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The Anglo-Australian Planet Search – XXI. A Gas-Giant Planet in a One Year Orbit and the Habitability of Gas-Giant Satellites[1]

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ABSTRACT

We have detected the Doppler signature of a gas-giant exoplanet orbiting the star HD 38283, in an eccentric orbit with a period of almost exactly one year ($P = 363.2 \pm 1.6$ d, $m \sin i = 0.34 \pm 0.02\,\mathrm{M_{Jup}}$, $e = 0.41 \pm 0.16$). The detection of a planet with period very close to one year critically relied on year-round observation of this circumpolar star. Discovering a planet in a 1 AU orbit around a G dwarf star has prompted us to look more closely at the question of the habitability of the satellites of such planets. Regular satellites orbit all the giant planets in our Solar System, suggesting that their formation is a natural by-product of the planet formation process. There is no reason for exomoon formation not to be similarly likely in exoplanetary systems. Moreover, our current understanding of that formation process does not preclude satellite formation in systems where gas-giants undergo migration from their formation locations into the terrestrial planet habitable zone. Indeed, regular satellite formation and Type II migration are both linked to the clearing of a gap in the protoplanetary disk by a planet, and so may be intextricably linked. Migration would also multiply the chances of capturing both irregular satellites and Trojan companions sufficiently massive to be habitable. The habitability of such exomoons and exo-Trojans will critically depend on their mass, whether or not they host a magnetosphere, and (for the exomoon case) their orbital radius around the host exoplanet.

Subject headings: planetary systems – stars: individual (HD 38283)

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1. Introduction

Depending on the definition of "confirmed" adopted, and the list of exoplanets that is consulted, the number of confirmed exoplanets is now either rapidly approaching, or has already passed, 500. The efficiency with which exoplanets are being detected has evolved to the point that new planet search programs are being actively considered to target the detection of terrestrial-mass planets in Earth-like orbits around Sun-like stars (see e.g. proposals for the G-CLEF (Jaffe et al. 2010), ESPRESSO (Pepe et al. 2010) and HARVESTER[7] instruments). However, given planet searches for Earth-like Doppler signatures will be undertaken *from* an Earth-like planet, one concern such programs will have is the accurate removal of the Doppler signature of the Earth itself, and the removal of the strong annual window function and selection effects that ground-based observations suffer in searching for one year periodicities.

The technology for detecting gas-giant planets at orbital periods of one year has been with us now for over a decade. It is somewhat surprising therefore that *no* exoplanets (amongst the almost 500 now in hand) have been discovered with periods of between 360 and 370 d! Gas-giant planets with periods of near one year are themselves of great intrinsic interest, because (as was realised by most researchers soon after the first gas-giant planets were discovered within 1 AU – see e.g. Williams et al. 1997) they are likely to host their own satellite systems, which could well be "habitable" in the same way that the Earth is habitable. That is, they may have solid surfaces, and be able to retain liquid water at their surfaces for periods of billions of years.

In this paper we report the discovery by the Anglo-Australian Planet Search (AAPS) of a $0.34\,\mathrm{M_{Jup}}$ (minimum mass) planet which orbits the star HD 38283 with a period of almost exactly one year (363.2 ± 1.6 d). In addition, we explore further the habitability of potential exomoons and exo-Trojan companions for giant exoplanets in the range ≈0.5-2 AU.

2. HD 38283

HD 38283 (HIP 26380) lies at a distance of 37.7 ± 0.9 pc (Perryman et al. 1997). It was classified as G0/G1V by Houk & Cowley (1975) and F9.5V by Gray et al. (2006). It has an absolute magnitude of $M_\mathrm{V} = 3.82$ ($V = 6.702$) and $B - V = 0.540$. Hipparcos photometry finds it to be photometrically stable at the 7 milli-magnitude level from 100 observations over the course of the Hipparcos mission (Perryman et al. 1997). Table 1 summarises the current state of the measurements of HD 38283's physical properties. In brief, HD 38283 is ≈150 K hotter and 2.35 times brighter than the Sun, has a metallicity about 50% lower (i.e. ≈ -0.2 dex), and a mass just slightly larger. In the analysis which follows we assume a mass of $1.085\mathrm{M}_\odot$ (Takeda et al. 2007). HD 38283 has a rotation velocity of $v \sin i = 3.0\,\mathrm{km\,s^{-1}}$ and is inactive with a mean $\log \mathrm{R}'_\mathrm{HK}$ from

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[7] http://exoplanets.astro.psu.edu/workshop/presentation/3-b-Johnson-AO.pdf

the two published measurements of -4.97. Based on this its stellar jitter due to activity is predicted by the updated Ca II jitter calibration of J.Wright (priv.comm.) to be $3.0\,\mathrm{m\,s^{-1}}$.

3. Observations & Analysis

AAPS began operation in 1998 January, and is currently surveying 250 stars. It has discovered some 34 exoplanets with $m \sin i$ ranging from $5.1\,\mathrm{M}_\oplus$ to $10\,\mathrm{M_{Jup}}$ (Tinney et al. 2001, 2002a, 2003, 2005, 2006, 2011; Butler et al. 2001, 2002; Jones et al. 2002, 2003a,b, 2006, 2010; Carter et al. 2003; McCarthy et al. 2004; O'Toole et al. 2007, 2009; Bailey et al. 2009; Vogt et al. 2010a). AAPS Doppler measurements are made with the UCLES echelle spectrograph (Diego et al. 1990). An iodine absorption cell provides wavelength calibration from 5000 to 6200 Å. The spectrograph point-spread function and wavelength calibration is derived from the iodine absorption lines embedded on every pixel of the spectrum by the cell (Valenti et al. 1995; Butler et al. 1996). Observations of HD 38283 began as part of the AAPS main program in 1998 January, and over the subsequent years it has been observed regularly in observations of 450-900s (depending on observing conditions) giving a signal-to-noise ratio (SNR) of ≈200 per spectral pixel in the iodine region.

The root-mean-square (rms) scatter about the mean velocity of all AAPS data for HD 38283 is $8.5\,\mathrm{m\,s^{-1}}$, which is substantially higher (by almost a factor of two) than would be expected based on measurement precision (the median value of the internal uncertainty produced by our iodine velocity fitting is $1.9\,\mathrm{m\,s^{-1}}$) and stellar jitter ($3.0\,\mathrm{m\,s^{-1}}$).

Preliminary analysis of these velocities indicated several years ago that a planet may be present, with a most likely orbital period of around one year. However, as the detection of periods at almost exactly one year strikes fear into the heart of all scientists who work on time series data, we resolved to acquire more data in order to be absolutely sure that the detection was not subject to either serious biases, or the result of a systematic error. We are fortunate that HD 38283 is a circumpolar star ($\delta = -73.699^\circ$) and can be observed below the pole in winter. This enables year-round coverage, as long as observations at airmass of >2 can be tolerated. In comparison, a more equatorial star would be inaccessible for several months a year. As a result, observations in the winter of 2010 have enabled us to substantially improve our window function by "filling" in the part of the year when it had not been previously observed.

Figure 1 shows a traditional Lomb-Scargle (LS) periodogram (Lomb 1976; Scargle 1982) for this data set. Overlain as a dashed line is the window function (suitably scaled) for our observations. This demonstrates how observation of this target through the winter of 2010 suppressed all significant window function peaks at one year periods. The highest peak is clearly at 363 days, with a second peak apparent at 120 days (we ignore the peak at 1 d as this is produced by the diurnal sampling of data acquired only at night, and such peaks are invariably not physically meaningful). The most significant peak in the window function is at ≈30 days, and arises from the sampling effect produced by the tendency for AAPS observations to be scheduled when the moon is up. However, as the discussion of the impact of aliases on Doppler planet periodicities of Dawson & Fabrycky (2010) demonstrates, the lunar ≈30,d window function peak will have no real impact on a planet of a much longer (i.e. 363 d) period. The next most significant peak in the window function is at 464 d, however the alias impacts of this window function peak will occur at $1/P = 1/363 \pm 1/464$ d or 203 and 1667 d, where we see no evidence for significant peaks in the observed power spectrum, giving us confidence we have correctly identified the primary periodicity in our data.

To assess the statistical significance of the two strongest periods in the LS periodogram in more detail, individual False Alarm Probabilities (FAPs) for them were calculated using the bootstrap randomisation method described by Kürster et al. (1997). This randomly shuffles the velocity observations while keeping the times of observation fixed. The periodogram of this shuffled data set is then computed and its highest peak recorded. In this way, we can determine the probability that a given periodogram peak will arise by chance, without making any assumptions about the error distribution of the data. The bootstrap FAPs of the two periodogram peaks are $< 0.001\%$ ($P =$363 d) and 7% ($P =$120 d). This suggests that the 120 d periodicity is marginal, at best.

