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A PLANETARY COMPANION TO A NEARBY M4 DWARF, GLIESE 876[1]

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ABSTRACT

Doppler measurements of the M4 dwarf star Gliese 876 taken at both Lick and Keck Observatories reveal periodic, Keplerian velocity variations with a period of 61 days. The orbital fit implies that the companion has a mass of $M = 2.1\ M_{\rm JUP}/\sin i$, an orbital eccentricity of $e = 0.27 \pm 0.03$, and a semimajor axis of $a = 0.21$ AU. The planet is the first found around an M dwarf and was drawn from a survey of 24 such stars at Lick Observatory. It is the closest extrasolar planet yet found, providing opportunities for follow-up detection. The presence of a giant planet on a noncircular orbit, 0.2 AU from a 0.32 $M_\odot$ star, presents a challenge to planet formation theory. This planet detection around an M dwarf suggests that giant planets are numerous in the Galaxy.

Subject headings: planetary systems — stars: individual (Gliese 876)

1. INTRODUCTION

Precise Doppler surveys of main-sequence stars have revealed eight companions that have masses under $5\ M_{\rm JUP}/\sin i$, with the orbital inclination i remaining unknown (Mayor et al. 1998; Marcy & Butler 1998; Noyes et al. 1997; Cochran et al. 1997). These "planetary" companions exhibit both circular and eccentric orbits, consistent with formation in dissipative circumstellar disks followed by gravitational perturbations (see Lin, Bodenheimer, & Richardson 1996; Artymowicz 1997; Levison, Lissauer, & Duncan 1998). The semimajor axes are all less than 2.5 AU, with most being less than 0.3 AU. This "piling up" of planets near their host stars appears to be a real effect, although enhanced by the selection effect that favors detection of small orbits. Jupiters orbiting between 0.5 and 1.5 AU would be easily detected with our current Doppler precision of 5 m s^{-1}, but none has been found. This distribution of orbits supports models in which orbital migration in a gaseous proto–planetary disk drags Jupiter-mass planets inward (Lin et al. 1996; Trilling et al. 1998).

The distribution of the masses of substellar companions reveals two populations. Our survey of 107 GK dwarfs revealed none that had $M \sin i = 10$–$80\ M_{\rm JUP}$ (Marcy & Butler 1998). Thus, "brown dwarf" companions occur with a frequency less than ~1% within 5 AU. Similarly, Mayor et al. (1997, 1998) surveyed ~500 GK dwarfs and found at most four companions between 10 and 80 $M_{\rm JUP}$. (*Hipparcos* astrometry has shown that seven previously suspected brown dwarfs from that sample are actually H-burning stars.) In contrast, at least 5% of GK stars harbor companions with masses from 0.5 to 5 $M_{\rm JUP}$. For example, in our Doppler survey of 107 main-sequence stars at Lick Observatory, we found six companions that have $M \sin i = 0.5$–$5\ M_{\rm JUP}$ (Marcy & Butler 1998; this paper). Thus, relative to this well-populated planetary decade of masses, there exists a brown dwarf "desert" at masses 10–80 $M_{\rm JUP}$ within 5 AU.

The efforts described above have focused on G- and K-type main-sequence stars having masses between 0.8 and 1.2 $M_\odot$. The question arises regarding the prevalence of planets around the M dwarfs, which constitute 70% of the stars in the Galaxy. Here we describe the detection of the first apparent planetary companion to an M dwarf, Gliese 876, located 4.7 pc from the Sun.

2. OBSERVATIONS

Gliese 876 (=HIP 113020) has V magnitude of 10.1, a spectral type of M4 V, and a parallax from *Hipparcos* of 0.213 (Perryman et al. 1997). Adopting this parallax and the bolometric correction of Delfosse et al. (1998) gives $M_{\rm Bol} = 9.52$, which implies a luminosity of $L = 0.0124\ L_\odot$. The mass of the star Gliese 876 can be derived from its K-band apparent magnitude ($K = 5.04$) and parallax, along with an empirical mass-luminosity relation (Henry & McCarthy 1993). This gives $M_* = 0.32 \pm 0.03\ M_\odot$. Gliese 876 is chromospherically inactive (Delfosse et al. 1998), which suggests that it is older than ~1 Gyr. However, its space motion is slow, which suggests that its age is less than 10 Gyr. Its metallicity is not known well, although a preliminary synthesis of the spectrum indicates that it is metal poor by a factor of 2–3 relative to the Sun (J. A. Valenti 1998, private communication).

