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AN $m \sin i$ = 24 M$_\oplus$ PLANETARY COMPANION TO THE NEARBY M DWARF GJ 176[1]

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ABSTRACT

We report the detection of a planetary companion with a minimum mass of $m \sin i = 0.0771\ M_{\rm Jup} = 24.5\ M_\oplus$ to the nearby ($d = 9.4$ pc) M2.5 V star GJ 176. The star was observed as part of our M dwarf planet search at the Hobby-Eberly Telescope (HET). The detection is based on 5 years of high-precision differential radial velocity (RV) measurements using the High-Resolution Spectrograph (HRS). The orbital period of the planet is 10.24 days. GJ 176 thus joins the small (but increasing) sample of M dwarfs hosting short-period planets with minimum masses in the Neptune-mass range. Low-mass planets could be relatively common around M dwarfs, and the current detections might represent the tip of a rocky planet population.

Subject headings: planetary systems — stars: individual (GJ 176) — techniques: radial velocities

1. INTRODUCTION

Over the past few years our preliminary knowledge about the frequency of extrasolar planets in the low-mass part of the HR diagram has increased significantly. An ever increasing number of M dwarfs is being monitored by various Doppler searches with high radial velocity (RV) precision. This has led to several discoveries of M dwarf planets that cover an enormous and surprising range in mass, almost comparable to the mass range of the planets in our solar system. Jovian planets were found around GJ 876 (Delfosse et al. 1998; Marcy et al. 1998, 2001), GJ 849 (Butler et al. 2006), and GJ 317 (Johnson et al. 2007), and Neptune-mass planets around GJ 436 (Butler et al. 2004), GJ 581 (Bonfils et al. 2005b), and GJ 674 (Bonfils et al. 2007). The low primary masses of M dwarfs combined with state-of-the-art RV precision even allowed the detection of additional planets with minimum masses below 10 $M_\oplus$ (so-called super-Earths) in the GJ 876 (Rivera et al. 2005) and GJ 581 (Udry et al. 2007) systems.

In this paper we report the detection of a new low-mass planet in a 10.24 day orbit around the M dwarf GJ 176. This is the fourth planet in the class of Neptune-mass companions orbiting M dwarfs. GJ 176 is already the third (previously unknown) planet host in our Hobby-Eberly Telescope (HET) M dwarf planet search (Endl et al. 2003, 2006) sample.

2. STELLAR PARAMETERS OF GJ 176

GJ 176 (HD 285968, HIP 21932, LHS 196) is a $V = 9.97$ M2.5 Ve star at a distance of 9.4 pc, according to the *Hipparcos* parallax of 106 ± 2.5 mas (Perryman et al. 1997). The star has a $B - V$ of 1.51 and an absolute V magnitude of 10.08. The 2MASS magnitudes for GJ 176 are $J = 6.462$, $H = 5.824$, and $K = 5.607$ mag (Cutri et al. 2003). Using the V-band and K-band mass-luminosity relationships of Delfosse et al. (2000), we estimate a mass of 0.48 and 0.50 $M_\odot$, respectively. We adopt the mean value of $0.49 \pm 0.014\ M_\odot$ as the mass of the star.

A photometric study by Weis (1994) did not find significant variability for GJ 176. The V-band scatter measured by Weis (1994) is 0.006 mag, equal to the measurement uncertainties. The *ROSAT* All Sky Survey catalog of nearby stars (Hünsch et al. 1999) reports a moderate coronal X-ray emission level of 3×10^{27} erg s^{-1}. GJ 176 is thus a moderately active star, possibly exhibiting starspots and flares, a quite typical behavior for M dwarfs. Rauscher & Marcy (2006) measured the equivalent widths of the Ca II H and K lines with 0.97 ± 0.10 Å and 0.69 ± 0.08 Å, respectively. Based on the V-band mass-metallicity relationship of Bonfils et al. (2005a), we estimate an [Fe/H]$= -0.1 \pm 0.2$ for GJ 176, so roughly solar metallicity.

3. OBSERVATIONS AND RV RESULTS

We observed GJ 176 as part of our ongoing Doppler search for planets around M dwarfs (Endl et al. 2003, 2006) using the HET (Ramsey et al. 1998) and its HRS spectrograph (Tull 1998). We started observations of GJ 176 in 2003 October 15 and collected a total of 28 spectra over 5 years. All observations were performed using our standard planet search setup and data reduction pipeline, described in detail in Cochran et al. (2004). We use the common I_2 cell technique to obtain high-precision differential RV measurements (e.g., Butler et al. 1996; Endl et al. 2000).

