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# SUB-SATURN PLANETARY CANDIDATES OF HD 16141 AND HD 46375[1]

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## ABSTRACT

Precision Doppler measurements from the Keck High-Resolution Echelle Spectrograph reveal periodic Keplerian velocity variations in the stars HD 16141 and HD 46375. HD 16141 (G5 IV) has a period of 75.8 days and a velocity amplitude of 11 m s$^{-1}$, yielding a companion having $M \sin i = 0.22$ $M_{JUP}$ and a semimajor axis of $a = 0.35$ AU. HD 46375 (K1 IV–V) has a period of 3.024 days and a velocity amplitude of 35 m s$^{-1}$, yielding a companion with $M \sin i = 0.25$ $M_{JUP}$, a semimajor axis of $a = 0.041$ AU, and an eccentricity of 0.04 (consistent with zero). These companions contribute to the rising planet mass function toward lower masses.

*Subject headings:* planetary systems — stars: individual (HD 16141, HD 46375)

## 1. INTRODUCTION

The 2000 nearest and brightest dwarf stars ranging in spectral type from late F through M are currently being surveyed by groups with a Doppler precision of ∼10 m s$^{-1}$ or better. To date, these surveys have resulted in the discoveries of 32 extrasolar planets (see Marcy, Cochran, & Mayor 2000; Marcy & Butler 2000; Vogt et al. 2000; Queloz et al. 2000; Udry et al. 2000; Noyes et al. 1997), including the first system of multiple planets (Butler et al. 1999) and the first detection of a transiting planet (Henry et al. 2000; Charbonneau et al. 2000).

Remarkably, all 32 companions found from precision Doppler surveys have $M \sin i < 8$ $M_{JUP}$, although companions with masses of 10–80 $M_{JUP}$ would have been much easier to detect. The companion mass function rises steeply toward smaller masses (Marcy & Butler 2000), but it turns over near 0.5 $M_{JUP}$, presumably because of poor detectability. With the conventional precision of 10 m s$^{-1}$, companions of 0.5 $M_{JUP}$ in 4 day orbits induce stellar motion only a few times greater than such Doppler errors. The stars 51 Pegasi and HD 75289 have the lowest known values of $M \sin i$, both 0.46 $M_{JUP}$ (Mayor & Queloz 1995; Udry et al. 2000). However, with a precision of 3 m s$^{-1}$, one may explore the mass distribution below 1 $M_{SAT}$ (=0.298 $M_{JUP}$). If sub-Saturn–mass companions occur less frequently than Jupiter-mass companions, the status of all Jupiter-mass companions as "planets" would be cast in doubt. Such a distribution of masses, peaked at ∼1 $M_{JUP}$, is not the case in our solar system, nor do theories of planet formation predict such a peak (e.g., Lissauer 1995; Boss 1995; Levison, Lissauer, & Duncan 1998).

Here we report Doppler variations in HD 16141 and HD 46375 exhibiting $M \sin i < 1$ $M_{SAT}$. Stellar characteristics and observations are discussed in the second section. Orbital solutions are presented in the third section, followed by a discussion of the results.

## 2. OBSERVATIONS AND STELLAR CHARACTERISTICS

HD 16141 (79 Cet, HIP 12048; G5 IV) and HD 46375 (HIP 31246; K1 IV–V) are slowly rotating, chromospherically inactive stars, based on the weak Ca II H and K emission in their spectra. Their *Hipparcos* (Perryman et al. 1997) distances are 35.9 and 33.4 pc, respectively, giving them absolute magnitudes of $M_V = 4.05$ and $M_V = 5.29$, respectively, which places both stars 1.0 mag above the zero-age main sequence. The *Hipparcos* mission made 60 and 63 photometric observations of HD 16141 and HD 46375, respectively, revealing that both stars are photometrically stable at the level of errors, ∼0.01 mag.