3.1. A single eccentric planet

The top panels of Figure 2(a,b) show the results of a single Keplerian fit to this data at a period near one year. Table 3 shows the parameters of this fit ($P = 363.2 \pm 1.6$ d, $m \sin i = 0.34 \pm 0.02\,\mathrm{M_{Jup}}$, $e = 0.41 \pm 0.16$) which has a reduced chi-squared (χ^2_ν) value of 1.68 and a root-mean-square (rms) scatter of $4.3\,\mathrm{m\,s^{-1}}$. A peak is evident at very low significance in the residual periodogram to this fit at 20 days. However, this is sufficiently close to the approximate estimate of the rotation period of HD 38283 (12 days – Noyes et al. 1984) that it is not considered likely to be the signature of an additional planetary body. Figure 3 shows this velocity data folded at a period of 363.2 d, demonstrating the almost uniform phase coverage we have been able to achieve for this circumpolar star.

To test the probability that the noise in our data might have resulted in a false detection for this eccentric planet, we have run simulations using the "scrambled velocity" approach of Marcy et al. (2005). This technique makes the null hypothesis that no planet is present, and then uses the actual data as the best available proxy for the combined noise due to our observing system and the star. Multiple realisations are created by scrambling the observed velocities amongst the observed epochs. We created 5000 of these scrambled velocity sets, and then subjected them to the same analysis as our actual data set for the case of a single eccentric planet. No trial amongst 5000 showed a χ^2_ν better than that obtained for the original data set, and the distribution of the scrambled χ^2_ν values (see Fig. 4) shows a clear separation from that obtained with the actual data. We conclude that there is a less than 0.02% probability of us having obtained a false detection due to a fortuitous selection from a system with no planet.

3.2. Two planets?

In much the same manner that an elliptical orbit can be approximated by two circular orbits arranged in an epicyclic configuration, a set of radial-velocity data which can be fit with one eccentric planet can often also be modelled as two planets in near-circular orbits (see e.g. Anglada-Escudé et al. 2010, and references therein). Fitting a single planet in a circular ($e = 0.0$) orbit to our HD 38283 data gives a reduced chi-squared value of 1.99 and a residual rms of $4.8\,\mathrm{m\,s^{-1}}$, and so is clearly not preferred over a single eccentric planet (see Table 3 and Fig. 2(c,d)). The residuals to this fit show marginally significant peaks remaining at 60 and 121d. However, fitting two planets (at ≈363 & 120 d) in circular orbits yields a reduced chi-square value of 1.42 and a residual rms of $3.8\,\mathrm{m\,s^{-1}}$, which is slightly better than that obtained for a single eccentric planet. (Allowing the eccentricities of the two planets to float, we obtain χ^2_ν =1.42 and an rms of $3.8\,\mathrm{m\,s^{-1}}$, a solution which is indistinguishable in quality from the two-planet, forced-circular case.) Attempting to fit a second planet at 60 d (rather than at 120 d) results in solutions with extremely unlikely eccentricities ($e > 0.8$), and moreover leaves the 120 d peak behind in the residuals to that two-planet fit. The residuals to a two planet fit with the second planet at 120 d removes both the 60 d and 120 d power-spectrum peak in the residuals to the one planet fit. So if there is a second planet in this system then it is *not* at a period near 60 d.

However, the question that arises is obviously, which of these two solutions – an eccentric single planet, or two circular planets near 3:1 resonance? To test the dynamical stability of a two-planet HD 38283 system, we used the HNBody orbital integrator (Rauch & Hamilton 2002). HNBody is a symplectic integrator which also includes general relativity. The parameters of the HD 38283 system (allowing non-zero eccentricities) were used as the initial input conditions, and the simulation allowed to run for 10^7 yr. The two-planet system remained stable for the full duration of this simulation, so this does not rule out the two planet solution on dynamical grounds.

To further examine whether HD 38283 contains a single or double planet system, we examined the data using a genetic algorithm. We restricted the allowed range in period for the ∼1 yr "b" planet to 300-400 d, while allowing a second "c" planet to take on periods between 50 and 200 d. The genetic algorithm employed was used in a similar manner to that which Cochran et al. (2007) used to distinguish among several possible orbital solutions for the outer planet in the HD 155358 system. Here, we ran 50,000 trials, in which the genetic algorithm performed 2-planet fits and logged the resulting χ^2. Each trial is the result of hundreds of generations, in which a population of 2-Keplerian orbital solutions evolves to a minimum χ^2 value. Figure 5 shows the χ^2 achieved for the allowed periods of the two planets. From these results, it is clear that the 363 d signal is the favoured solution for planet "b". However, the putative "c" planet can take on a wide range of parameters, with no clearly favoured χ^2 minimum. From Fig. 5 we see that, while our least-squares fit prefers a 120 d second planet, the χ^2 surface is quite complex. In our previous experience with genetic algorithms, a correct solution should "evolve" rapidly toward a sharp χ^2 minimum when brought to bear on data containing real and coherent Keplerian signals. We therefore conclude that these genetic results cast doubt on the uniqueness and reliability of any two-planet solution.

Combining these strands of evidence, we conclude that the data do not conclusively demonstrate the existence of a second planet in this system. What data we have is only suggestive, at best. Occam's Razor then leads us to conclude that the "simpler" model of a single planet in an eccentric orbit is to be preferred, until intensive monitoring can confirm the existence of the radial velocity features that would be expected on short timescales were the system to be one in a 3:1 resonance.

4. Discussion

4.1. Is this Really a Planet?

As noted above, scientists are generally (and justifiably) wary of time series data that show periodicities at integer multiples or divisors of one year. Bugs in the codes used for applying systematic corrections to the data are an obvious route for the creation of artificial signals like these (e.g. Bailes et al. 1991; Lyne & Bailes 1992). The only correction that (if it were in error) could conceivably generate a false signal in our data is the barycentric correction. We see no evidence in any of our other AAPS target stars for objects with periods at almost exactly one year. Moreover, the signal we see in HD 38283 is relatively large $10\,\mathrm{m\,s^{-1}}$ one – such a signal would be trivial to detect in systems like HD 102365, HD 16417, and 61 Vir (Tinney et al. 2011; O'Toole et al. 2009; Vogt et al. 2010a), all of which were discovered by the AAPS and all of which host planets with substantially smaller Doppler amplitudes than $10\,\mathrm{m\,s^{-1}}$. For a barycentric correction bug to produce this signal, there would have to be something unsusual about the relevant input parameters (i.e. position & proper motion) of this star. However, there is nothing unusual about HD 38283's position or proper motion – they have been precisely determined by HIPARCOS, and in particular are as accurate as the vast majority of the other targets in the AAPS sample, which show no sign of an annual signature. An obvious check is to ask whether other objects close on the sky to HD 38283 show any similar effect. HD 39091 lies just 6.8° away from HD 38283 and has a similar spectral type (G1V), the same level of activity ($\mathrm{R}'_{\mathrm{HK}}$=−4.97) and is just 1.04 mag brighter in V. HD 39091 is known to host a very massive planetary companion (Jones et al. 2002). If we fit our data for this companion (P=2086 d, $m \sin i$=10.1 $\mathrm{M_{Jup}}$ e=0.64), we find the residual LS periodogram shown in Figure 6. In this system we see no evidence for a peak at 364 d – the nearest peak in the residual periodogram is at 420 d and well-separated from one year. We conclude that the periodicity we see in HD 38283 is indeed astrophysical, and therefore the signature of an exoplanet.

4.2. The Frequency of One Year Planets

Figure 7 plots the period histogram for Doppler exoplanets detected with periods of between 300 and 400 d (as compiled at November 2010 by the Exoplanet Explorer database[8] – the distribution derived from the similar Exoplanet Encyclopaedia compilation[9] is essentially identical). The figure does not include HD 38283 b. The distribution shows an obvious "hole" at the bin centred on 365 d, compared to the neighbouring bins. The mean frequency of planets per 10 day bin for the whole period range plotted is 2.5±0.5 (the uncertainty is the standard error in the mean), while that for the four bins adjoining the one year period is 4±0.5. So, while the number statistics in the individual bins are admittedly small at present, the hole at one year is nonetheless significant.

This dip is almost certainly due to the difficulty in sampling planets with periods close to one year, combined with the understandable desire of planet search teams to have overwhelming evidence in hand before they are prepared to publish planets at such periods. Indeed, given these considerations it would be suspicious if there were *not* a dip at this location. The histogram would suggest that HD 38283 b represents just one quarter of the exoplanets one would expect to find in the ensemble of exoplanets currently being surveyed, in the absence of observational and sampling biases.

One obvious strategy that could be employed to address the difficulty in reliably identifying planets with periods near one year, is to specifically target samples of host stars that, like HD 38283, are circumpolar (or near-circumpolar). Such stars can be observed throughout the year, suppressing aliases and delivering a clean window function. Another strategy would be to tolerate observations at large hour angles (and so large airmasses) near twilight in order to extend the time coverage of target stars further into the period each year when they are generally considered to be inaccessible.

