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A PAIR OF RESONANT PLANETS ORBITING GJ 876[1]

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ABSTRACT

Precise Doppler measurements during 6 yr from the Lick and Keck observatories reveal two planets orbiting GJ 876 (M4V). The orbital fit yields companion masses of $M \sin i = 0.56$ and 1.89 M_J, orbital periods of $P = 30.1$ and 61.0 days, semimajor axes of $a = 0.13$ and 0.21 AU, and eccentricities of $e = 0.28$ and 0.10, respectively. The orbital periods are nearly in the ratio of 2:1, unprecedented among major planets but common among moons and asteroids. Moreover, the axes of the elliptical orbits appear to be nearly aligned. The inner companion was not recognized previously owing to the 2:1 ratio of periods, which allowed its signature to masquerade as added orbital eccentricity of the outer planet. Dynamical simulations show that the system is stable within a subset of the observed orbital parameters. The stability may be provided by a mean-motion resonance and the apparent alignment of the major axes. These planets pose unsolved questions about their formation and dynamical evolution, which brought them within 0.08 AU of each other and locked them in resonance.

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

1. INTRODUCTION

To date, ∼50 planets orbiting nearby stars have been discovered (see Marcy, Cochran, & Mayor 2000; Halbwachs et al. 2000; Butler et al. 2000). Two stars harbor more than one planetary companion, namely υ And (Butler et al. 1999) and possibly HD 168443 (Marcy et al. 2001a; Udry et al. 2001). Upsilon And exhibits nearly equal values of the longitudes of periastron for its outer two planets. This alignment enhances the stability of the system (Rivera & Lissauer 2000; Rivera & Lissauer 2000).

Doppler observations of the M4 main-sequence star GJ 876 initially revealed a single planet with a mass of $M = 2.1$ $M_J/\sin i$, an orbital eccentricity of $e = 0.27 \pm 0.03$, and a semimajor axis of $a = 0.21$ AU (Marcy et al. 1998). Similar orbital parameters were found independently by Delfosse et al. (1998b). The star was, and remains, the only M dwarf known to host a planet, and it is also the closest host star of a secure extrasolar planet, with a distance of 4.69 pc (Perryman et al. 1997).

The velocity residuals were unusually large in our original orbital fit, with rms = 14.4 m s^{-1} compared with known velocity errors of 3–5 m s^{-1}. The spectral type of M4 led us to wonder if unusual surface activity could be the cause of velocity "jitter." Similar M dwarfs at $V = 10$ do not show such jitter in our Keck survey, and they normally exhibit rms of 3–5 m s^{-1} (Vogt et al. 2000). Moreover, in Marcy et al. (1998), we noted two unusually discrepant velocities for GJ 876, "We note that two points from Lick sit off the Keplerian curve by 2σ...," which we attributed, with wishful thinking, to unmodeled errors. Thus alerted, we have followed GJ 876 with additional velocity measurements and found many that are not explained by a single Keplerian orbit.

2. STELLAR CHARACTERISTICS AND VELOCITY MEASUREMENTS

2.1. *Stellar Characteristics*

The stellar characteristics of GJ 876 (M4V) were described in Marcy et al. (1998). We continue to adopt a mass of $M = 0.32 \pm 0.05$ $M_\odot$, based on its parallax of 213 mas (Perryman et al. 1997) and K-band magnitude (Henry & McCarthy 1993). Delfosse et al. (1998a) and Reid, Hawley, & Gizis (1995) provide excellent studies of the properties of GJ 876 and of M dwarfs in general.

2.2. *Velocity Observations*

We began velocity measurements for 20 M dwarfs, including GJ 876, in 1994 with the Lick Observatory Telescope and its Hamilton echelle spectrometer (Vogt 1987). We are also surveying ∼560 FGKM dwarfs, 120 of which are M dwarfs, on the Keck I telescope and its HIRES echelle spectrometer (Vogt et al. 1994).

We search for Doppler variability using repeated, high-resolution spectra, $R \approx 80{,}000$. The Keck spectra span the wavelength range from 3900–6200 Å, and the Lick spectra span 4900–9000 Å. An iodine absorption cell provides wavelength calibration and the instrumental profile from 5000 to 6000 Å (Marcy & Butler 1992; Butler et al. 1996). Typical signal-to-noise ratios are 100 per pixel for GJ 876 from Keck and about 30 from Lick. At Keck we routinely obtain Doppler precision of 3 m s^{-1} for $V = 10$ M dwarfs, as evidenced by the majority of such stars that show no variation at that level. From Lick we obtain precision of 15–30 m s^{-1} for stars having $V = 10$. Exposure times are 8 minutes at Keck and 20 minutes at Lick.