The mass of HD 16141 is $M = 1.01$ $M_\odot$, and it has [Fe/H] = 0.02, as determined by high-resolution spectral synthesis (Fuhrmann 1998). The mass of HD 46375 is probably ∼1.0 $M_\odot$ also. Its spectral type of K1 IV–V and color, $B-V = 0.86$, would normally indicate a mass of 0.9 $M_\odot$. But its metallicity appears to be high, [Fe/H] =∼ 0.34, as judged from narrowband photometry (K. Apps 2000, private communication). This high metallicity implies a higher mass than is associated with solar-metallicity stars of its color, giving it an estimated mass of 0.9–1.0 $M_\odot$. Here we adopt a mass of $1.0 \pm 0.1$ $M_\odot$ for computation of $M \sin i$ and a semimajor axis. HD 46375 resides only a few arcminutes northeast of the bright nebulosity of the Rosette Nebula (which is over 1 kpc in the background), leaving some concern about the contamination of the optical spectra and the photometry of the star.

The velocities of HD 16141 and HD 46375 have been monitored since 1996 and 1998, respectively. The technique is the same as described in Vogt et al. (2000), using the Keck I Telescope High-Resolution Echelle Spectrograph (Vogt et al. 1994). The H and K lines near 3950 Å provide a simultaneous chromospheric diagnostic (Saar, Butler, & Marcy 1998), giving $\log R'(\mathrm{HK}) = -5.05$ and $-4.94$ for HD 16141 and HD 46375, respectively, typical for chromospherically quiet stars (Noyes et al. 1984). The photospheric Doppler "jitter" of such stars is less than 3 m s$^{-1}$ (Saar et al. 1998).

## 3. ORBITAL SOLUTIONS

The 46 observations of HD 16141 are shown in Figure 1 and listed in Table 1. These observations have an rms of

[1] Based on observations obtained at the W. M. Keck Observatory, which is operated jointly by the University of California and the California Institute of Technology.

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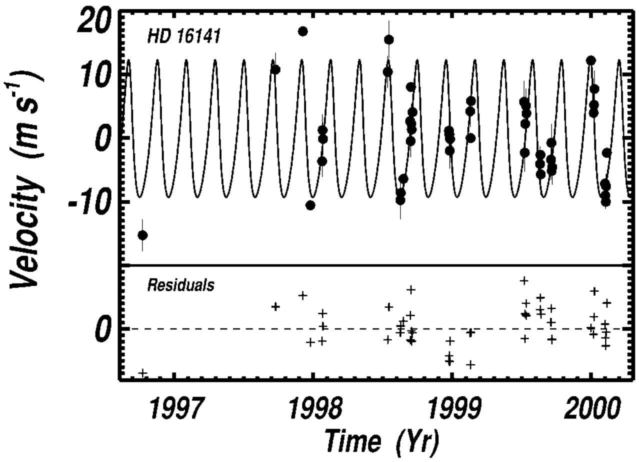


FIG. 1.—Keck Doppler velocities, with error bars, for HD 16141. The solid line through the points shows the best Keplerian fit. The residuals having rms = 3.24 m $s^{-1}$ are shown at the bottom (*crosses*) with arbitrary zero point (*horizontal dashed line*).

7.0 m $s^{-1}$, 2.5 times larger than the measurement error. A periodogram of these velocities (Fig. 2*a*) reveals a dominant period at 75.6 days. The reality of this periodicity is supported by two tests. We broke the velocity set into its first half and second half, yielding separate periodograms with the highest peaks at 75 and 77 days, respectively, both having a false-alarm probability under 1%. Thus, both halves of the measurements reveal the 76 day periodicity. We also computed the false-alarm probability of the 76 day periodicity in the full velocity set by using a Monte Carlo approach (Gilliland & Baliunas 1987). We generated $10^5$ sets of artificial velocities drawn from a Gaussian error distribution while retaining the actual times of observation. None of these artificial velocity sets yielded a periodogram peak as high as that actually found for HD 16141 (Fig. 2*a*). Thus, the false-alarm probability is less than $1 \times 10^{-5}$.