4.3. The Habitability of Satellites of Gas-giants in One Year Orbits

The search for "habitable" exoplanets – where the definition of "habitability" can vary substantially (see e.g. Horner & Jones 2010, and references therein), but usually centres on the presence of liquid water on the surface of a rocky planet – has to date generated substantially more heat than light. Or at least substantially more publications describing theoretical predictions, than actual detections. The profound difficulty in detecting these "habitable" planets in orbit around G dwarfs like the Sun (requiring as it does the measurement of either a $90\,\mathrm{mm\,s^{-1}}$ amplitude Doppler variation, or a $10\,\mu$mag transit, and doing so repeatedly over several years) has seen the focus in "habitability" theory and observation move towards low-mass, M-dwarf host stars. In low-mass stars, the habitable zone shrinks to much smaller orbital radii and periods, making both Doppler

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[8] www.exoplanets.org

[9] www.exoplanet.eu

amplitudes and transit variations larger. And, perhaps even more critically, shorter periods mean that observing programs must only control their systematics over much shorter periods – i.e. several months, rather several years. The $m \sin i = 3.1 M_\oplus$, $P = 36\,d$ planet Gl 581 g (Vogt et al. 2010b) appears to be the most "habitable" planet yet detected, and was detected by exploiting exactly this approach – a focus on low-mass planets orbiting low-mass stars in short period orbits.

Nonetheless, it remains true that the prototype for all habitability searches[10] remains the Earth – a rocky, terrestrial planet orbiting at ≈1 AU in a near-circular orbit around a G dwarf star. One obvious potential location for such an environment became obvious soon after the first exoplanets were detected in the mid-1990's. This first handful of gas-giant planets were discovered at orbital radii of 0.01-2 AU, placing them substantially interior to where gas-giant planets were expected to form based on the then extant understanding of planet formation (then highly tuned to the only planetary system previously known – the Solar System). It was suggested almost immediately (Williams et al. 1997) that if these gas-giant exoplanets hosted large, rocky moons, then those moons could potentially be habitable.

The formation of the gas-giant satellites of our Solar System is the subject of a substantial literature which it is not feasible to completely summarise in this communication – the interested reader should consult the reviews of Mosqueira et al. (2010); Estrada et al. (2009); Canup & Ward (2009), and references therein. These models distinguish between the formation of the "regular" (or "Galilean") and "irregular" satellites. The regular satellites lie on inner, nearly-circular, low inclination, prograde orbits indicating they formed within a circumplanetary disk around their host planet. The fact that all the gas-giant planets of the Solar System harbour regular satellites suggests that their formation may be an inevitable consequence of giant planet formation (Estrada et al. 2009). The irregular satellites – characterised by high eccentricities and inclinations, and a significant fraction of retrograde orbits – are considered to be captured bodies.

4.4. Regular Exomoons

There is a general consensus that the primary epoch of the formation of the regular satellites takes place as (and after) the gas-giant is finishing its formation, and in particular as (and after) the gas-giant has cleared a gap in the protoplanetary nebula (Mosqueira et al. 2010; Canup & Ward 2009), with the result that the accretion of material into the circumplanetary disk may take place largely through the planet's two Lagrange points (Estrada et al. 2009). Sasaki et al. (2007) have recently produced updated models for the formation of the Jupiter and Saturn systems that are based on the Canup & Ward (2009) formulation, but which attempt to model both planet formation and satellite formation together in a manner informed by the enhanced knowledge we now have of

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[10] Or at least all habitable planet searches based on "life as we know it" – if that restriction is relaxed the range of potentially habitable environments becomes almost completely unconstrained.

exoplanet formation.

The relevant dynamical times in circumplanetary disks are typically orders of magnitude shorter than in circumstellar disks (Estrada et al. 2009), and estimates for the timescales of the formation of the satellites range from 10^4-10^7 yr. The formulation of Canup & Ward (2009) predicts timescales for the processing of material through the circumplanetary disk at the longer end of this range. Moreover it proposes that orbital migration *within the circumplanetary disk* could see multiple generations of satellites formed and ultimately lost via collision with the host planet – the surviving satellites are simply the last surviving generation and reflect the inflow conditions in the circumplanetary disk at the time accretion stopped.

A complicating issue is how the timescale for the formation of exomoons compares with the timescales for the orbital migration believed to transfer gas-giant exoplanets from their formation locations at $\gtrsim$5 AU to the locations at which they are commonly being discovered (and in particular at the $\sim$1 AU locations at which planets like HD38283 b orbit). Currently the two predominant models for exoplanetary migration are; via gravitational interaction of an exoplanet and the disk in which it is embedded, via spiral density waves (Type I migration – e.g. Ward 1986, 1997); and Type II migration which occurs after a gas-giant has opened a gap in its protoplanetary disk and its orbital evolution becomes coupled to the viscous evolution of the disk (Lin & Papaloizou 1986). The relevant timescales for these two types of migration are $\sim 10^4$ and $\sim 10^5$ yr respectively. This would suggest that satellite formation remains possible for gas-giants undergoing both forms of migration – either at an inner disk location *after* the faster Type I migration has halted (if it halts at all), or *while* the slower Type II migration is taking place. The latter situation is perhaps the most intriguing, since it is the opening of a gap in the circumstellar disk that allows Type II migration to take place, *and* which is thought to be the point at which significant formation of the regular gas-giants satellites takes place.

These two processes (regular satellite formation and Type II planetary migration) are likely to be inextricably linked. The impact of simultaneous migration and regular satellite formation needs further modelling to determine the impact on both satellite mass and satellite composition – both of which are critical parameters for understanding exomoon habitability. Williams et al. (1997) have pointed out that for satellites to retain a substantial and long-lived atmosphere they would need to be quite large ($>0.12\,\mathrm{M}_\oplus$) – five times more massive than the largest satellites in our Solar System (Ganymede and Titan) and ten times more massive than the Moon. An alternative derivation by Kaltenegger (2000) determines an even more massive lower limit of $>0.23\,\mathrm{M}_\oplus$. The four "Galilean" satellites of Jupiter (Ganymede, Callisto, Io and Europa) together total a small fraction of Jupiter's mass ($M_G/\mathrm{M}_{\mathrm{Jup}} = 2.1 \times 10^{-4}$), while the equivalent quantity for the Saturnian system is a very similar 2.5×10^{-4}. This suggests that the process that form regular satellites may only to grow to a maximum size (Canup & Ward 2009). If the same formation mechanisms hold for exomoons, then massive gas-giants (i.e. 5-10 $\mathrm{M}_{\mathrm{Jup}}$) will offer a better chance of hosting a habitable satellite than planets of Jovian mass.

What would we expect the composition of these exomoons to be? We know that in the Solar System, the largest gas-giant satellites are composed of roughly 50% rock and 50% ice (Mosqueira et al. 2010). Of course, if Ganymede or Titan were moved from >5 AU to 1 AU, the volatiles which make up almost 50% of their mass budget would be significantly heated, resulting in either a very thick atmosphere, or thick oceans, or both. Williams et al. (1997), for example, note that if Solar System satellites like Ganymede or Callisto which were formed at $\gtrsim$5 AU were migrated to 1 AU, they would be covered by oceans to a depth of ~1000 km.

How the composition of an exomoon would differ from that of Ganymede or Titan if it were formed *as it migrated* from >5 AU to ~1 AU is hard to predict – we are aware of no simulations carried out to date of satellite formation while the host planet undergoes migration. Given the prevalence of known Doppler and transit gas-giants that clearly *have* undergone migration, this is clearly another area of research crying out for further study.

4.5. Irregular Exomoons

The Solar System gas-giants host significant populations of irregular satellites – bodies thought to have originated elsewhere in the Solar System. The large orbital radii, wide range of orbital eccentricities and inclinations, and the significant fraction of retrograde orbits displayed by the irregular satellites indicates that they were captured by their host planets, rather than forming in situ (e.g. Jewitt & Sheppard 2005; Nicholson et al. 2008). The majority of these objects move in distinct collisional "families" – groups of satellites with similar orbital properties, suggesting that they have formed from the break-up of a smaller population of larger bodies (Nesvorný et al. 2003, 2004; Turrini et al. 2008). Indeed, taking into account detection biases, it seems likely that each of the giant planets harbours roughly the same number of irregular satellite families (and hence originally captured approximately the same number of larger bodies). This is remarkable when one considers that there is a factor of ~20 difference in mass between Jupiter and Uranus (Jewitt & Sheppard 2005).

