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## A Long-Period Jupiter-Mass Planet Orbiting the Nearby M Dwarf GJ 849<sup>1</sup>

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**ABSTRACT.** We report precise Doppler measurements of GJ 849 (M3.5 V) that reveal the presence of a planet with a minimum mass of  $0.82M_{\text{Jup}}$  in a 5.16 yr orbit. At  $a = 2.35$  AU, GJ 849b is the first Doppler-detected planet discovered around an M dwarf orbiting beyond 0.21 AU, and is only the second Jupiter-mass planet discovered around a star less massive than  $0.5 M_{\odot}$ . This detection brings to four the number of M stars known to harbor planets. Based on the results of our survey of 1300 FGKM main-sequence stars we find that giant planets within 2.5 AU are  $\sim 3$  times more common around GK stars than around M stars. Due to GJ 849's proximity of 8.8 pc, the planet's angular separation is  $0.27''$ , making this system a prime target for high-resolution imaging using adaptive optics and future space-borne missions such as the *Space Interferometry Mission PlanetQuest*. We also find evidence of a linear trend in the velocity time series, which may be indicative of an additional planetary companion.

### 1. INTRODUCTION

Of the 152 stars within 200 pc of the Sun known to harbor planets,<sup>6</sup> the majority are Sun-like, with masses between 0.7 and  $1.3 M_{\odot}$  (Butler et al. 2006). Main-sequence stars with masses greater than  $1.3\text{--}1.4 M_{\odot}$  (spectral types earlier than  $\sim F5$  V) are typically unsuitable for high-precision radial velocity (RV) monitoring because their spectra lack narrow absorption lines (Galland et al. 2005; Johnson et al. 2006) and have excessive atmospheric “jitter” (Wright 2005). However, at the lower end of the mass spectrum, M-type dwarfs are much more amenable to precision Doppler measurements, with the primary observational limitation being their relative faintness. Over 200 M dwarfs ( $M_* < 0.6 M_{\odot}$ ) have been monitored by various groups using large telescopes (e.g., Wright et al. 2004; Kürster et al. 2003; Endl et al. 2003). These surveys have so far discovered five planets orbiting only three host stars: the triple system around GJ 876 (Marcy et al. 1998, 2001; Delfosse et al. 1998; Rivera et al. 2005) and the Neptune-mass planetary companions to GJ 436 (Butler et al. 2004) and GJ 581 (Bonfils et al. 2005b). Only one of these three systems, GJ 876, contains

Jupiter-mass planets, and despite the  $\geq 2$  yr duration of these surveys, none has revealed a planet beyond 0.21 AU.<sup>7</sup>

The RV precision attainable from the spectra of middle-age ( $> 2$  Gyr) M dwarfs is similar to that of G- and K-type stars, and the stars themselves typically exhibit low levels of photospheric jitter (Wright 2005). In addition, the Doppler reflex amplitude scales as  $K \propto a^{-1/2} M_p M_*^{-1/2}$ , which makes planets of a given mass easier to detect around low-mass stars. The detectability of planets orbiting M dwarfs is therefore comparable to that of FGK stars, allowing a comparative understanding of the planet formation process in different stellar mass regimes. Based on the lack of planet detections in their survey of 90 M dwarfs, Endl et al. (2006) estimate that fewer than 1.27% of stars with  $M_* < 0.6 M_{\odot}$  harbor Jupiter-mass planets with  $a < 1$  AU, which stands in stark contrast to the 5% occurrence rate of gas giants around solar-type stars (Marcy et al. 2005a). This finding seems to indicate that protoplanetary disks around low-mass stars produce Jovian planets at a decreased rate compared to the disks of Sun-like stars.

The formation of planets around low-mass stars has been studied in the context of the core-accretion planet formation model. In this formation scenario, rocky cores are built up through collisions in the protoplanetary disks around young stars (Wetherill & Stewart 1989; Kokubo 2001). Once a critical core mass is reached, gas accumulates onto the core through a runaway accretion process, resulting in a gas giant by the time the supply of disk gas is exhausted (e.g., Pollack et al.