The best-fit Keplerian model to the velocities of HD 16141 is shown in Figure 1 and yields a period $P = 75.82$ days. The amplitude $K = 10.8$ m $s^{-1}$, and the eccentricity $e = 0.28$. The rms of the residuals to the Keplerian fit is 3.2 m $s^{-1}$, similar to the median internal error of 2.8 m $s^{-1}$. Adopting a stellar mass of 1 $M_{\odot}$, the companion has $M \sin i = 0.22\ M_{\rm JUP}$, and the semimajor axis is 0.35 AU. A periodogram of the velocity residuals is shown in Figure 2*b*, which reveals no significant peaks, indicating that no additional companions are evident.

The 24 observations of HD 46375 are listed in Table 2. Figure 3 shows observations obtained between 2000 February 6 and 11, revealing a 3 day period. A phased version of the entire data set spanning 515 days is shown in Figure 4. The same best-fit sinusoid is shown in both Figures 3 and 4. The rms of the sinusoidal fit is 2.59 m $s^{-1}$, slightly greater than the velocity uncertainty of 2.2 m $s^{-1}$. The best-fit Keplerian gives $e = 0.04 \pm 0.04$ (which is not significant) and yields an rms of 2.44 m $s^{-1}$. The period is 3.024 days, and the velocity semiamplitude $K = 35$ m $s^{-1}$. Assuming that the host star is 1 $M_{\odot}$, the companion has $M \sin i = 0.25\ M_{\rm JUP}$, and the semimajor axis is 0.041 AU. The orbital parameters for HD 16141 and HD 46375 are listed in Table 3.

TABLE 1
VELOCITIES FOR HD 16141

| JD (−2,450,000+) | Radial Velocity (m $s^{-1}$) | Error (m $s^{-1}$) |
|---|---|---|
| 365.9888 ....... | −15.1 | 2.5 |
| 715.1077 ....... | 10.9 | 2.7 |
| 786.8339 ....... | 16.9 | 3.1 |
| 806.8945 ....... | −10.4 | 2.9 |
| 837.7389 ....... | −3.5 | 2.5 |
| 838.7150 ....... | 1.4 | 2.5 |
| 839.7379 ....... | 0.0 | 2.5 |
| 1010.1177 ...... | 10.6 | 2.5 |
| 1013.1171 ...... | 15.6 | 2.9 |
| 1043.0747 ...... | −9.6 | 3.0 |
| 1044.1033 ...... | −8.5 | 2.5 |
| 1050.9976 ...... | −6.2 | 2.8 |
| 1068.9550 ...... | 2.8 | 2.2 |
| 1070.1031 ...... | −0.3 | 2.4 |
| 1070.9812 ...... | 8.2 | 3.0 |
| 1071.9963 ...... | 2.4 | 3.1 |
| 1072.9689 ...... | 1.5 | 2.7 |
| 1074.9096 ...... | 4.2 | 2.8 |
| 1170.8101 ...... | 1.3 | 2.7 |
| 1171.7517 ...... | 0.7 | 2.6 |
| 1172.8463 ...... | −1.8 | 2.8 |
| 1173.7982 ...... | 0.0 | 2.9 |
| 1226.7259 ...... | 4.4 | 2.4 |
| 1227.7267 ...... | 0.2 | 2.0 |
| 1228.7149 ...... | 6.0 | 2.5 |
| 1368.1243 ...... | 5.8 | 3.3 |
| 1370.1264 ...... | −2.1 | 3.0 |
| 1371.1179 ...... | 2.4 | 2.7 |
| 1373.1326 ...... | 5.3 | 2.7 |
| 1374.1180 ...... | 4.0 | 3.1 |
| 1410.1390 ...... | −3.9 | 2.8 |
| 1411.0372 ...... | −2.5 | 3.0 |
| 1412.0972 ...... | −5.5 | 3.3 |
| 1438.9326 ...... | −3.2 | 3.1 |
| 1439.9281 ...... | −0.6 | 3.0 |
| 1440.9359 ...... | −5.0 | 3.0 |
| 1441.9363 ...... | −4.4 | 2.8 |
| 1543.8553 ...... | 12.4 | 2.8 |
| 1550.7971 ...... | 4.1 | 3.0 |
| 1551.7998 ...... | 5.4 | 2.5 |
| 1552.8500 ...... | 7.9 | 2.8 |
| 1580.7274 ...... | −7.0 | 2.8 |
| 1581.7594 ...... | −8.9 | 2.1 |
| 1582.7209 ...... | −9.9 | 2.0 |
| 1583.7356 ...... | −7.4 | 2.1 |
| 1585.7334 ...... | −2.2 | 2.9 |