It is therefore possible that, just as Neptune captured the relatively massive irregular satellite Triton, an exoplanet may capture its own large, irregular exomoon as it migrates from its formation location to a potential habitable zone orbit. Unfortunately, none of the suggested capture mechanisms for the irregular satellites of the Solar System are able to convincingly reproduce the characteristics observed for those satellites (Jewitt & Haghighipour 2007). The capture by a $1\,\mathrm{M_{Jup}}$ planet of an exomoon large enough to be habitable would require seizing control of a body at least twice as massive (relative to its host planet) as Triton is compared to Neptune. It is problematic whether such a capture could be mediated via the dissipative mechanisms proposed to explain the capture of the Solar System irregular satellites (i.e. "gas drag" and "pull down" – Jewitt & Haghighipour 2007). The capture of such large irregular exomoons would require a three-body encounter – i.e. either the large object encounters a pre-existing regular satellite during a close encounter (Goldreich et al. 1989; Woolfson 1999), or the large object itself has a satellite which is shed during their mutual encounter with the giant planet (Agnor & Hamilton 2006; Vokrouhlický et al. 2008). Such encounters are likely to be rare events (as evidenced by Triton being the only large irregular satellite in the Solar System). On the other hand they have obviously happened at least once in the Solar System – albeit for an exomoon about a factor of two too small (relative to its host exoplanet) to be habitable. Encounters leading to capture could potentially happen even more frequently for a host exoplanet migrating *inwards* through a *denser* protoplanetary disk rich in planetismals and proto-terrestrial planets, than that which Neptune is thought to have passed through during its own *outward* migration through a more sparse disk (e.g. Malhotra 1993; Hahn & Malhotra 1999; Gomes et al. 2004). Dynamical simulations of the capture of irregular satellites by inward migrating exoplanets, therefore, should be another profitable area for further study.

4.6. Exo-Trojans

An additional region in the "habitability phase space" is provided by the "exo-Trojans" – potential Trojan companions of gas-giant exoplanets in 0.5-2 AU orbits. Trojans are objects trapped within a planet's 1:1 mean-motion resonance, and typically librate around the L4 and L5 Lagrange points, 60° ahead and behind the planet in its orbit. Within our own Solar System, large numbers of Trojans have been discovered – thousands sharing Jupiter's orbit, a couple moving with Mars, and seven in resonance with Neptune[11]. When discovery biases are taken into account, it is hypothesized that the Jovian Trojan population numbers of order 1 million objects (greater than 1km in diameter), with the Neptunian Trojan population housing potentially ten times that number (Sheppard & Trujillo 2006). This is a substantially larger population (numerically) than the Solar System irregular satellites, which likely number in the hundreds-to-thousands (Jewitt & Sheppard 2005).

The Trojans within our Solar System move on orbits covering a range of eccentricities and inclinations, which suggests that they were captured (Lykawka & Horner 2010; Lykawka et al. 2009; Morbidelli et al. 2005), rather than forming in situ during the migration of the giant planets (see e.g. Minton & Malhotra 2005; Hahn & Malhotra 2005, and references therein). Lykawka & Horner (2010) have modelled the capture of Trojans by Neptune during its outward migration, and found a Trojan capture efficiency (i.e. objects encountered, captured and then remaining Trojans until migration ceases) of between 10^{-6} and 10^{-3}. Though such a capture probability might appear small, the large distances over which exoplanets at 0.5-2 AU must migrate would allow ample opportunity for large embryos and proto-planets to be captured and carried along with the giant planet, resulting in a habitable exo-Trojan. Indeed, the presence of a large Trojan companion to the proto-Earth has been suggested as the source of the Mars-sized impactor thought to have been involved in the collision that lead to the formation of the Moon (e.g. Belbruno & Gott

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[11] An up-to-date tally of known Trojans is maintained on the Minor Planet Centre website, at www.minorplanetcenter.org/iau/lists/Trojans.html.

2005). Had that proposed body remained on a stable Trojan orbit to the current day, rather than being destabilized (ultimately to collide with the Earth), it would surely be a habitable planet.

Exo-Trojans have been the subject of some investigation to date. Laughlin & Chambers (2002), for example, studied the stability of systems in which two equal mass planets were locked in mutual 1:1 mean-motion resonance, and showed that such scenarios could be stable so long as the cumulative mass of the two planets did not exceed $\sim 1/26^{\mathrm{th}}$ the mass of their host star. More relevant for the question of habitabilty in systems with a gas-giant in the habitable zone, is the study of Dvorak et al. (2004), who considered the specific example of putative terrestrial exo-Trojans for three known giant exoplanets in ~ 1AU orbits. They concluded that stable, terrestrial exo-Trojan configurations were indeed plausible. More recently – motivated by their potential detectability via Transit Timing Variations (see e.g. Ford & Holman 2007; Madhusudhan et al. 2009, and references therein) – there has been a focus on studies of Trojan companions to known transiting planets in very small orbits. Indeed, for the forseeable future this is the only means available for the actual detection of exoplanetary Trojans (though to date no detections have emerged – Madhusudhan et al. 2009). Nonetheless, it seems prudent to consider suitably massive Trojans ($\gtrsim 0.12\,\mathrm{M}_\oplus$, Williams et al. 1997) of giant exoplanets in habitable orbits as a potential source of habitable worlds. These habitable exo-Trojans could easily have been transported many AU as their giant planet migrated inwards, and so it is easy to see them having abundant water – neatly avoid the question of how telluric planets can be sufficiently hydrated to be habitable (see e.g. Horner & Jones 2010). In addition, unlike an exomoon, they will not suffer from being immersed in the high-energy particle environment of, or be subject to tidal heating by, their host planet (see below).

4.7. Potential Hosts of Habitable Exomoons

Exomoon stability and habitability has been the subject of a rapidly expanding literature in recent years. However this has been almost entirely prompted by the prospect of detecting exomoons orbiting transiting exoplanets, and so has focussed almost exclusively on the short-period, small-orbit systems that are likely to transit (e.g. Weidner & Horne 2010; Barnes & O'Brien 2002; Kaltenegger 2010; Kipping 2010). Barnes & O'Brien (2002), however, did examine the stability of massive exomoons on longer period orbits and found that, while stellar tides from a $1\,\mathrm{M}_\odot$ star are inimical to massive satellites orbiting a $1\,\mathrm{M}_{\mathrm{Jup}}$ planet within $\sim$0.1 AU, they do not impact on the stability of $1\,\mathrm{M}_\oplus$ exomoons beyond 0.25 AU, or $0.1\,\mathrm{M}_\oplus$ exomoons beyond 0.2 AU.

In general, for a satellite to be stably bound in orbit around a $1\,\mathrm{M}_{\mathrm{Jup}}$ planet in a 1 AU orbit, it will need to orbit well within the planet's Hill radius of $\approx 0.068(1-e)$ AU. Detailed dynamical simulations suggest the relevant radius is actually less than half (49%) of the Hill radius for prograde satellite orbits, and about 93% of the Hill radius for retrograde orbits (Domingos et al. 2006). Simulations of the orbital stability of satellites undergoing migration have been carried out for the simplifying assumption that they formed *before* any migration takes place (Namouni 2010). It was found that the Galilean satellites of Jupiter, and the equivalent inner satellites of Saturn, would remain stably bound as their host planet underwent migration, in to semi-major axes of at least 0.5 AU. For both prograde and retrograde orbits, satellites will become tidally locked to their planet within a few billion years. Such satellites will have diurnal periods ranging from a few days to a few months, with any one point on the surface potentially subject to large diurnal temperature variations as a result. In addition, these satellites will receive a varying total stellar flux as they move from conjunction to opposition with respect to the host star – e.g. a tidally locked satellite orbiting at half the Hill radius (for a $1\,\mathrm{M_{Jup}}$ planet orbiting at at 1 AU) will see a conjunction to opposition flux ratio of $[(1 + 0.068)/(1 - 0.068)]^2 \approx 1.31$. Similarly, if the gas-giant has an elliptical orbit, the satellite will see an annual variation in the incident flux with the ratio between the planetary periastron and apastron fluxes of $[(1 + e)/(1 - e)]^2$. For low eccentricity gas-giants (i.e. $e < 0.05$), these two effects could be of similar magnitude, and would not appear to preclude a satellite's habitability.

One obvious question to ask, then is just how many exoplanets are currently known that could host habitable exomoons. There have been a variety of determinations of the "habitable zone" for terrestrial exoplanets, with a variety of assumptions about stellar luminosity and temperature, and planetary and atmospheric composition (e.g. Selsis et al. 2007; von Bloh et al. 2009, 2007; Kasting et al. 1993). Most of these have asssumed a planet of $1\,\mathrm{M_\oplus}$ (or larger), and to date there has been little study of the impact on potential habitability for rocky bodies of smaller mass (like the exomoons being considered here), nor of the different composition an exomoon is likely to have.

