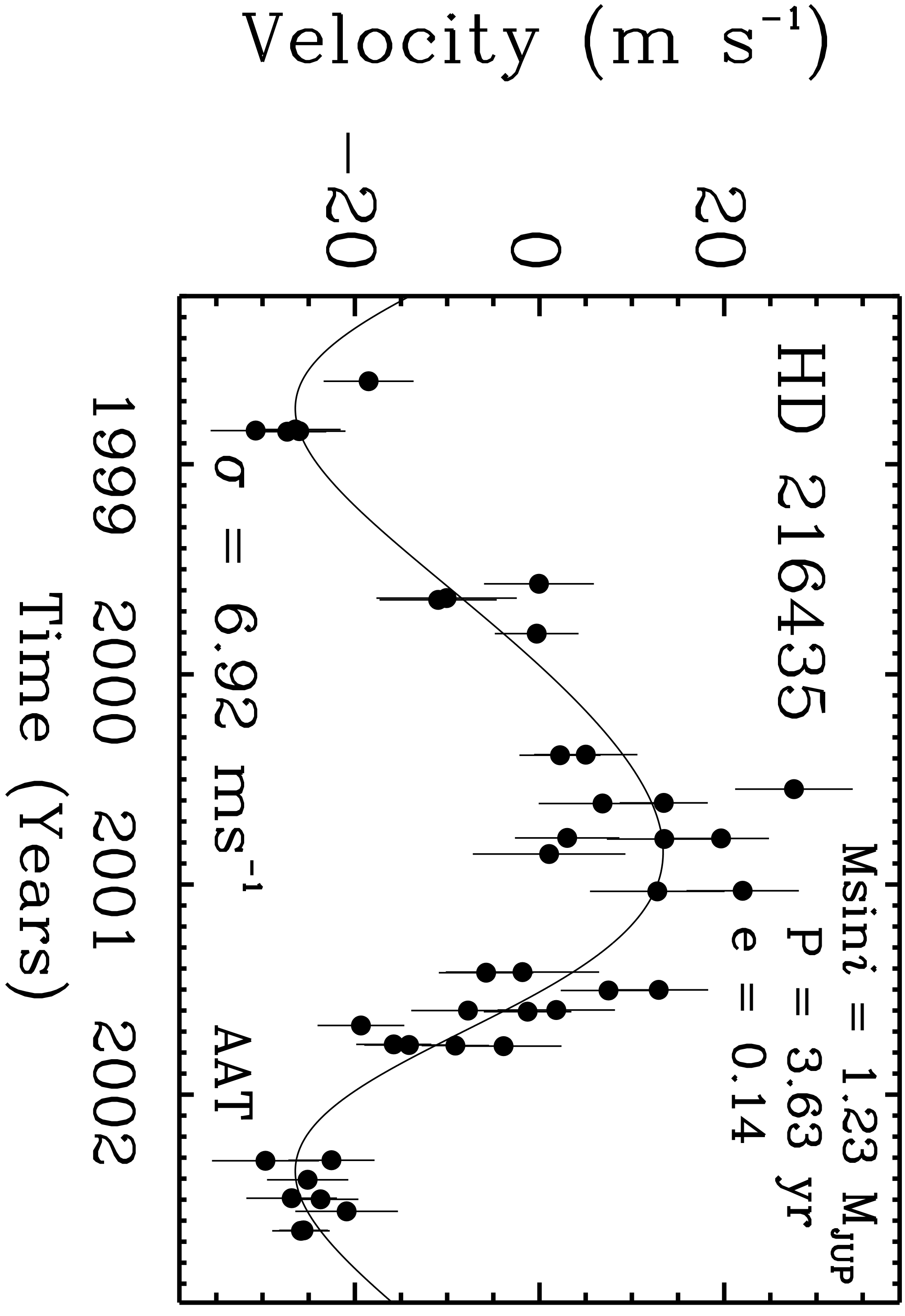

Figure 2. Doppler velocities obtained for τ^1 Gruis from 1998 August to 2002 August. The solid line is a best fit Keplerian with the parameters shown in Table 1. The rms of the velocities about the fit is 6.83 m s^{-1}. Assuming 1.25 M$\odot$ for the primary, the minimum (M sin i) mass of the companion is 1.23 M_{JUP} and the semimajor axis is 2.6 au.