## 4. DISCUSSION

HD 16141 exhibits the smallest velocity amplitude, $K = 10.8$ m $s^{-1}$, reported for any planetary candidate, thus warranting an assessment of stellar and instrumental sources of error. Chromospherically inactive stars are intrinsically stable at the level of 3 m $s^{-1}$ (Saar et al. 1998). Furthermore, the majority of our program stars exhibit no instrumental "drift" in the velocity zero point at the 2 m $s^{-1}$ level during the last 4 yr (Vogt et al. 2000). There is no plausible stellar timescale near 75 days except rotation. But spots are not important since HD 16141 is chromospherically quiet at Ca II H and K and photometrically stable at 0.01 mag from *Hipparcos*. Thus, the most likely explanation for the Doppler variations is an orbiting planet.

The eccentricity for the planet around HD 16141 is not yet well determined, $e = 0.28 \pm 0.15$, and indeed cannot be reliably distinguished from a circular orbit without further measurements. However, all 21 planets orbiting beyond 0.2 AU (Marcy & Butler 2000) have eccentricities above 0.1, and thus this planet will constitute an interesting test case of the eccentricities of a possibly low mass planet.

The companion to HD 46375 is similar to the other "51 Peg–like" planets with their orbital periods of 3–5 days

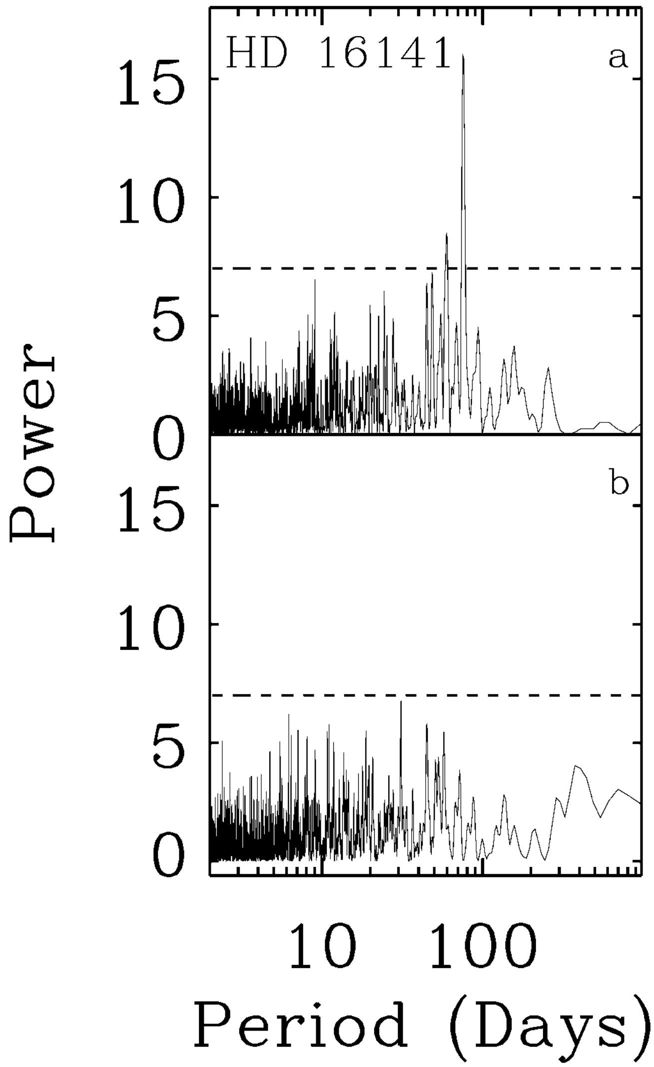


FIG. 2.—(*a*) Periodogram of the measured Doppler velocities of HD 16141. The dashed line shows the 1% false-alarm level. The highest peak at 75.6 days has a false-alarm probability of less than $1 \times 10^{-5}$ from Monte Carlo tests. (*b*) Periodogram of the velocities of HD 16141, after removing the best-fit Keplerian. No significant peaks remain.