Here we adopt the conservative "continuously habitable zone" (i.e. the region that is habitable over the 4.6 Gyr lifetime of the Solar System) of Kasting et al. (1993) for a G2V star, which was estimated to extend from 0.95 to 1.37 AU. We can scale that habitable zone for stars of different luminosities using $a_{\mathrm{HZ}} = 1\,\mathrm{A}U(L_{star}/L_\odot S_{eff})^{0.5}$ (and following Kaltenegger 2010, in adopting S_{eff} to take into account the wavelength dependent intensity distribution of the spectral classes, and then setting it to unity for F,G & K stars, which have only a very weak dependence on this parameter). Scaling the observed semi-major axes using the luminosities of the known exoplanetary host stars of luminosity class V and IV compiled by the Exoplanet Explorer database[12], we derive the sample listed in Table 4 of gas-giant exoplanets that lie within the "Earth-like" planet habitable zone, and so could host habitable exomoons. We derived luminosities for the host stars from their measured parallaxes and V magnitudes, together with tabulated visual bolometric corrections for luminosity class V from Allen (1976). Although some of the stars in question are classified as luminosity class IV, these corrections are still useful and result in bolometric magnitudes to better than ±10%. We used $M_{\mathrm{Bol}\odot}$=4.75 (Torres et al. 2010) to place the resulting bolometric magnitudes from Allen (1976) on a consistent system.

The resulting list is surprisingly small – just 9 of the more than 490 exoplanets presently known. We have divided these into three classes – those with $e < 0.05$ and so almost circular like the orbit of the Earth; those with $e < 0.1$ and so slightly elliptical, but similar to the ellipticity of

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[12] www.exoplanets.org

the orbit of Mars (e=0.0933); and those with $e < 0.17$, which we somewhat arbitrarily adopt as an upper limit for habitability on the basis of annual flux variations due to orbital eccentricity being less than a factor of two. In examining these classes, though it is important to bear in mind the substantial (and usually under-estimated) uncertainties associated with the measurement of orbital eccentricities. For systems with orbital periods this long, uncertainties of ±0.1-0.2 in eccentricity are not uncommon, so it is possible that future updates to the orbits for the known exoplanets may move other objects into, or some of these objects out of, this list.

The list includes both planets orbiting within 1 AU around stars less luminous than the Sun (e.g. 55 Cnc f, HD45364 c) and planets orbiting beyond 1 AU around more luminous stars (e.g. HD216435 b, HD10697 b). Due to HD 38283's over-luminosity, HD 38283 b itself does not fall into this class of habitable exomoon hosts – with a bolometric absolute magnitude of 3.79 it is a factor of 2.42 times more luminous than the Sun and so its habitable zone lies at $\sim 1.5 - 2.1$ AU. As noted earlier, there appears to be a maximum mass for the formation of Solar System regular satellites. If similar formation processes hold in exoplanetary systems, this would argue that the most likely locations for habitable exomoons is in orbit around the larger exoplanets listed in Table 4 – HD 28185 b, HD 10697 b and HD 221287 b.

Other physical processes in their environments will significantly impact on habitability, but are at present poorly understood and poorly constrained in the exoplanet context. Exomoons will be subject to tidal heating, the strength of which will depend substantially on their orbital radii. We know that in the Jupiter system, Io (orbiting at $5.9\,\mathrm{R_{Jup}}$) suffers significant tidal heating with the result that its surface heat flux ($\sim 2\,\mathrm{Wm^{-2}}$, Lopes & Williams 2005) exceeds its radiogenic and gravitational contraction flux by factors of hundreds, resulting in such significant vulcanism that it would not appear habitable for any definition of habitability that was based on Earth-like conditions. On the other hand, just the right amount of tidal heating may serve to promote tectonic activity and vulcanism in an exomoon that might otherwise be too small to support such a geology by radiogenic heating alone.

Similarly, the radiation environment for an exomoon will impact on its habitability. Williams et al. (1997) noted that the high-energy electron flux for the satellites that orbit in Jupiter's inner magnetosphere (especially Io) is around one thousand times larger than that seen at the orbit of Mars. The presence of a strong exomoon magnetosphere that can protect the planetary surface from charged particle bombardment is probably a precondition for Earth-like habitability on exomoons.

The high-energy electron flux will also vary strongly as a function of orbital radius – fluxes of 11 MeV electrons (Jun et al. 2005) drop by a factor of ∼1000 between the orbits of Io ($5.9\,\mathrm{R_{Jup}}$) and Ganymede ($15.1\,\mathrm{R_{Jup}}$). So an exomoon analogous to Ganymede therefore may not see a particle flux much worse than that seen at Mars due to the solar wind, and could be habitable if it hosts its own protective magnetosphere. Exomoons in inner orbits like Io, however, may suffer an unsurvivable radiation flux regardless of their magnetospheric status.

Orbital radius will clearly play a critical role in the habitability of exomoons – a radius that is too small will lead to overly vigourous tidal heating and high levels of high-energy radiation, while a radius that is too large will lead to a very long, tidally-locked diurnal period, and larger variations in incident solar flux as it orbits.

5. Conclusions

We have detected the Doppler signature of at least one gas-giant exoplanet orbiting the star HD 38283 with an orbital period of almost exactly one year. Our most likely solution for this system is that it hosts a single eccentric planet, though we cannot (at present) rule out the possibility of there being two planets in near-circular orbits in 3:1 resonance (i.e. 363.2 and 121.3 d). The robust confirmation of the periodicity of this planet at a period near one year critically relied upon our ability to observe the host star throughout the year – observing strategies that specifically target observations at large hour angles near twilight (which are usually avoided by planet search programs) may be highly desirable for minimising the annual window function. Specifically targeting stars within 30° of the poles may be advantageous for the same reason.

The detection of a gas-giant planet in a 1 AU orbit around a G dwarf star has prompted us to look more closely at the question of the habitability of the satellites of such planets. HD 38283 b itself turns out to be unable to host habitable exomoons, both because of its significant eccentricity (for the single eccentric planet solution), and because of the over-luminosity of its host star compared to the Sun. However, the ubiquity of the regular gas-giant satellites in the Solar System suggests strongly that their formation is a natural outcome of the planet formation process. There is no reason therefore to assume that exomoon formation is not similarly likely to happen when gas-giants form in exoplanetary systems. Moreover, our current understanding of that formation process does not preclude satellite formation or retention, in systems where gas-giants undergo migration from their formation locations into the habitable zone for terrestrial planets. Such migration may even encourage the capture of irregular satellites or Trojans (both ubiquitous in the Solar System) sufficiently massive to be habitable. The habitability of an exomoon or exo-Trojan will probably depend critically on the object's mass, whether or not a magnetosphere is present, and (for the exomoon case) the orbital radius around its host exoplanet.