<sup>1</sup> 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. Keck time has been granted by both NASA and the University of California.

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<sup>6</sup> For the updated catalog of extrasolar planets, their parameters, and the properties of the host stars, see <http://exoplanets.org>.

<sup>7</sup> Three additional low-mass planet host stars have been discovered by gravitational lensing surveys (Bond et al. 2004; Gould et al. 2006; Beaulieu et al. 2006). However, due to the faintness of these candidates, the stellar mass estimates of all but one have large uncertainties. Using *Hubble Space Telescope* ACS imaging, Bennett et al. (2006) determined that OGLE-2003-BLG-235 is likely a late K-type dwarf, with a mass of  $0.6 M_{\odot}$ .

1996). Laughlin et al. (2004) showed that the lower disk masses, decreased surface density of solids, and longer orbital timescales of M dwarf protoplanetary disks inhibit the growth of planetesimals enough that the disk gas dissipates before the critical core mass is reached. The resulting prediction is that there should be a relative abundance of Neptune-mass “ice giants” around M dwarfs, but a far smaller number of gas giants. This prediction agrees well with the findings of Ida & Lin (2005), who studied the frequency of planets for stellar masses ranging from 0.4 to  $1.5 M_{\odot}$ . Based on their Monte Carlo simulations, they find that the number of giant planets drops significantly with decreasing mass for  $M_* < 1 M_{\odot}$ . These theoretical results are in accordance with the available observational data.

However, due to the relatively shorter time baselines of most M dwarf Doppler surveys, the current observational data only provide information about planets orbiting within  $\sim 2$  AU of their host stars. As the durations of the M dwarf planet surveys increase, it will become evident whether the current observed paucity of gas giants holds for larger orbital separations, or there exists a separate, larger population of Jupiter-mass planets residing in long-period orbits. In addition, the prediction of inhibited core growth around lower mass stars is made under the assumption that disk mass scales proportionally with stellar mass (Laughlin et al. 2004). If this assumption is relaxed, Kornet et al. (2006) find that low-mass stars actually form giant planets at an *increased* rate compared to solar-mass stars. Searching for planets around more M dwarfs, as well as at larger orbital separations, will provide an important test of these theories.

We report the detection of a Jupiter-mass planet in a 5.16 yr orbit around the M3.5 dwarf GJ 849. We present the stellar characteristics of the host star in § 2. In § 3 we discuss our observations and orbit solution. We conclude in § 4 with a discussion of the latest M dwarf planetary system and the occurrence of planets around M dwarfs.

## 2. STELLAR PROPERTIES

We have been monitoring a sample of 147 low-mass, late K through M dwarfs as part of the California and Carnegie Planet Search (CCPS; Butler et al. 2006; Rauscher & Marcy 2006). One of them, GJ 849 (HIP 109388, LHS 517), is an M3.5 V star with  $V = 10.42$  and  $B - V = 1.52$  (ESA 1997). Its *Hipparcos*-based parallax ( $\pi = 114$  mas) implies a distance of 8.8 pc and an absolute visual magnitude  $M_V = 10.69$ . Figure 1 shows the position of GJ 849 with respect to the other M-type stars with known planetary companions. Also shown is the CCPS sample, the stars listed in the *Hipparcos* catalog within 50 pc of the Sun, and the mean *Hipparcos* main sequence as defined by Wright (2005).

Despite the star’s location slightly below (0.13 mag) the mean *Hipparcos* main sequence, the *K*-band photometric metallicity-luminosity calibration of Bonfils et al. (2005a) and IR magnitudes of Leggett (1992) suggest that GJ 849 has a metallicity consistent with solar:  $[\text{Fe}/\text{H}] = +0.16 \pm 0.2$ . The