and circular orbits. Circular orbits are expected from tidal coupling with the primary star (Rasio & Ford 1996; Marcy et al. 1997; Ford, Rasio, & Sills 1999). Since the primary in the HD 46375 system has not been spun up, the mass of the planet is constrained to be less than ~15 $M_{JUP}$ (Ford et al. 1999; Marcy et al. 1997). The suspected high metallicity of HD 46375 of [Fe/H] = 0.34 (K. Apps 2000, private communication) supports the suggestion that 51 Peg–like planets are associated with high-metallicity stars (Gonzalez, Wallerstein, & Saar 1999; Queloz et al. 2000).

The value of $M \sin i = 0.25\ M_{JUP}$ for the companion to HD 46375 is smaller than that of any known 51 Peg–like extrasolar planet, with the smallest having been 51 Peg (0.46 $M_{JUP}$; Mayor & Queloz 1995) and HD 75289 (0.46 $M_{JUP}$; Udry et al. 2000). This suggests that if orbital migration brings such planets inward (Lin, Bodenheimer, & Richardson 1996), the process may continue to operate at masses near 1 $M_{SAT}$, pending knowledge of sin *i*.

With a demonstrated precision of 3 m $s^{-1}$ (Vogt et al. 2000), the Keck survey is currently capable of making 3 $\sigma$ detections of 51 Peg–like planets down to the Neptune-mass range. Knowledge of the companion mass function of 51 Peg–like planets down into this range will provide useful constraints on models that explain the formation and subsequent dynamics of 51 Peg–like planets.

TABLE 2
VELOCITIES FOR HD 46375

| JD (−2,450,000+) | Radial Velocity (m $s^{-1}$) | Error (m $s^{-1}$) |
|---|---|---|
| 1070.1367 ...... | 16.4 | 2.5 |
| 1171.9009 ...... | −38.0 | 2.5 |
| 1226.8575 ...... | −20.2 | 3.7 |
| 1227.8334 ...... | 30.3 | 2.6 |
| 1228.9406 ...... | −37.2 | 3.7 |
| 1544.0196 ...... | −35.2 | 2.6 |
| 1550.9756 ...... | 22.3 | 2.0 |
| 1551.7716 ...... | 17.3 | 2.2 |
| 1551.9140 ...... | 5.1 | 1.7 |
| 1552.0074 ...... | 2.3 | 1.7 |
| 1552.8292 ...... | −37.3 | 2.1 |
| 1552.9381 ...... | −39.5 | 2.3 |
| 1580.8203 ...... | −5.8 | 2.0 |
| 1580.9892 ...... | 0.5 | 1.4 |
| 1581.7296 ...... | 25.3 | 2.4 |
| 1581.9588 ...... | 16.8 | 2.3 |
| 1582.7138 ...... | −33.5 | 1.7 |
| 1582.7945 ...... | −34.2 | 2.1 |
| 1582.8802 ...... | −39.2 | 1.4 |
| 1583.7291 ...... | −16.9 | 1.3 |
| 1583.9223 ...... | 0.2 | 2.2 |
| 1584.8240 ...... | 23.0 | 3.5 |
| 1585.8850 ...... | −41.6 | 1.4 |
| 1585.9671 ...... | −42.2 | 1.9 |

The effective temperature of a planet in a 3.024 day orbit about HD 46375 would be ~1400 K (Burrows et al. 1998). Henry (2000) reports that no transit occurs, implying that $\sin i < 0.992$. The expected amplitude of a transit signal is about 0.015 mag (Burrows et al. 1998; Henry et al. 2000; Charbonneau et al. 2000).