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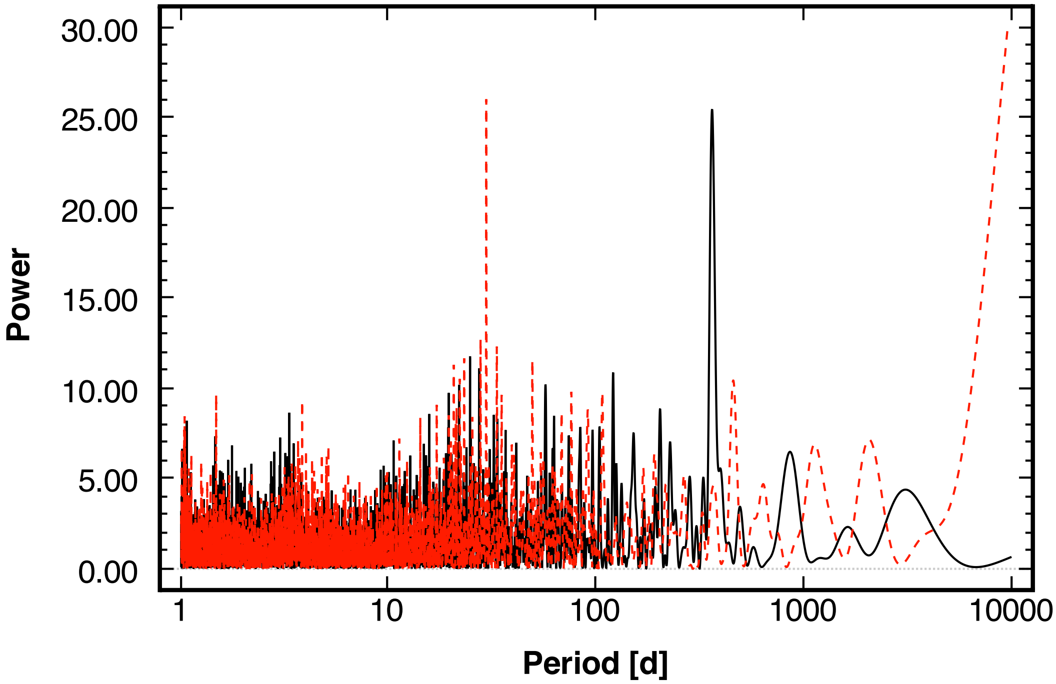
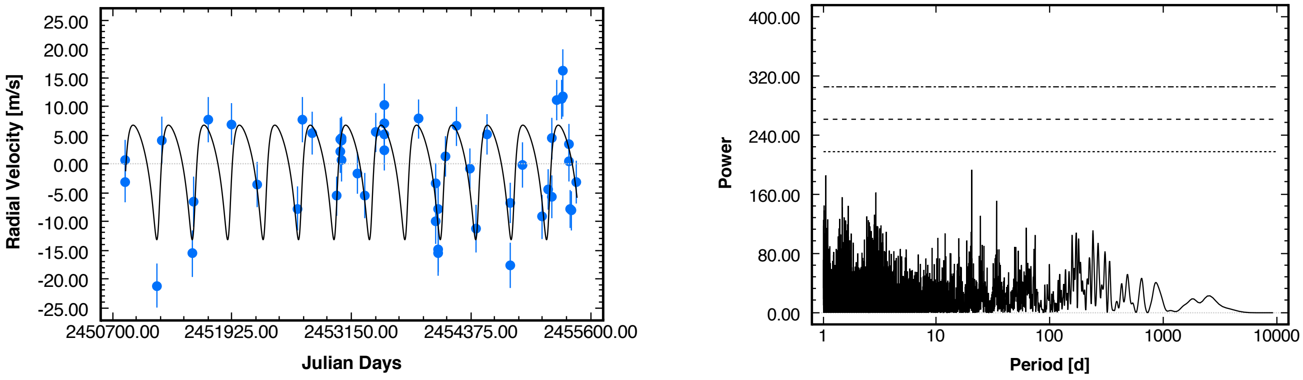
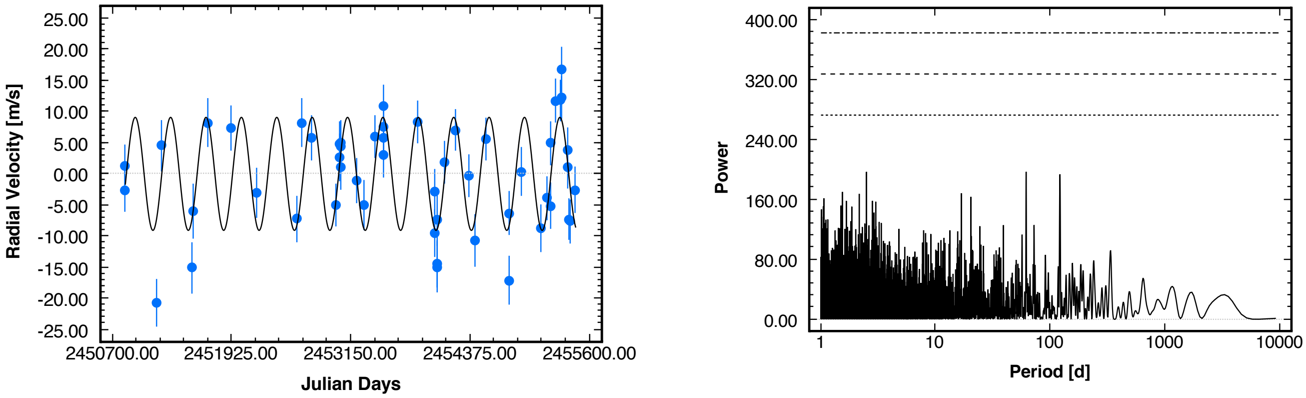


Fig. 1.— Lomb-Scargle Periodogram *(solid line)* and Window Function *(dashed line)* for HD 38283 AAPS data. Observations through the winter of 2010 have have produced a window function with no large peaks that could be confused with the power spectrum peak at 363 d.



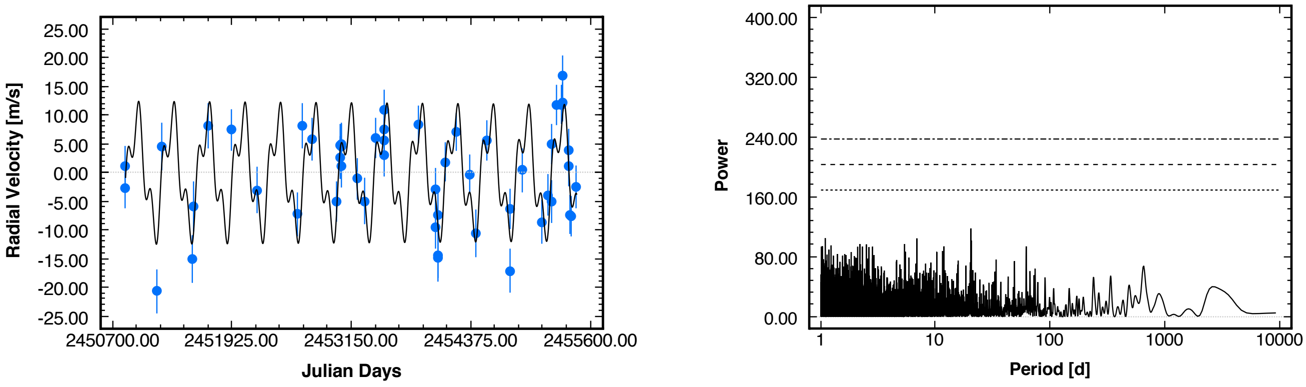
(a) One Eccentric Planet Fit

(b) One Eccentric Planet Residuals



(c) One Circular Planet Fit

(d) One Circular Planet Residuals



(e) Two Circular Planet Fit

(f) Two Circular Planet Residuals

Fig. 2.— Keplerian fits (a,c,e) and Power spectra of residuals to those fits (b,d,f) for : (a,b) a single eccentric planet with period 363.2 d; (c,d) a single circular (e=0) planet with period 363.5 d; and, (e,f) two circular planets with periods of 363.2 d and 121.3 d.

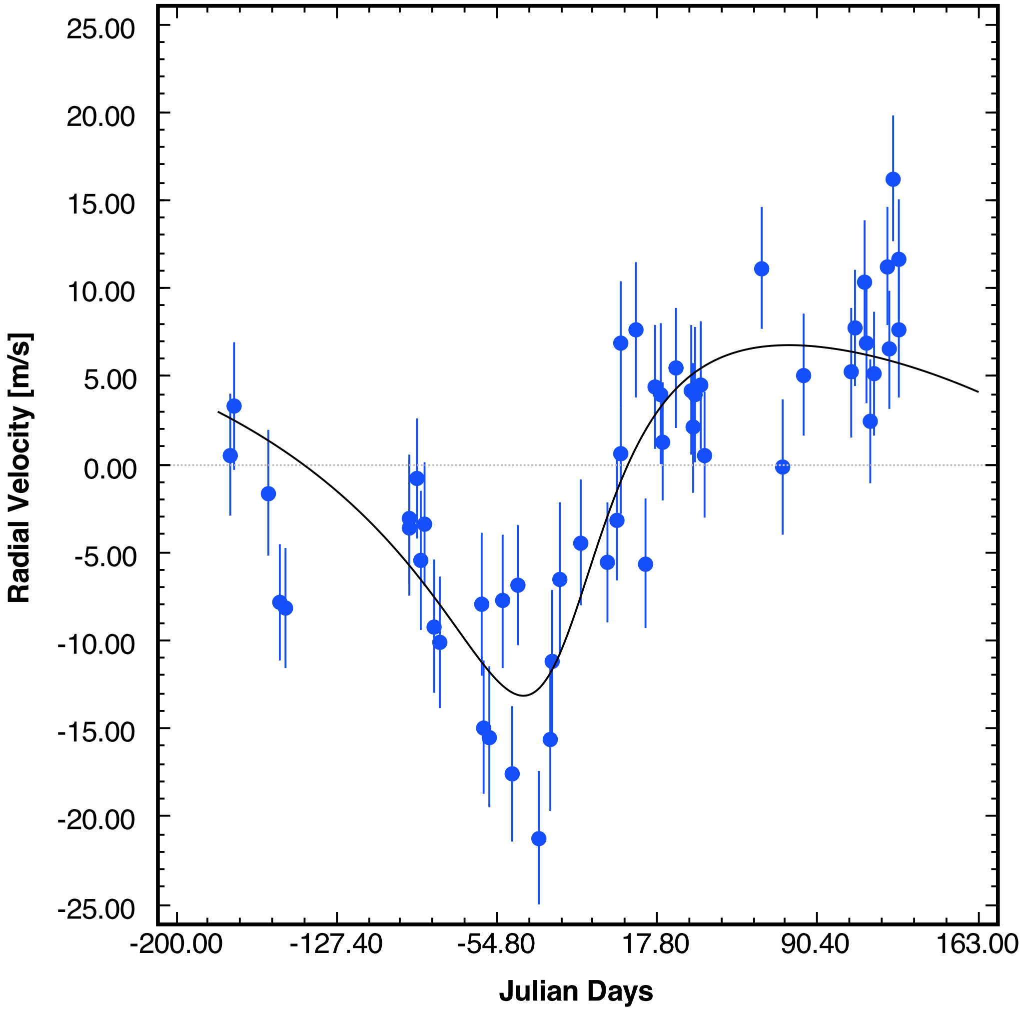


Fig. 3.— The preferred Keplerian fit of a single eccentric planet (as shown in Figure 2a) folded at the planet period to highlight the near uniform phase coverage achieved.