Since the discovery of the planet in a 60 day orbit, we have continued to obtain velocity measurements, which now span 3.6 yr at Keck (1997.4–present) and 6 yr at Lick

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

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TABLE 1

VELOCITIES FOR GJ 876 FROM KECK

JD (−2450000)	Relative Velocity (m s^{-1})	Uncertainty (m s^{-1})
602.0931	343.72	4.6
603.1084	365.47	4.4
604.1181	351.54	4.6
605.1101	350.22	5.1
606.1113	336.81	4.7
607.0845	303.53	4.3
609.1164	222.16	5.1
666.0503	355.24	5.2
690.0071	−94.35	5.1
715.9647	216.61	4.5
785.7044	384.32	8.4
983.0458	−36.66	4.6
984.0939	−54.64	4.8
1010.0446	−21.76	4.5
1011.1007	1.94	3.5
1011.9851	27.83	2.8
1013.0891	54.83	4.7
1013.9650	75.05	3.2
1043.0205	−13.06	4.9
1044.0002	−43.19	4.0
1050.9278	−84.93	4.5
1052.0030	−73.89	5.3
1068.8766	−60.87	4.7
1069.9841	−31.45	4.2
1070.9659	−37.16	3.9
1071.8778	−8.05	4.4
1072.9385	8.72	4.6
1170.7038	−53.11	6.7
1171.6917	−63.96	6.1
1172.7025	−45.46	5.5
1173.7015	−37.03	5.8
1312.1273	−74.75	4.4
1313.1172	−76.22	4.9
1343.0407	100.56	4.6
1368.0011	−123.03	4.4
1369.0018	−125.42	4.6
1370.0595	−106.98	4.5
1372.0586	−101.57	7.9
1409.9867	−21.27	4.1
1410.9486	−20.88	4.0
1411.9217	−35.03	4.5
1438.8020	0.00	4.2
1543.7017	−82.71	7.1
1550.7015	−120.48	6.5
1704.1027	179.58	4.6
1706.1077	133.95	5.3
1755.9803	322.88	7.5
1757.0379	304.24	6.0
1792.8221	−147.25	4.6
1883.7251	244.52	5.8
1897.6820	111.77	6.4
1898.7065	108.71	5.6
1899.7243	100.14	6.3
1900.7036	80.24	5.5

TABLE 2

VELOCITIES FOR GJ 876 FROM LICK

JD (−2450000)	Relative Velocity (m s^{-1})	Uncertainty (m s^{-1})
−320.3684	58.07	19.7
−86.0287	39.56	29.1
3.6980	136.89	46.4
263.9395	−220.65	24.4
300.8446	194.30	26.5
326.8829	−189.96	22.3
614.9787	−97.98	25.6
655.9063	128.76	24.8
681.8951	−223.27	20.5
1004.9431	−185.06	21.2
1005.9532	−150.76	23.8
1026.8841	254.04	24.9
1027.9327	263.53	19.8
1416.8707	−83.78	24.4
1446.7224	204.41	24.8
1894.5961	−17.89	19.6

(1994.9–present). Actually, we have eight velocity measurements for GJ 876 during the period 1987–1994. But these spectra were obtained with a CCD having only 800^2 pixels, and thus they contain only $\sim\frac{1}{3}$ the spectral information of the more recent Lick observations. We will refer only parenthetically in § 3 to these older Lick measurements that have errors of $\sim$36 m s^{-1} and add little to the analysis here. Table 1 lists all 50 Doppler measurements of GJ 876 obtained from Keck. Table 2 lists the 16 Doppler measurements from Lick since 1994.9.

The internal uncertainties in the velocities are judged from the velocity agreement among the approximately 400 2 Å chunks of the echelle spectrum, each chunk yielding an independent Doppler shift. The internal velocity uncertainty of a given measurement is the uncertainty in the mean of the $\sim$400 velocities from one echelle spectrum. For Keck and Lick, the typical internal errors are 4.6 and 27 m s^{-1}, respectively. The difference in precision reflects the ratio in telescope aperture area (10) and spectrometer throughput (2) between the Keck and Lick systems.