Doppler shifts for Gliese 876 have been obtained at both Lick and Keck Observatories, using the Hamilton and HIRES echelle spectrometers, respectively (Vogt 1987; Vogt et al. 1994). The first observations were made in 1994.9 (at Lick) and in 1997.4 (at Keck), and both data sets extend to the present. The calibration of wavelength and the measurement of the spectrometer point-spread function was determined for each exposure and for each 2 Å chunk of spectrum by using iodine absorption lines superposed on the stellar spectrum (Butler et al. 1996). Figures 1 and 2 show all of the individual velocity measurements as a function of time, along with the separate Keplerian fits.

The velocities from Lick Observatory have typical uncertainties of 30 m s^{-1}, and those from Keck are 6 m s^{-1}. Poisson statistics of the photons dominate the velocity errors for this relatively faint ($V = 10.1$) star. Error bars on all points are the uncertainty in the mean of the velocities $[\sigma/(N_{\rm chunk})^{1/2}]$ from the many 2 Å wide chunks into which the spectrum was divided. Doppler measurements of Gliese 876 at Haute Provence

[1] Based on observations obtained at Lick Observatory, which is operated by the University of California, and 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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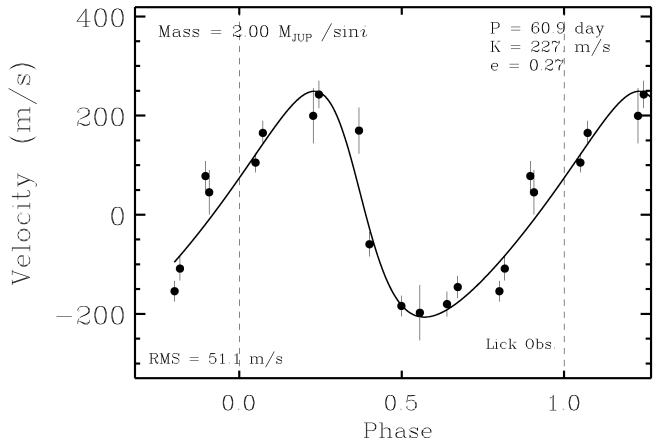

FIG. 1.—Lick radial velocities for Gliese 876 obtained from 1994 to 1998.6 vs. orbital phase. The solid line is the radial velocity curve from the best-fit orbital solution from the Lick data alone.

by Delfosse et al. (Mayor et al. 1998) also show an amplitude and periodicity in agreement with those reported here, thus constituting an immediate confirmation. It remains to be seen if their orbital parameters agree with those quoted here.

The Lick and Keck data each carry independent and arbitrary velocity zero points. The relative zero point has been determined by combining the two data sets and adjusting the velocity offset until the Keplerian fit (see § 3) yields a minimum in the χ^2 statistic. Thus, the Lick and Keck velocities were forced to have the same zero point.

3. ORBITAL SOLUTION

Independent Keplerian fits were determined from the Lick and Keck data sets, and the resulting curves and orbital parameters are shown in Figures 1 and 2. The final orbital parameters are given in Table 1, based on an orbital fit to the combined data set. The uncertainties reflect the differences in the two independent orbital fits. The two solutions agree within their uncertainties. The joint orbital period is $P = 60.85 \pm 0.15$ days, and the eccentricity is $e = 0.27 \pm 0.03$. The orbital solution implies a planetary orbital semimajor axis of 0.21 ± 0.01 AU, and a minimum mass of $M \sin i = 2.1 \pm 0.2\ M_{\rm JUP}$. This inferred $M \sin i$ is proportional to the assumed