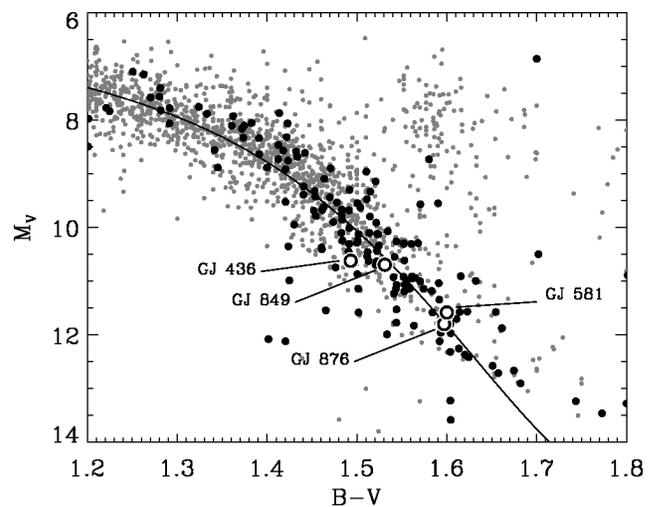


FIG. 1.—H-R diagram illustrating the properties of the four M dwarfs known to harbor planets (*large open circles*) compared to the sample of stars in the CCPS (*black filled circles*); the stars in the *Hipparcos* catalog with distances  $< 50$  pc (*gray filled circles*); and the mean *Hipparcos* main sequence defined by Wright (2005; *solid line*).

*K*-band mass-luminosity calibration of Delfosse et al. (2000) yields a stellar mass  $M_* = 0.47 \pm 0.04 M_{\odot}$ . This mass estimate agrees well with the  $0.51 \pm 0.05 M_{\odot}$  mass predicted by the *K*-band mass-luminosity relationship of Henry & McCarthy (1993). We adopt the mean of these two estimates,  $M_* = 0.49 \pm 0.05 M_{\odot}$ , as the mass of GJ 849.

Examination of our high-resolution spectra reveals no Balmer line emission. Delfosse et al. (1998) report a projected equatorial rotational velocity  $V_{\text{rot}} \sin i = 2.4 \text{ km s}^{-1}$ , and Marcy & Chen (1992) measure  $V_{\text{rot}} \sin i = 1.0 \pm 0.6 \text{ km s}^{-1}$ . The low chromospheric activity and slow rotation of GJ 849 are consistent with a middle-age dwarf older than 3 Gyr (A. West 2006, private communication).

## 3. OBSERVATIONS AND ORBITAL SOLUTION

We have been monitoring GJ 849 with the Keck I 10 m telescope for 6.9 years as part of the NASA Keck M Dwarf Survey and the CCPS. We obtained high-resolution spectra using the HIRES echelle spectrometer (Vogt et al. 1994) with an iodine cell mounted directly in front of the entrance slit (Valenti 1994). The Doppler shift is measured from each star-plus-iodine observation using the modeling procedure described by Butler et al. (1996). Figure 2 shows our velocity measurements for four stable M Dwarfs, demonstrating our long-term Doppler precision of 3–4  $\text{m s}^{-1}$ .

A total of 29 precision Doppler measurements of GJ 849 spanning 6.9 years are listed in Table 1 and shown in Figure 3. The measurement uncertainties listed in Table 1 represent the weighted standard deviation of the velocities measured from the 700  $\text{\AA}$  wide spectral “chunks” used in our Doppler anal-