3. ORBITAL SOLUTIONS

We first attempt to fit the complete set of velocities from Keck (Table 1) with a single orbiting companion, as we did in Marcy et al. (1998). This fit is shown in Figure 1, and it implies a companion with $P = 60$ days and $K = 240$ m s^{-1}, similar to our previous values. However, such a fit is inadequate, as the velocity residuals exhibit rms = 46 m s^{-1}. In comparison, measurement uncertainties are only 4.5 m s^{-1} (median of internal errors). In particular, this single-planet

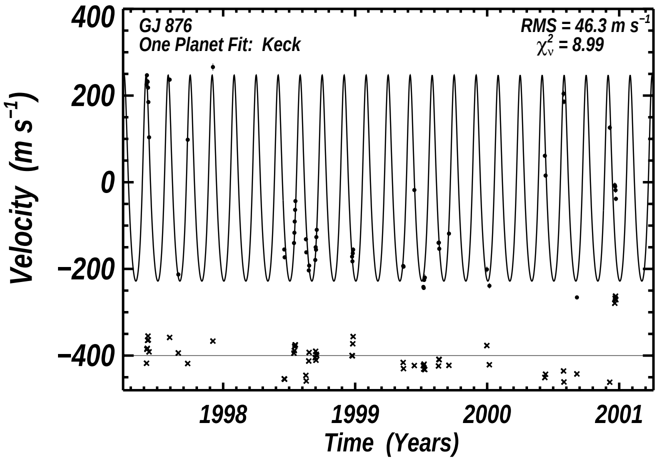

FIG. 1.—Velocities for GJ 876 from Keck, fitted with a single planet. The value of χ^2_ν is 9, clearly an unacceptable fit.

Keplerian model gives a reduced χ^2 statistic of $\chi_\nu^2 = 9$, clearly casting doubt on the model. Most other M dwarfs of the same brightness exhibit a velocity rms of 3–5 m s^{-1} from our Keck observations (see Fig. 3 in Vogt et al. 2000). Thus we expect velocity residuals from GJ 876 to exhibit rms scatter of $\sim$4 m s^{-1}. Clearly, the rms of the velocity residuals of 46 m s^{-1} for a one-planet model of GJ 876 is inconsistent with such expected uncertainties.

We further attempted to fit the velocities with a Keplerian and a simple linear trend. Such fits gave a χ_ν^2 of 7, not significantly improved over the simple single-Keplerian model. The velocity residuals reveal power at periods near 10 days. But attempts to fit the data with two Keplerians having periods near 60 and 10 days produce fits that are similarly poor.

Here we attempt to fit the observed Keck velocities with two orbiting planetary companions. The model contains two independent Keplerians as separate two-body problems, without accounting for mutual perturbations between the planets. This two-planet Keplerian fit to the Keck velocities yields the following orbital parameters: $P = 30.1$ and 61.0 days, $K = 81$ and 211 m s^{-1}, $e = 0.29$ and 0.11, and $\omega = 328\overset{\circ}{.}9$ and $327\overset{\circ}{.}7$, respectively. Such a double-Keplerian fit is shown in Figure 2.

This two-planet model yields velocity residuals with an rms = 7.9 m s^{-1}, a significant drop from 46 m s^{-1}. The value of χ_ν^2 dropped to 1.87 (from 9), suggesting that two companions represent a significantly superior model, even accounting for the introduction of an additional five free parameters. The rms of 7.9 m s^{-1} remains higher than the known measurement errors of 3–5 m s^{-1}. We cannot determine if this difference is significant or is perhaps caused by intrinsic jitter in the star's atmosphere. This difference may be caused by the gravitational interactions between the planets (see Laughlin & Chambers 2001; Rivera & Lissauer 2001), which are not accounted for in our Keplerian fitting model. In any case, further additions to the two-planet model are not warranted with the present data. We will continue to observe GJ 876 to determine if further additions are useful.

The necessity of the second planet is demonstrated visually in Figure 3, which is simply a magnified view of Figure 2 showing the Keck velocities and the associated double-Keplerian fit. Figure 3 shows a detailed view of the Keck velocities from 1998.4–1999.1. In this period of time, the velocities exhibit distinct inflections on timescales of a few days caused by the inner planet. The velocities exhibit a rise caused by the inner planet near both 1998.65 and 1998.98. Many other inflections (especially near 2000.9) in the observed velocities of Figure 2 are also caused by the inner planet, demonstrating its presence.