Figure 1 shows the time series of our HET/HRS RV measurements with the small secular acceleration of the RV of 0.36 m s^{-1} yr^{-1}, as computed from the Hipparcos parallax and proper motion information, already subtracted. The data have an overall rms scatter of 9.84 m s^{-1} and average internal errors of 4.69 ± 0.63 m s^{-1}.

[1] Based on observations obtained with the Hobby-Eberly Telescope, which is a joint project of the University of Texas at Austin, the Pennsylvania State University, Stanford University, Ludwig-Maximilians-Universität München, and Georg-August-Universität Göttingen.

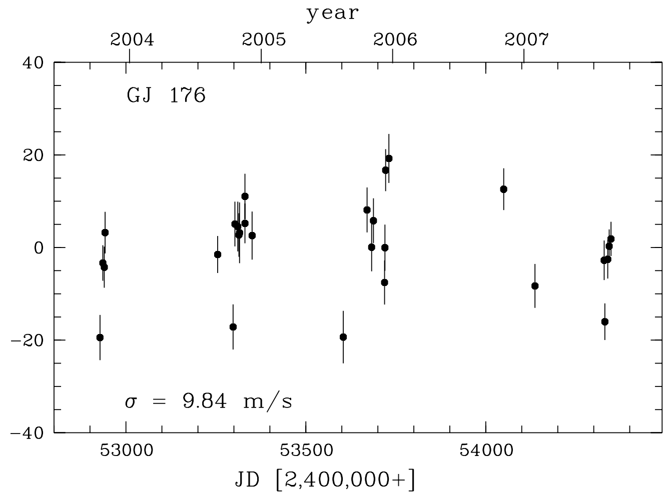

FIG. 1.—Plot of 5 yr of HET/HRS RV measurements of GJ 176. The data have a scatter of 9.84 m s^{-1} and an average measurement uncertainty of 4.69 m s^{-1}.

The total scatter is more than twice the measurement uncertainties, indicative of intrinsic RV variability of this target. The HET RV data are listed in Table 1.

4. PERIOD SEARCH AND ORBITAL SOLUTION

We searched the RV data of GJ 176 for any significant periodicities using the classic Lomb-Scargle periodogram (Lomb 1976; Scargle 1982). Figure 2 displays the resulting power spectrum. A strong peak is visible at a period of 10.24 days. We estimate the false-alarm probability (FAP) of this signal with the bootstrap randomization scheme (e.g., Kürster et al. 1997). After 100,000 bootstrap reshuffling runs, we find that the FAP of the 10.24 day signal is only 0.0004.

As the next step we use GAUSSFIT (Jeffereys et al. 1988) to find a Keplerian orbital solution to our RV data. A circular orbit fit yields a χ^2 of 35.2 ($\chi^2_{\rm red} = 1.47$) and a residual RV scatter of 5.57 m s^{-1}. A slightly better fit is obtained with an eccentric orbit with $e = 0.23 \pm 0.13$: χ^2 of 32.86 ($\chi^2_{\rm red} = 1.49$) and residual rms of 5.32 m s^{-1}. The large uncertainty in e and the fact that a circular orbit yields a lower $\chi^2_{\rm red}$ urges us to remain cautious concerning the reality of the noncircular orbit. However, future observations will allow us to determine whether the orbit is indeed eccentric. A moderately eccentric orbit could be an indication of additional planets around this star and thus warrants intensive follow-up monitoring.

Figure 3 shows the RV measurements and both orbital solutions (circular and eccentric) phased to the best-fit period. The circular orbital solution yields a minimum mass for the companion of $0.077 \pm 0.012\ M_{\rm Jup} = 24.5 \pm 3.9\ M_\oplus$, while an eccentric orbit would lower the minimum mass slightly to $0.076 \pm 0.010\ M_{\rm Jup} = 24.1 \pm 3.1\ M_\oplus$. The orbital parameters are summarized in Table 2.

4.1. *Stellar Activity versus Planet Hypothesis*

The case of GJ 674 has demonstrated clearly that star spots can introduce low-level signals in high-precision RV data of M dwarfs (Bonfils et al. 2007). Can the GJ 176 signal also be caused by rotational modulation due to star spots and not a planet? This scenario is very unlikely, because a rotation period of 10.2 days would mean that GJ 176 would rotate more than 3 times faster than GJ 674, and this should lead to a higher activity level than GJ 674. This is not the case, as GJ 176 has a slightly lower coronal X-ray emission than GJ 674 (Hünsch et al. 1999). As mention before, Weis (1994) did not detect photometric variability in GJ 176, and we also did not find any significant variability or periodicity in the *Hipparcos* photometry for this star (the highest peak at 3.7 days has a FAP of 1.5%.)