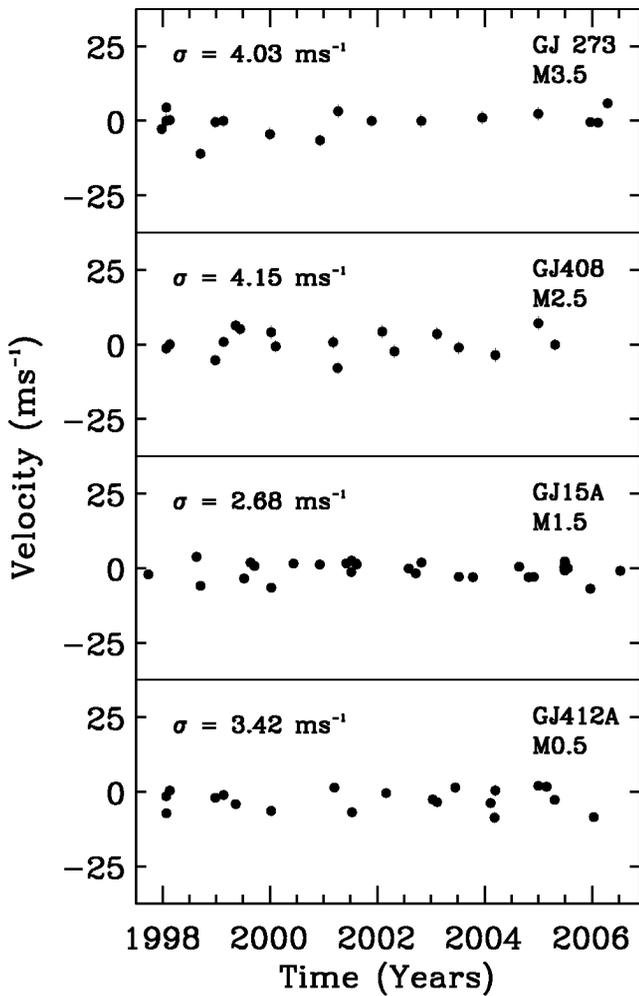


FIG. 2.—Radial velocity time series for four stable M dwarfs in our Keck Doppler survey.

ysis (Butler et al. 1996). The solid line shows the best-fit Keplerian plus linear trend, which has a slope of  $-4.6 \text{ m s}^{-1} \text{ yr}^{-1}$ . The Keplerian parameters are listed in Table 2, along with their estimated uncertainties, which were derived using a Monte Carlo method (e.g., Marcy et al. 2005b). Our best fit orbital solution yields a 5.16 yr period, velocity semiamplitude  $K = 22 \text{ m s}^{-1}$ , and eccentricity  $0.06 \pm 0.09$ —consistent with circular. Using our adopted stellar mass  $M_* = 0.49 M_\odot$ , we calculate a minimum planet mass  $M_p \sin i = 0.82 M_{\text{Jup}}$  and semimajor axis  $a = 2.35 \text{ AU}$ . The rms of the fit residuals is  $4.55 \text{ m s}^{-1}$ , resulting in a reduced  $\chi_r^2 = 1.6$ .

Figure 3 shows that much of the rms scatter is dominated by two observations that sit more than  $2 \sigma$  below the best-fit Keplerian. These two observations have the largest measurement uncertainties in our data set, and if they are excluded the rms of the best-fit Keplerian plus linear trend improves to  $2.1 \text{ m s}^{-1}$ , and  $\chi_r^2 = 0.91$ . Exclusion of these outliers does not change the derived orbital parameters beyond the uncertainties

TABLE 1  
VELOCITIES FOR GJ 849

JD - 2,450,000	Radial Velocity (m s <sup>-1</sup> )
1410.0215	38.9 ± 2.0
1439.8654	35.3 ± 2.0
2095.0814	1.5 ± 2.6
2096.0458	-1.4 ± 2.2
2133.0128	-20.2 ± 3.3
2160.9092	-7.6 ± 2.1
2161.8459	-7.5 ± 2.1
2162.8870	-2.9 ± 2.3
2535.8516	-19.3 ± 2.2
2807.0106	-12.0 ± 2.4
2834.0130	-10.9 ± 2.1
2989.7201	-1.7 ± 2.6
3014.7104	-1.4 ± 2.2
3015.7110	-0.9 ± 2.4
3016.7060	1.1 ± 2.2
3154.0798	8.5 ± 2.6
3180.1084	10.6 ± 2.4
3196.9314	5.3 ± 2.3
3238.9290	10.7 ± 2.4
3301.8384	13.6 ± 2.4
3302.7425	13.3 ± 2.1
3303.7984	14.0 ± 2.0
3603.9387	1.5 ± 2.4
3724.7115	-1.8 ± 2.1
3746.7182	-6.0 ± 2.0
3749.6979	-19.9 ± 2.9
3927.0148	-22.9 ± 2.5
3959.0867	-24.5 ± 2.3
3960.9584	-22.7 ± 1.4