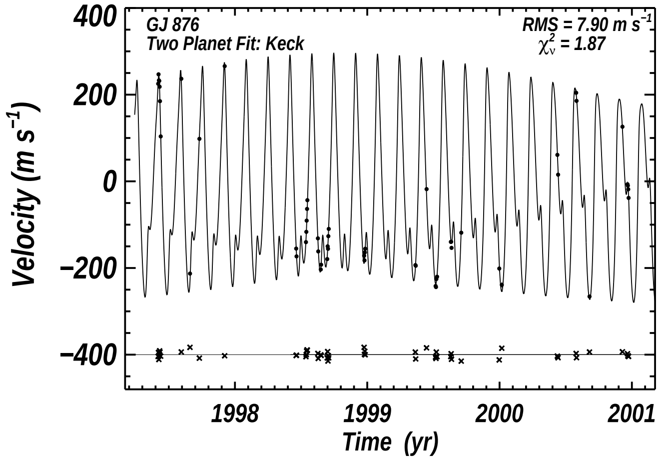

FIG. 2.—Velocities for GJ 876 from Keck Observatory, fitted with a model containing two noninteracting Keplerian planets. The value of $\chi_\nu^2 = 1.9$ is clearly superior to that obtained with only one planet (Fig. 1).

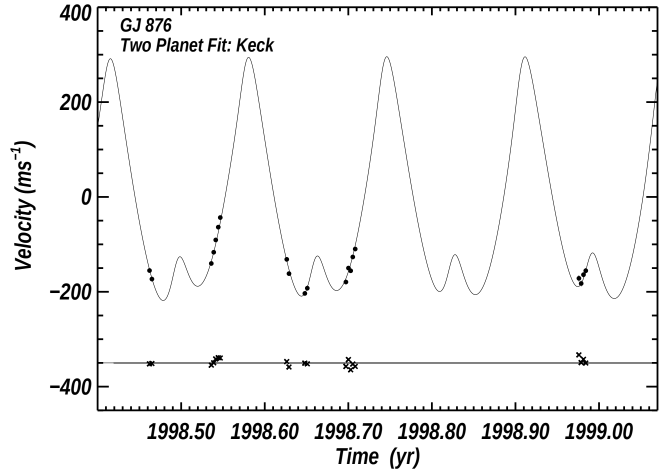

FIG. 3.—Same as Fig. 2, but focussed on the interval of time between 1998.4 and 1999.1. The inflections in the velocities reveal, to the eye, the presence of the inner companion.

We checked the argument for a second planet by using the independent velocity measurements made at Lick Observatory from 1994.9–2000.9. The 16 Lick velocities are listed in Table 2, and a two-planet fit is shown in Figure 4. The two-planet fit to the Lick data yields velocity residuals with an rms = 12.7 m s^{-1}, a significant drop from 56 m s^{-1} obtained without the second planet. The value of χ_ν^2 dropped to 0.82 for the Lick velocities, in comparison with $\chi_\nu^2 = 2.9$ from the one-planet model. Our best-fit to the Lick data alone yields periods of 30.14 and 60.93 days, both within 0.1 day of the periods found from the Keck data alone. Thus, the introduction of a second planet with period

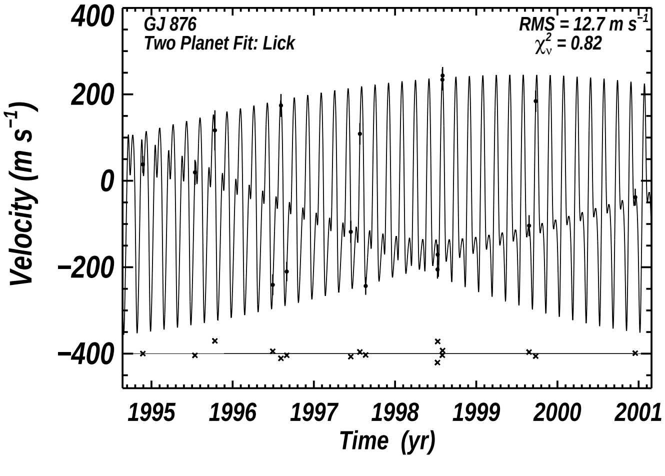

FIG. 4.—Sixteen velocities for GJ 876 from Lick Observatory, independently fitted with a model containing two Keplerian planets (11 free parameters). The best-fit periods are 61.0 and 30.2 days, nearly identical to those found from the Keck data (Fig. 2). The value of $\chi_\nu^2 = 0.8$ suggests that a model with two planets adequately fits the velocities.

of 30.1 days and amplitude of 85 m s^{-1} significantly improves the χ_ν^2 statistic of the fit to the velocities from Lick Observatory, just as occurred with the Keck velocities.