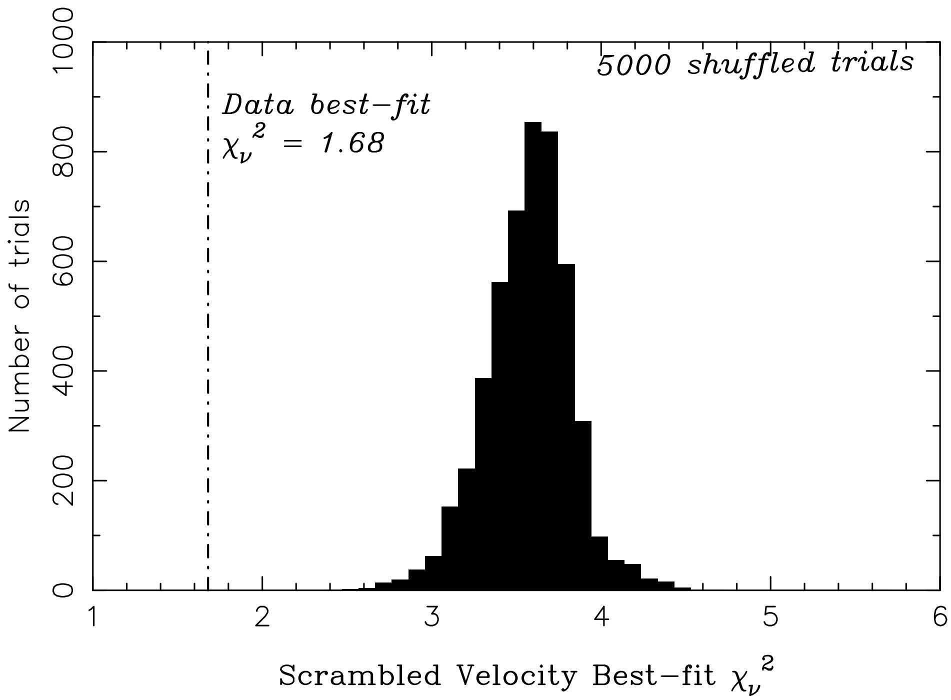


Fig. 4.— Scrambled false alarm probability results for a single eccentric planet. The histogram shows the χ^2_ν values that result from the best Keplerian fits to 5000 realisations of scrambled versions of the AAPS velocities for HD 38283. The dashed line shows the reduced χ^2_ν for the single, eccentric planet fit to the original data.

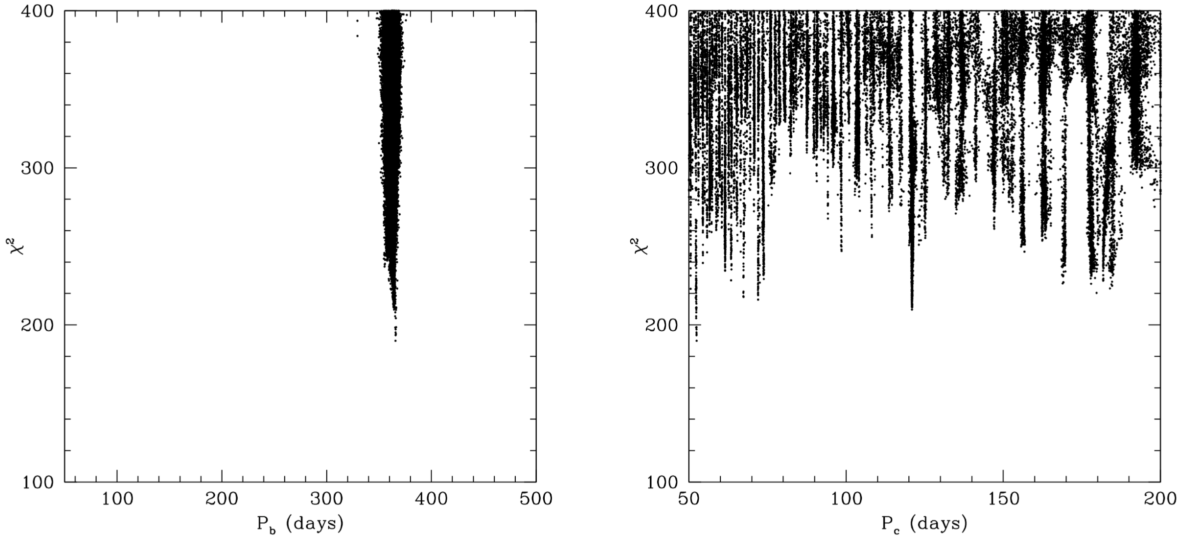


Fig. 5.— Chi-squared surfaces resulting from a two-planet fit using a genetic algorithm. Left panel: the main signal at 363 days is highly favoured (for a period range allowed in the genetic search of 300-400 d). Right panel: the second signal is less clear, as many local minima are present in the allowed range of 50-200 d. The most-favoured solution for a second planet is at P_c=52 days, though with an eccentricity at the upper allowed limit ($e = 0.6$), casting doubt on the uniqueness and reliability of a two-planet solution.

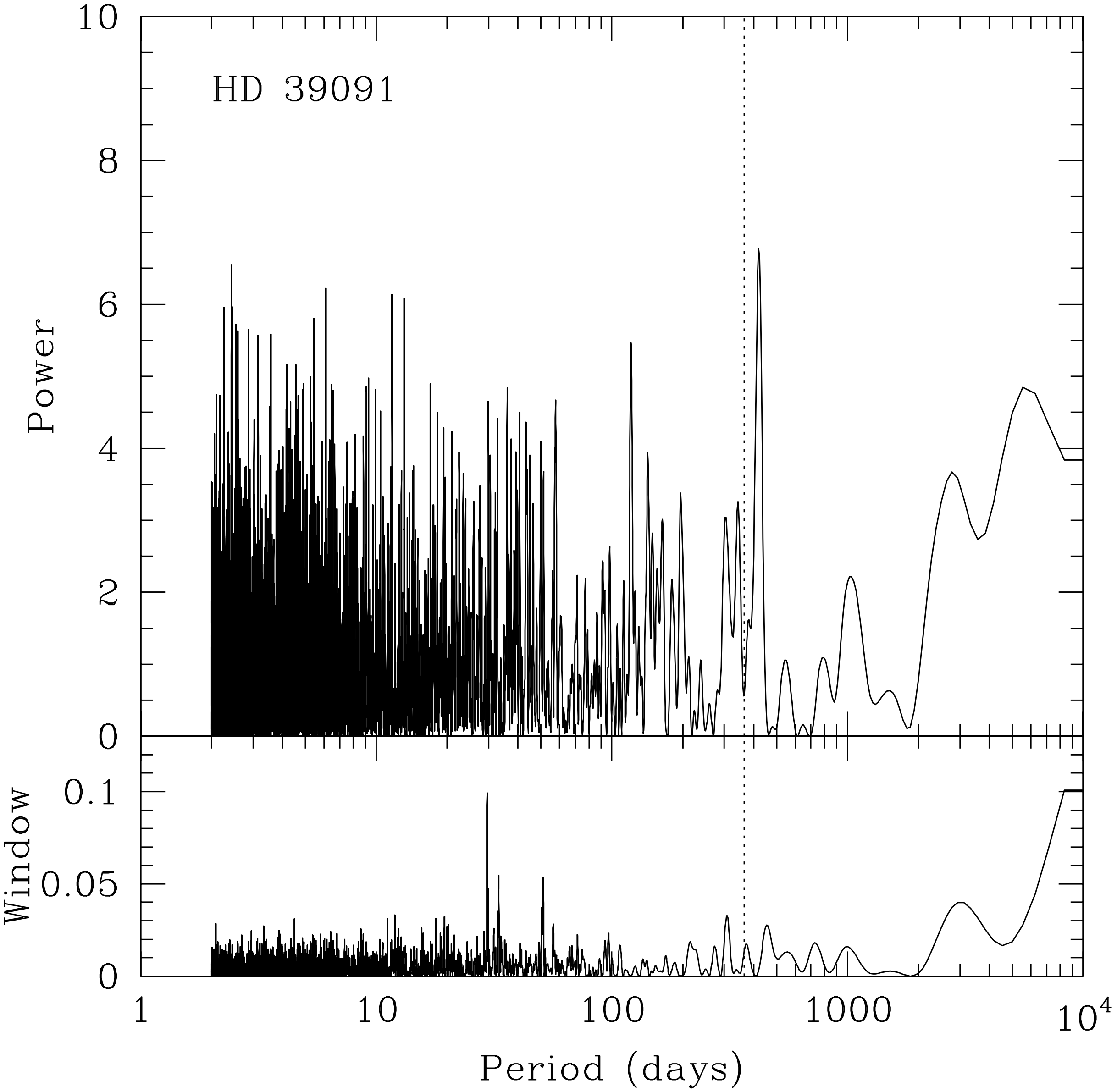


Fig. 6.— Standard LS periodogram for the residuals to a massive exoplanet fit to the AAPS data for HD 39091 (P=2086 d, $m \sin i$=10.1 $\mathrm{M_{Jup}}$ e=0.64). No power peak is seen at close to a one year period (dotted line).