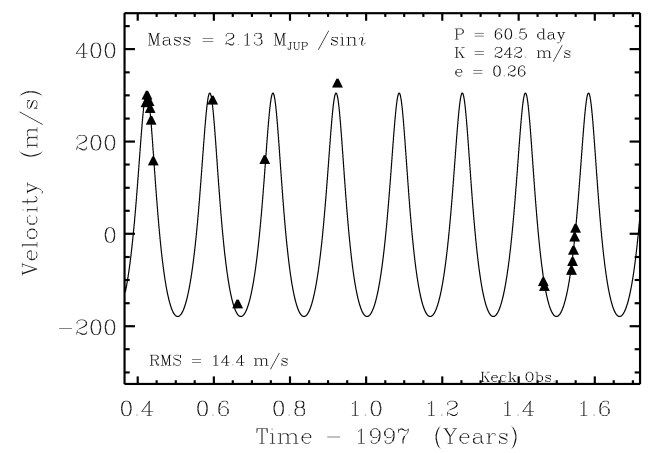

FIG. 2.—Keck radial velocities for Gliese 876. The solid line is the radial velocity curve from the orbital solution from the Keck data alone.

TABLE 1

COMBINED ORBITAL SOLUTION FOR GLIESE 876

Parameter	Value	Uncertainty
Orbital period P (days)	60.85	0.15
Velocity semiamplitude K (m s^{-1})	239	5
Eccentricity e	0.27	0.03
Longitude of periastron ω (deg)	24	6
Periastron date T_0 (Julian Date)	2450301.0	1.0
$M \sin i$ ($M_{\rm JUP}$)	2.11	0.20
Semimajor axis a (AU)	0.21	0.01

mass of the host star ($0.32 \pm 0.03\ M_\odot$), which contributes most of the uncertainty in the companion mass.

The periodic repetition of an asymmetric radial velocity variation is apparent from the raw data and from the fits in Figures 1 and 2. The orbit is clearly not circular. There is no pattern in the residuals, thus excluding the presence of any second planet with a mass greater than 1 $M_{\rm JUP}$ and a period of 4 yr or less in the Gliese 876 system. The Lick and Keck velocities can be merged to yield a final fit, as shown in Figure 3. This shows that the two sets share a common orbital phase in addition to similar best-fit orbital parameters. We note that two points from Lick sit off the Keplerian curve by 2 σ, and we suspect that the quoted errors of ~30 m s^{-1} in those cases may be underestimated due to the low signal-to-noise ratios of those spectra.

The large velocity amplitude of 220 m s^{-1} for Gliese 876 leaves orbital motion as the probable cause of the velocity variations. Spots on a rotating star can, in principle, cause artificial velocity variations. But for Gliese 876, the equatorial rotation velocity is less than 2 km s^{-1}, and the star is photometrically variable at ± 0.02 mag (Marcy & Chen 1992; Weis 1996; Delfosse et al. 1998). Therefore, spots cannot alter the apparent velocity by more than $\sim 0.02 \times 2000 = 40$ m s^{-1}. We have not checked for stellar pulsations, but the photometric stability suggests that any pulsations are not significant here. Moreover, acoustic oscillations and g-modes for a 0.3 $M_\odot$ dwarf would have timescales of minutes and hours, respectively, unlike the observed 60 day velocity period.

4. DISCUSSION

The companion to Gliese 876, with $M \sin i = 2.1 \pm 0.2$

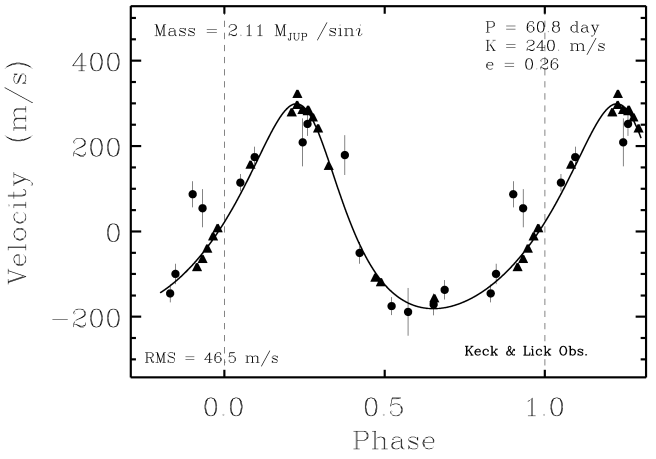

FIG. 3.—Combined Lick and Keck radial velocities for Gliese 876, plotted vs. orbital phase. Filled circles are from Lick, and the triangles come from Keck. The solid line is the radial velocity curve from the orbital solution.