The Lick velocities do not stand alone to provide overwhelming evidence for the second companion. With only 16 measurements and errors of 27 m s^{-1} from Lick, the two-planet model would not be incontrovertible. However, the Lick velocities are not only consistent with the second companion that is strongly suggested by the Keck velocities, but they indeed exhibit significantly reduced χ_ν^2 with the introduction of that additional companion. The significant reduction in the χ_ν^2 statistic for the two-planet fit relative to the one-planet fit to the Lick velocities independently offers compelling evidence for both companions. Moreover, the Lick velocities independently yield the same orbital periods within 0.1 days for both planets.

We combined the velocities from the Lick and Keck telescopes, and the combined fit using two planets is shown in Figure 5. From the combined set of velocities, we determine the final best-fit orbital parameters. We allowed the relative zero-point of the velocities between the two telescope systems to be a free parameter.

The best-fit orbital parameters for the two companions are listed in Table 3, based on the combined velocities from both telescopes. The periods are 30.12 and 61.02 days, the eccentricities are 0.27 and 0.10, and the velocity amplitudes are 81 and 210 m s^{-1}. These values are driven largely by the Keck measurements because of their smaller uncertainties, $\sim$4 m s^{-1} compared with $\sim$15 m s^{-1} for Lick, the difference stemming from photon statistics. The inferred values of $M \sin i$ are 0.56 and 1.89 M_J for the inner and outer companions, respectively. The final values for ω are 333° and 330°, respectively, with an uncertainty in both of $\sim$12°. The fit is marginally acceptable, with $\chi_\nu^2 = 1.88$.

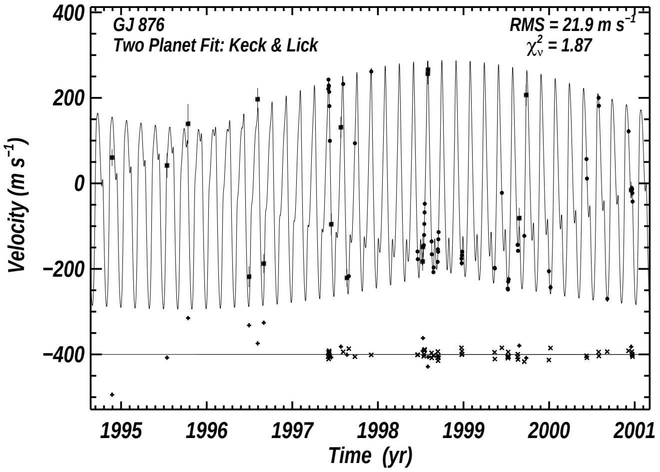

FIG. 5.—Combined velocities for GJ 876 from Lick and Keck since 1995, fitted with a model containing two Keplerian planets. The value of $\chi^2 = 1.8$ suggests that a model with two planets adequately fits the velocities. The filled circles represent Keck velocities and filled squares represent those from Lick. Residuals are shown at bottom, with different symbols for each telescope.

TABLE 3

ORBITAL PARAMETERS

Parameter	Inner	Outer
Orbital period P (day)	30.12 (0.02)	61.02 (0.03)
Velocity amp. K (m s^{-1})	81 (5)	210 (5)
Eccentricity e	0.27 (0.04)	0.10 (0.02)
ω (deg)	330 (12)	333 (12)
Periastron time (JD)	2450031.4 (1.2)	2450106.2 (1.9)
$a_1 \sin i$ (AU)	0.00022	0.00117
$M \sin i$ (M_J)	0.56 (0.09)	1.89 (0.3)
a (AU)	0.130	0.208

We considered the possibility that the 30 day periodicity in the velocities was actually due to a nonuniform distribution of surface magnetic fields on the rotating star rather than caused by reflex motion of the star itself. If so, we expect to find a chromospheric periodicity with a period of 30 days.