Moreover, the vast majority of the data of Bonfils et al. (2007) were collected over a relatively short period of time (≈200 days), during which rotational modulation could mimic a Keplerian signal of a planet because the active regions on the star remain constant for this period of time. However, over a longer span of time, active regions will reconfigure and emerge at different stellar longitudes, causing a phase as well as amplitude change in the RV signal. The GJ 176 signal remains stable in phase and amplitude over 5 years, which makes the planet hypothesis much more plausible as the origin of the RV signal.

5. DISCUSSION

Remarkably, GJ 176 is already the third M dwarf with a Neptune-mass companion that was included in our HET sample of 60 M dwarfs. GJ 436 and GJ 581 were part of our M dwarf sample before the planets around them were announced. The frequency of short-period Neptune-mass planets around M dwarfs in our HET sample is hence 5%, which is higher than the frequency of hot Jupiters around FGK-type stars of ≈1.2% (Marcy et al. 2005). Neptunes and super-Earths could be relatively

TABLE 1
DIFFERENTIAL RADIAL VELOCITIES FOR GJ 176 FROM THE HET/HRS

JD (2,400,000+)	*d*RV (m s^{-1})	σ (m s^{-1})	JD (2,400,000+)	*d*RV (m s^{-1})	σ (m s^{-1})
52927.82553	−19.88	4.88	53669.99475	7.67	4.86
52935.80776	−3.78	3.83	53682.74654	−0.38	5.20
52939.79789	−4.69	4.44	53687.75180	5.35	4.84
52941.98273	2.78	4.49	53718.67107	−8.00	4.76
53254.93830	−1.95	3.99	53719.66762	−0.47	4.98
53297.80620	−17.60	4.88	53721.64443	16.26	4.54
53302.79940	4.63	4.84	53730.82258	18.79	5.29
53310.78943	4.09	5.37	54049.74686	12.15	4.51
53313.97346	2.26	4.69	54136.72087	−8.74	4.74
53315.77643	2.73	6.56	54328.97056	−3.20	4.27
53330.71871	4.76	4.30	54330.96817	−16.47	3.95
53330.72892	10.60	4.89	54338.95808	−2.98	4.16
53350.66330	2.13	5.19	54342.93427	−0.15	3.62
53603.95259	−19.79	5.67	54347.92539	1.41	3.70

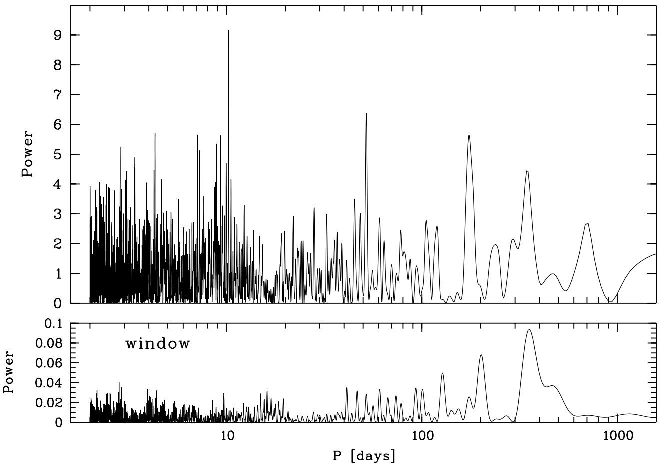

FIG. 2.—Lomb-Scargle periodogram of the RV data of GJ 176. The highest peak is at 10.24 days and has a false-alarm probability of 0.0004. The bottom panel displays the window function of our observations.

TABLE 2
PARAMETERS OF GJ 176b FOR CIRCULAR AND ECCENTRIC ORBIT

Parameter	Circular Orbit	Eccentric Orbit
P (days)...........................	10.2369 ± 0.0039	10.2366 ± 0.0038
T (BJD)...........................	2454550.6672 ± 0.39	2455037.7979 ± 1.1
K (m s^{-1})........................	11.62 ± 1.61	11.72 ± 1.62
e.......................................	0.0 ± 0.0 (fixed)	0.232 ± 0.127
ω (deg)............................	0.0 ± 0.0 (fixed)	210.4 ± 32.5
$M \sin i$ ($M_{\rm Jup}$)..................	0.0771 ± 0.0122	0.0757 ± 0.0096
$M \sin i$ ($M_\oplus$)....................	24.5 ± 3.9	24.1 ± 3.1
a (AU)............................	0.0727 ± 0.0007	0.0727 ± 0.0007
rms (m s^{-1}).....................	5.57	5.32

common around low-mass stars. Of course, with M dwarfs we are still limited by small number statistics, as compared to the few thousand FGK-type stars already observed by various Doppler surveys around the world.