The companions to HD 16141 and HD 46375 have the lowest values of $M \sin i$ (0.22 and 0.25 $M_{JUP}$, respectively) found to date for extrasolar planets. The observed histogram of $M \sin i$ shows a steep rise toward the lowest masses, consistent with a power law, $dN/dM \propto M^{-1}$ (Marcy & Butler 2000). These new planets support the suggestion that the mass distribution continues rising to 1 $M_{SAT}$. Verification of any rise in the plan-

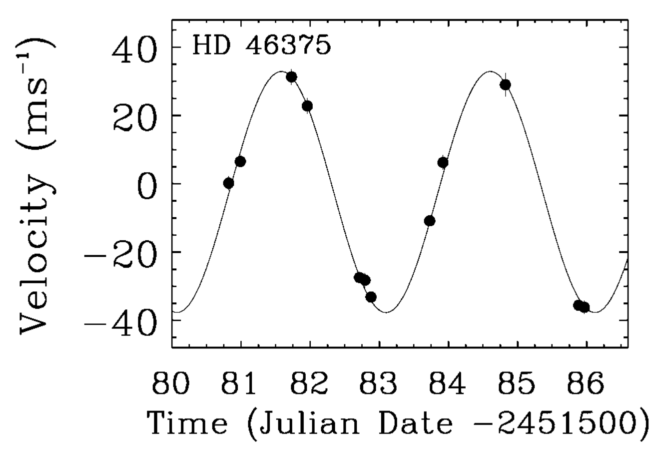


FIG. 3.—Keck Doppler velocities for HD 46375 from the 2000 February observing run. A 3 day periodicity is evident for this six-night observing string. Measurement uncertainties are ~2.2 m $s^{-1}$.

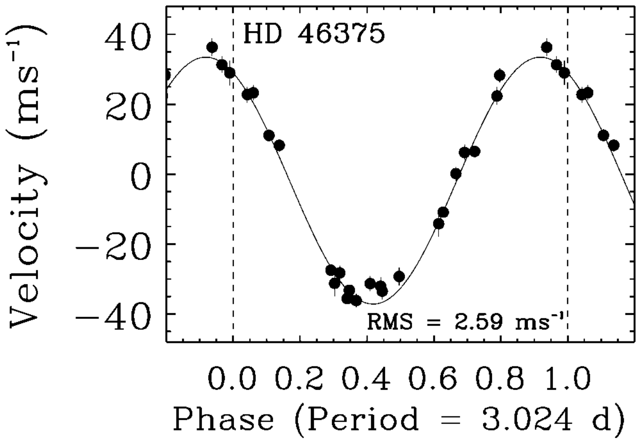


FIG. 4.—Phased Doppler velocities for HD 46375. The same best-fit sinusoid is shown in Fig. 3. The rms to the sinusoidal fit is 2.59 m $s^{-1}$, which is essentially identical to the best-fit Keplerian. The period is 3.024 days, and the semiamplitude is 35 m $s^{-1}$. Assuming that the mass of HD 46375 is 1 $M_{\odot}$, the minimum ($M \sin i$) mass of the companion is 0.25 $M_{JUP}$, and the semimajor axis is 0.041 AU.

TABLE 3
ORBITAL PARAMETERS

| Parameter | HD 16141 | HD 46375 |
|---|---|---|
| Orbital period $P$ (days) | 75.82 (0.4) | 3.024 (0.0005) |
| Velocity amplitude $K$ (m $s^{-1}$) | 10.8 (1.4) | 35.2 (1.7) |
| Eccentricity $e$ | 0.28 (0.15) | 0.04 (0.04) |
| $\omega$ (deg) | 41 (22) | 62 (50) |
| Periastron time (JD) | 2451547.2 (4.1) | 2451582.10 (0.23) |
| $M \sin i$ ($M_{JUP}$) | 0.215 (0.03) | 0.249 (0.03) |
| $a$ (AU) | 0.35 | 0.041 |

etary mass function below 1 $M_{SAT}$ will require more detections to account properly for incompleteness.

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