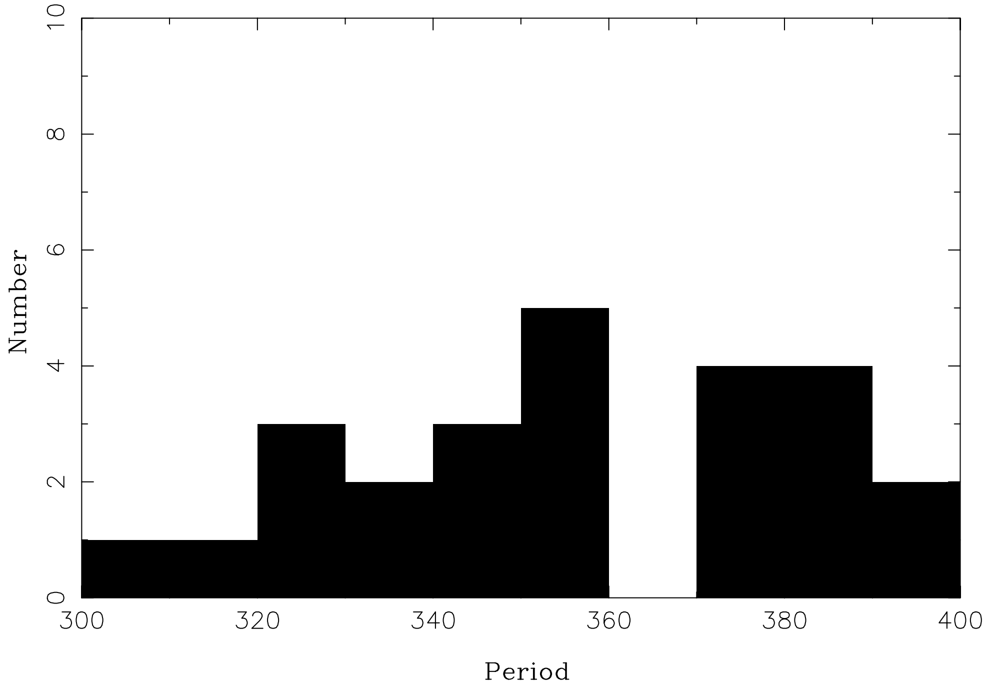


Fig. 7.— Period histogram of Doppler exoplanets as compiled at November 2010 by the Exoplanet Explorer database (www.exoplanets.org) in the period range 300-400 d, showing a pronounced "hole" at 360-370 d. Data from the Exoplanet Encyclopaedia (www.exoplanete.eu) shows an almost identical distribution.

Table 1. Properties of HD 38283

Reference	$T_{\rm eff}$	[Fe/H]	Mass	log(g)	Age	$v \sin i$	$R'_{\rm HK}$
Valenti & Fischer (2005); Takeda et al. (2007)[a]	5998 K	-0.12	$1.085 \pm 0.02 M_\odot$	4.15	6.2 ± 0.5 Gyr[1]	$3.0\,{\rm km\,s^{-1}}$	···
Holmberg et al. (2009)	6011 K	-0.15	···	···	3.9-6.8 Gyr	···	···
Gray et al. (2006)	6002 K	-0.25	···	4.34	···	···	···
Bond et al. (2006)	5945 ± 100 K	-0.24 ± 0.07	···	4.19 ± 0.2	···	···	···
Tinney et al. (2002b)	···	···	···	···	···	···	-4.97
Henry et al. (1996)	···	···	···	···	···	···	-4.97

[a] Mass and age from Takeda et al. (2007), remaining parameters from Valenti & Fischer (2005)

[b] $T_{\rm eff}$ from infrared flux method

Table 2. Velocities for HD 38283

JD (−2450000)	RV (m s^{-1}	Uncertainty (m s^{-1})	JD (−2450000)	RV (m s^{-1}	Uncertainty (m s^{-1})
0829.98715	-3.91	1.62	4011.27861	-4.14	1.74
0831.11229	-0.09	1.58	4018.25781	-10.81	2.15
1157.14186	-21.97	2.25	4037.19295	-8.70	2.63
1213.00749	3.27	2.63	4038.22751	-15.67	2.27
1526.07540	-16.33	2.64	4040.19859	-16.20	2.61
1530.13214	-7.23	3.04	4118.99518	0.55	1.39
1683.84877	6.89	2.35	4221.85330	5.78	1.33
1921.13329	6.12	1.87	4371.28213	-1.55	1.55
2188.26174	-4.32	2.40	4432.16897	-11.96	2.70
2594.17219	-8.51	2.15	4545.96264	4.34	1.57
2654.09309	6.91	2.30	4777.16298	-18.36	2.31
2751.89940	4.50	2.02	4780.22632	-7.60	1.57
3004.05786	-6.32	1.51	4899.97097	-0.89	2.33
3042.04257	3.46	2.05	5105.27658	-9.94	2.20
3043.01088	1.36	2.08	5171.10590	-5.17	1.76
3044.05527	3.23	2.24	5201.13157	-6.38	2.04
3047.04262	3.76	1.94	5205.04230	3.64	1.66
3048.08718	-0.19	1.87	5252.94873	10.42	1.66
3214.31949	-2.37	1.84	5309.87885	10.50	1.37
3283.27433	-6.23	2.48	5312.85737	15.48	1.83
3399.05141	4.71	1.54	5315.85569	10.95	1.47
3483.85265	9.57	1.73	5376.33930	-0.20	1.59
3484.86036	6.20	1.68	5377.34067	2.59	1.89
3486.87850	1.70	1.75	5398.31554	-8.60	1.24
3487.88962	4.41	1.69	5401.33183	-8.91	1.54
3842.85829	7.06	1.25	5457.28952	-3.84	2.07

Table 3. Orbital Solutions for HD 38283b

	One eccentric planet	One circular planet	Two circular planets	
Orbital period P (days)	363.2 ± 1.6	363.5 ± 1.5	363.2 ± 1.5	121.3 ± 0.9
Velocity semi-amplitude K ($\mathrm{m\,s^{-1}}$)	10.0 ± 0.8	9.1 ± 0.9	8.9 ± 0.7	4.2 ± 0.9
Mean anomaly (degrees)	27 ± 23	259.0 ± 3.8	248 ± 5	306 ± 16
Eccentricity e	0.41 ± 0.16	(0.0)	(0.0)	(0.0)
Periastron date (JD−2450000)	802.6 ± 12	568.45 ± 11	580.2 ± 11	726.8 ± 11
$m \sin i$ ($\mathrm{M_{Jup}}$)	0.34 ± 0.02	0.34 ± 0.04	0.33 ± 0.04	0.11 ± 0.02
Semi-major axis (AU)	1.02 ± 0.07	1.02 ± 0.07	1.02 ± 0.07	0.49 ± 0.07
$\mathrm{N_{fit}}$	52 ±	52 ±	52 ±	±
χ^2_ν ($\mathrm{m\,s^{-1}}$)	1.68	1.99	1.42	
RMS ($\mathrm{m\,s^{-1}}$)	4.3	4.8	3.8	

Table 4. Known Exoplanets which Could Host Habitable Exomoons

Planet Name	Planet $m\sin i$ ($M_{\rm Jup}$)	Planet Period (d)	Planet e	Star SpT	Star Mass ($M_\odot$)	Star π (mas)	Star V	Star $L/L_\odot$	Planet $a^\dagger$ (AU)	Planet a' ‡ (AU)
	$e < 0.05$ – "Earth-like" eccentricities									
HD28185 b	5.80	379	0.05	G5	0.99	23.62	7.80	1.15	1.02	0.95
55 Cnc f	0.15	260.7	0.0002	G8V	0.96	81.03	5.96	0.58	0.79	1.04
	$0.05 < e < 0.1$ – "Mars-like" eccentricities									
HD221287 b	3.12	456.1	0.08	F7V	1.25	18.09	7.82	1.82	1.25	0.93
HD45364 c	0.66	342.9	0.0974	G8V	0.82	30.59	8.08	0.58	0.90	1.18
HD216435 b	1.21	1311	0.07	K0	1.24	30.66	6.03	3.90	2.52	1.28
HD10697 b	6.24	1075.2	0.099	G5	1.11	30.7	6.27	2.79	2.13	1.28
	$0.1 < e < 0.17$									
HD108874 b	1.29	394.5	0.1276	G5	0.95	15.97	8.76	1.04	1.04	1.01
HD188015 b	1.47	461.2	0.137	G5IV	1.06	17.54	8.24	1.39	1.19	1.01
mu Ara b	1.75	643.25	0.128	G3	1.14	64.47	5.12	1.81	1.53	1.14

$^\dagger a$ is the semi-major axis of the exoplanet's orbit.

$^\ddagger a' = a/\sqrt{(L/L_\odot)}$ as described in the text.