M_{JUP}, has a likely mass of 2–4 M_{JUP}, assuming unbiased orbital inclinations. For an assumed companion mass of 2.1 M_{JUP}, the astrometric semimajor axis would be 0.28 mas. *Hipparcos* astrometry exhibits no wobble at a 2 σ upper limit of 4 mas (Perryman et al. 1997). Thus, the upper limit to the companion mass is 29 M_{JUP}.

At 4.7 pc, this is the closet known extrasolar planet. The semimajor axis implies an angular separation of 0".045, with a greatest separation of 0".062. It is thus a prime candidate for direct imaging with IR adaptive optics and with interferometry (i.e., Keck, Large Binocular Telescope, *Space Interferometry Mission*, Very Large Telescope Interferometer). Astrometric detection is also favored due to (1) its close proximity to the Sun, (2) the large mass of the planet, (3) the low mass of the star, and (4) the small orbital period, which permits many cycles to be monitored within a season.

Gliese 876 is apparently the first M dwarf with a known planetary companion. We have surveyed only 24 M dwarfs from Lick Observatory during the past 4 yr (with poor precision of 25 m s^{-1}), which implies that the occurrence of Jupiter-mass planets within 2 AU of M dwarfs could be a few percent, based on this one detection. The duration and paucity of Keck observations render them not yet adequate (~1 yr) to add information on the occurrence of planets around M dwarfs.

The small orbital semimajor axis of $a = 0.21$ AU and the eccentricity of $e = 0.27$ pose two profound puzzles regarding the origin of such planetary orbits. There is too little mass within a planetary feeding zone in a nominal proto–planetary disk at distances of 0.2 AU to provide 2 M_{JUP} of material to a growing planet (see Lissauer 1995). One suggestion is that giant planets form several astronomical units from the star and then migrate inward. Orbital migration can be induced by interactions between the planet and the gas in the proto–planetary disk, bringing the planet inward (Lin et al. 1996; Trilling et al. 1998).

However, it is not clear what would cause the planet around Gliese 876 to cease its migration at 0.2 AU. Neither tidal interactions with the star nor a magnetospherically cleared hole at the disk center would extend to 0.2 AU, and thus they cannot halt the migration. A similar, as yet unidentified parking mechanism appears needed for the planets around 55 Cancri and ρ Cor Bor (Noyes et al. 1997; Butler et al. 1997).

The noncircular orbits for both ρ Cor Bor ($e = 0.16 \pm 0.06$) and this planet around Gliese 876 ($e = 0.27 \pm 0.03$) imply that significant orbital eccentricities are common for Jupiter-mass companions orbiting between 0.1 and 0.3 AU from their star. Some physical mechanism must be identified that generally produces sizable eccentricities, in contrast to the inexplicably low eccentricities of the giant planets in our solar system. Infrared speckle reveals no companions to Gliese 876 from 1 AU outward (Henry & McCarthy 1990), and the lack of large variations in the velocities rule out stellar companions within 1 AU. Thus, the eccentricity of the planetary companion around Gliese 876 could not have been pumped by a stellar companion.

Apparently, migration, if necessary, did not enforce circularity in the final orbits of Gliese 876 or ρ Cor Bor. One possible explanation is that gravitational scattering of planetary cores (of Earth-mass and larger) can dominate the orbital evolution (Rasio & Ford 1996; Weidenschilling & Marzari 1997; Lin & Ida 1997). Orbit crossings and global instabilities among planets in the disk can lead to dramatic orbit changes and large eccentricities (Levison et al. 1998).

Long-lived gas in a proto–planetary disk may lead to circular orbits in such planetary systems. Other systems that lose their gas may suffer dynamical instabilities, leading to eccentric orbits at a variety of semimajor axes. However, the latter scenario, if common, does not explain the apparent paucity of Jupiters from 0.5 to 1.5 AU, and it remains to be seen if Jupiters are common farther out.

The equilibrium temperature at optical depth unity in the atmosphere of the planet around Gliese 876 is estimated to be −73°C to −88°C, too cold for water in liquid form (D. Saumon 1998, private communication). Temperatures would be higher at deeper layers in the atmosphere. Any bodies orbiting interior to 0.2 AU would have surface temperatures above −70°C. It would be interesting to determine if planets could reside in stable orbits within 0.2 AU, perhaps in mean-motion resonances with the giant planet discovered here.

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