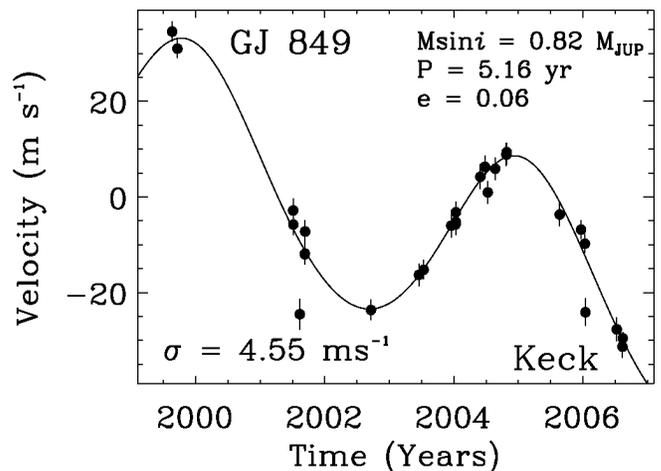


FIG. 3.—Doppler velocities for GJ 849. These data span 6.9 years. The best-fit Keplerian, including a linear  $-4.6 \text{ m s}^{-1} \text{ yr}^{-1}$  trend, is shown as a solid line. The orbital solution has a period  $P = 5.16 \text{ yr}$ , semiamplitude  $K = 22 \text{ m s}^{-1}$ , eccentricity  $e = 0.06$ , yielding  $M_p \sin i = 0.82 M_{\text{Jup}}$  and semimajor axis of 2.35 AU. The rms of the velocity is  $4.55 \text{ m s}^{-1}$ .

TABLE 2  
ORBITAL SOLUTION AND STELLAR PROPERTIES FOR GJ 849

Parameter	Value
Orbital period $P$ (days) .....	$1890 \pm 130$
Orbital period $P$ (yr) .....	$5.16 \pm 0.35$
Velocity semiamplitude $K$ ( $\text{m s}^{-1}$ ) .....	$22 \pm 2$
Eccentricity $e$ .....	$0.06 \pm 0.09$
Periastron date (Julian Date) .....	$2,451,462 \pm 540$
Linear velocity trend ( $\text{m s}^{-1} \text{ yr}^{-1}$ ) .....	$-4.6 \pm 0.8$
$\omega$ (deg) .....	$351 \pm 60$
$M \sin i$ ( $M_{\text{Jup}}$ ) .....	0.82
Semimajor axis (AU) .....	2.35
$N_{\text{obs}}$ .....	29
rms ( $\text{m s}^{-1}$ ) .....	4.55
$V$ .....	10.42
$K$ .....	5.59
$B - V$ .....	1.52
$M_V$ .....	10.69
Distance (pc) .....	8.8
Stellar mass ( $M_{\odot}$ ) .....	$0.49 \pm 0.05$
Metallicity ([Fe/H]) .....	$0.16 \pm 0.2$

listed in Table 2. We see no correlations or additional periodicities in the residuals.

#### 4. DISCUSSION

We present here the detection of a Jupiter-mass planetary companion to the M3.5 dwarf GJ 849. This detection brings to four the number of M dwarfs harboring Doppler-detected planets, together with GJ 876 (Marcy et al. 2001; Rivera et al. 2005), GJ 436 (Butler et al. 2004), and GJ 581 (Bonfils et al. 2005b). The GJ 849 planetary system is remarkable in two respects: the orbital separation ( $a = 2.35$  AU) of the planet is more than an order of magnitude greater than any other Doppler-detected M dwarf planet, and the system is only the second known to include a Jupiter-mass planet.