We are currently increasing the size of the HET M dwarf sample, and combined with the results of other programs observing M dwarfs, we should be able to derive important constraints for planet formation models. The present information about Neptune-mass planets on short-period orbits suggests that they may be the tip of the terrestrial planet distribution, for several reasons. First, a number of hot Neptunes have 2 or 3 sibling gas giant planets orbiting at much greater distances: ρ 1 Cnc, μ Ara, and GJ 876 all have such systems. This planetary system architecture is the same as our own solar system, with inner terrestrial planets and outer gas giant planets, and suggests that the hot Neptunes in these systems formed inside their gas giants, making them likely to be rocky planets. Theoretical models of the collisional accumulation of terrestrial planets predict that rocky planets as massive as about 21 $M_\oplus$ would result from a protoplanetary disk with a surface density of gas and solids high enough to form a gas giant planet by core accretion in a few million years (Wetherill 1996; Inaba et al. 2003). Formation of the Neptunes interior to their gas giants seems to be a much more likely scenario than formation as ice giants on orbits outside the orbits of the gas giants, followed by migration somehow past the gas giants to their current short-period orbits. While GJ 876 is the only M dwarf of these three stars, one might expect a common explanation for its hot Neptune as a rocky world, as well as those of GJ 436 and GJ 581. This interpretation bodes well for the eventual detection of Earth-mass planets on habitable orbits around low-mass stars. For M dwarfs with masses of $<0.2\ M_\odot$ we already have the sensitivity to detect $m \sin i \approx 1\ M_\oplus$ planets in the habitable zone (M. Endl & M. Kürster 2008, in preparation).

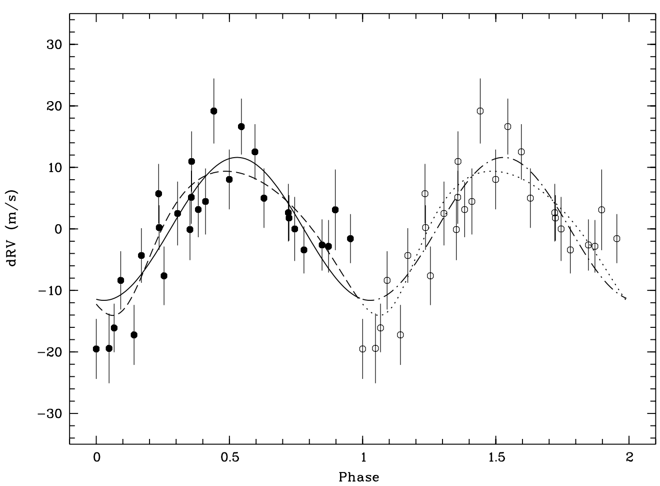

FIG. 3.—Best-fit orbital solutions are shown for circular (*solid line*) and eccentric (*dashed line*) orbits, along with the HET/HRS RV measurements phased to the orbital period of 10.24 days (the data are plotted twice for a second cycle). The semiamplitude K of 11.6 m s^{-1} corresponds to a minimum mass of 24.5 $M_\oplus$ for the companion. All parameters of the orbital solution are summarized in Table 2. The residual scatter around the fit is 5.57 m s^{-1} (circular) and 5.32 m s^{-1} (eccentric orbit).

While M dwarfs appear to have hot Neptunes at a higher rate than G dwarfs, they appear to have short-period gas giant planets at a somewhat smaller rate than G dwarfs (Endl et al. 2006; Johnson et al. 2007). Similarly, microlensing surveys have detected planetary companions at asteroidal distances to M dwarf stars at frequencies that suggest that planets at such locations are more likely to be Neptune-mass than Jupiter-mass. These results may simply be a result of M dwarfs having lower mass protoplanetary disks than G dwarfs, with the consequent result that the planets that form tend to have a mass distribution that is shifted downward. However, this apparent preference for cold super-Earths over Jupiters can also be explained at present by both the core accretion and disk instability formation mechanism for gas giant planets. In the case of core accretion, the lengthened orbital periods around M dwarfs could lead to most cores growing too slowly to accrete significant gaseous envelopes, making failed cores the usual outcome, rather than gas giants (Laughlin et al. 2004). Disk instability explains the appearance of both gas giants and super-Earths at asteroidal distances around M dwarfs by appealing to rapid formation of gaseous protoplanets by disk instability, followed by conversion to ice giants (cold super-Earths) by photoevaporation at asteroidal distances in region of high-mass star formation (Boss 2006). Because most M dwarfs form in regions of high mass formation, they should be orbited at asteroidal distance primarily by super-Earths. M dwarfs that form in the region of a low-mass star will have gas giant planets at those distances, if disk instability is operative (Boss 2006). It remains for these theoretical speculations to be tested by completing the extrasolar planetary census.

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