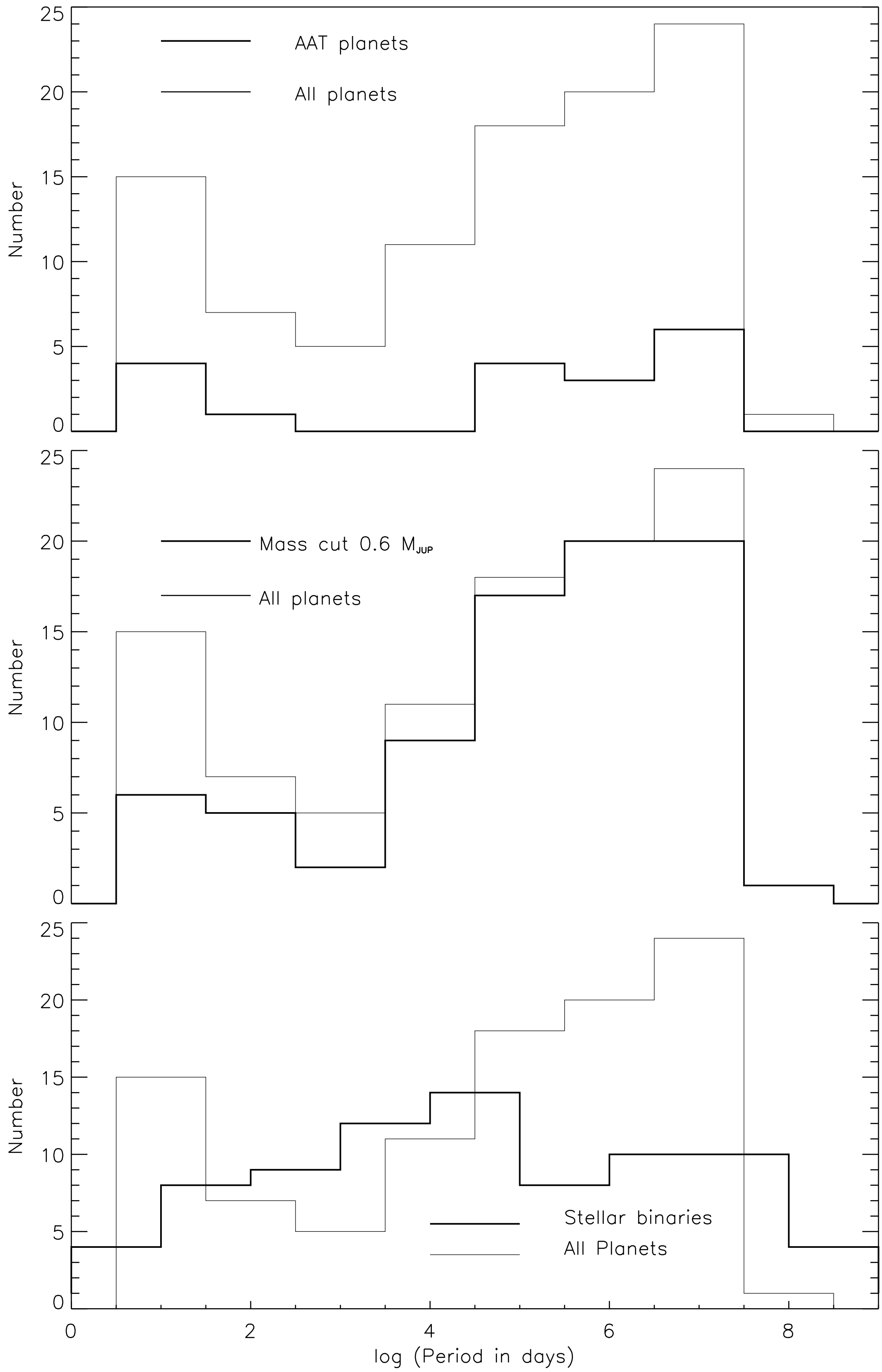

Figure 3. The number of exoplanets discovered within natural logarithm period bins is shown. The top part of the figure compares all radial velocity planets announced based on exoplanets.org/almanacframe.html (2002 August 21) with those published by the AAT. This includes planets in the AAT sample that were first published by other planet search projects. The middle part of the figure compares the period distributions of all planets to those with masses less than 10 M_{JUP} sin i and greater than 0.6 M_{JUP} sin i. The bottom part compares all published planets with the stellar binaries as found by Duquennoy & Mayor (1991).

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Table 1. Velocities for τ^1 Gruis. Julian Dates (JD) are heliocentric. Radial Velocities(RV) are heliocentric but have an arbitrary zero-point determined by the radial velocity of the template.

JD -2451000	RV m s^{-1}	Error m s^{-1}
34.2105	-9.5	4.9
118.0436	-17.4	4.9
119.9400	-21.7	4.9
120.9997	-17.0	5.0
121.9209	-18.3	4.2
386.3182	8.9	5.9
411.1493	-1.1	7.6
414.2635	-2.0	6.3
472.9492	8.7	4.5
683.3180	14.0	5.6
684.3245	11.2	4.4
743.2420	36.6	6.4
767.1997	22.5	4.8
768.2187	15.8	6.9
828.0383	12.0	5.7
828.9589	28.7	5.2
829.9527	22.5	6.2
856.0436	10.0	8.3
919.9251	31.0	6.1
920.9303	21.8	7.3
1061.2803	7.2	8.3
1062.3446	3.2	5.1
1092.2145	21.9	5.4
1093.2415	16.5	5.2
1127.1922	10.8	6.4
1128.1475	1.3	6.1
1130.1052	7.7	4.7
1154.0982	-10.3	4.7
1186.9518	-6.8	4.1
1188.0403	-5.1	4.8
1188.9741	-0.1	3.6
1189.9808	5.1	6.3
1388.3132	-13.5	4.7
1389.3008	-20.7	5.8
1422.3045	-16.1	4.4
1454.3375	-17.8	4.9
1456.2765	-14.7	4.1
1477.1981	-11.9	5.6
1510.2436	-16.6	2.6
1511.0242	-16.8	3.1

Table 2. Orbital parameters for the companion to τ^1 Gruis.

Parameter	τ^1 Gruis b
Orbital Period (d)	1326±300
Eccentricity	0.14±0.14
ω (deg)	115±60
Velocity amplitude K (m s^{-1}	20±2
Periastron Time (JD)	50894±300
M sin i (M_{JUP})	1.23±0.18
a (AU)	2.6±0.6
RMS to Fit	6.92