We have been monitoring 147 late K and M dwarfs ( $0.2 M_{\odot} \leq M_* < 0.6 M_{\odot}$ ) at Keck Observatory for nearly 7 years, with a typical Doppler precision of  $3 \text{ m s}^{-1}$  (Wright 2005; Rauscher & Marcy 2006). Of these stars, 114 have eight or more observations spanning a minimum time baseline of 5.5 yr. Within this subset of M dwarfs our survey is sensitive to planets that induce  $K > 12 \text{ m s}^{-1}$  ( $4 \sigma$  level) for periods  $P < 3.5$  yr. These limits on  $P$  and  $K$  correspond to minimum planet masses of  $M_p \sin i > 0.4 M_{\text{Jup}}$  and orbital separations of  $a < 1.8$  AU, assuming a nominal stellar mass of  $0.5 M_{\odot}$ . Only one star in this sample, GJ 876, harbors planets that meet these criteria. Thus, the occurrence of planets having a minimum mass over  $0.4 M_{\text{Jup}}$  within 1.8 AU around M dwarfs is  $\sim 0.9\%$ , albeit with large fractional uncertainty ( $\sigma \approx 1\%$ ). Note that GJ 849b is not included in this domain of  $a$  and  $M_p \sin i$ , as it has  $a > 1.8$  AU. If we extend the maximum orbital separation from 1.8 to 2.5 AU, then GJ 849b is included. This relaxed threshold corresponds to  $K > 10 \text{ m s}^{-1}$ , implying only a  $3 \sigma$  detection threshold. Thus, for  $a < 2.5$  AU the occurrence rate of giant-

mass planets is  $2/114 = 1.8\% \pm 1.2\%$ , but it remains uncertain due to small-number statistics.

The planet occurrence rate for M dwarfs ( $M_* < 0.6 M_{\odot}$ ) can be compared to the corresponding rate for higher mass G- and K-type stars observed at Keck as part of the CCPS. In this sample, there are 232 GK stars with  $0.6 M_{\odot} \leq M_* \leq 1.1 M_{\odot}$  and eight or more observations spanning more than 4 years. Of these stars, 13 have Jupiter-mass planets within 1.8 AU, yielding an occurrence rate of  $5.6\% \pm 1.6\%$ . Thus, giant-mass planets are almost 6 times more likely to be detected orbiting within 1.8 AU of GK stars than around M dwarfs. The fraction of planets orbiting GK stars within 2.5 AU is also  $5.6\% \pm 1.6\%$ , resulting in a factor of 3 higher likelihood of finding planets orbiting solar-mass stars within this range of orbital separations compared to M dwarfs.

This simple analysis does not account for the sparse nominal sampling rate (eight observations spanning 4–6 years), which may miss signals with amplitudes near  $K = 12 \text{ m s}^{-1}$ , especially those in highly eccentric orbits. Indeed, several of our M dwarfs show RV variations consistent with Jupiter-mass companions but lack sampling sufficient enough to determine a unique orbital solution. Thus, additional monitoring is necessary before firm conclusions can be drawn about the fraction of M dwarf planet hosts compared to higher mass stars.

Also not addressed by our analysis is the effect of metallicity, which has already been established as a strong tracer of planet occurrence (Fischer & Valenti 2005). If there exists any correlation between mass and metallicity within our overall stellar sample, then the apparent relationship between stellar mass and planet occurrence would be difficult to separate from the effects of metallicity. Such a correlation between mass and metallicity could arise as a result of systematic errors in LTE abundance determinations or selection biases in our stellar sample. While no such selection bias affects our sample of M dwarfs, which is complete for distances less than 20 pc and apparent magnitudes brighter than 11.5, it is possible that a bias exists at the high-mass end of our sample. Accounting for such effects is beyond the scope of this paper and will be addressed in a future publication (J. A. Johnson et al. 2007, in preparation).

At 8.8 pc, the orbital separation of GJ 849b corresponds to a projected separation of  $0.27''$ . Thus, the proximity of GJ 849 provides a unique opportunity for high-resolution imaging using adaptive optics and future space-borne astrometric missions such as the *Space Interferometry Mission PlanetQuest*.

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