We measured the chromospheric emission reversal at the Ca II K line from each of our Keck spectra. The periodogram of the emission reveals a peak at a period of 92 days, with a false alarm probability of 3%. No peaks are found at periods near the nominal orbital periods of 30 or 61 days. We tested the possibility that the chromospheric periodicity at 92 days might be the cause of the velocity variations, perhaps due to some alias effect. We attempted to fit the velocities with the sum of two Keplerian curves, one having a period of 61 days (caused by the known planet) and the other with a period of around 92 days, within a few days. No satisfactory fit to the velocities was found, and indeed the best fit yielded a reduced χ^2 statistic no better than 6.0, which is far poorer than the value of 1.87 achieved when the second planet was invoked with a period of about 30 days. There is no evidence of a periodicity in the velocities near this "chromospheric period" of 92 days, as shown by a periodogram. Therefore, we find no evidence that the velocity periodicities are related to chromospheric activity on the star. Nonetheless, it is intriguing that the chromospheric periodicity with period 92 days is nearly a multiple of the orbital periods of 30 and 61 days. Knowledge of the rotation period of GL 876 would be helpful in this regard.

We remain interested in the large deviations from the fit (up to 90 m s^{-1}) of the points (from Lick) during 1994-1996 seen in Figure 5. These deviations are significantly larger than the uncertainties ($\sim$30 m s^{-1}) in the velocities. Similarly, the six old velocities obtained at Lick Observatory from 1987–1994, which carry formal errors of 36 m s^{-1}, show departures from the current orbital predictions of $\sim$100 m s^{-1}. These orbital predictions do not include mutual perturbations between the planets. The velocities obtained prior to 1995 may simply be poorer than we think, or they may indicate mutual gravitational perturbations of the planets. We find that the mutual gravitational perturbations of the planets are large and have not been accounted for in our orbital fitting. Using dynamical models which account for mutual planetary parameters (Laughlin & Chambers 2001; Rivera & Lissauer 2001) may well produce significantly better fits.

4. COMPANION MASSES AND STABILITY: ASTROMETRY AND DYNAMICS

Both companions could have masses arbitrarily higher than their values of $M \sin i$. For randomly oriented orbits, the probability that the inclination, i, is smaller (more face-on) than i' is $P(i < i') = 1 - \cos i$. A random sample of orbital planes would exhibit $\sin i < 0.33$ with probability of only 0.057. The difference in apastron distances of the inner and outer planets is less than 0.06 AU. Thus, if the two companions have masses much greater than several M_J, one wonders if the system would be stable against dynamical disruption. Both astrometry and dynamical simulations may place limits on the plausible masses and orbits of these two planets.

4.1. *Astrometry*

The outer planet probably causes the largest astrometric wobble, both because of its larger orbit and its larger $M \sin i$. The stellar motion induced by the outer planet is given by $a_1 \sin i = 0.0012$ AU. At the 4.7 pc distance of GJ 876, this implies an angular wobble, α, constrained by $\alpha \sin i = 0.25$ mas, with a period of 61 days.

Hipparcos astrometry reveals no wobble at a 1 σ upper limit of 2 mas (Perryman et al. 1997), implying an upper limit to α of ~ 2 mas. This sets a lower limit on the orbital inclination, $\sin i > 0.12$. Thus, the upper limit for the mass of the outer companion ($M \sin i = 1.89\ M_J$) is $M < 16\ M_J$. This mass is slightly higher than our adopted upper limit for planets of 13 M_J. However, the outer companion of GJ 876 likely has a mass below 13 M_J, rendering it likely a " planet " by conventional definitions (see Marcy et al. 2001a; Basri 2001; de Pater & Lissauer 2001). The inner companion would not be detectable astrometrically with *Hipparcos* even if its orbit were within a few degrees of face-on.

4.2. *Resonances and Dynamical Stability*

The orbital parameters for the two planets reveal two interesting features. The orbital periods of 61.0 days and 30.1 days are nearly in the ratio of 2:1. The possibility exists for mean-motion resonance between the two planets. However, the periods are not exactly in the ratio 2:1. The uncertainty of the periods, ~ 0.03 days, implies that their ratio is significantly different from 2:1. Indeed, both the Keck and Lick velocities independently yield periods of 30.1 and 61.0 days. Such differences from perfect resonance are physically plausible (they can be caused by precession of the longitudes of the planets' periastra or lines of nodes) and are common in the solar system (e.g., Malhotra 1998; Malhotra, Duncan, & Levison 2000).

The values of the longitudes of periastron, ω, for the two planets are the same within measurement uncertainties (see Table 3). This suggests a possible dynamical alignment of the axes of their orbits (e.g., Chiang & Goldreich 2000). A secular resonance may play a role, along with the mean-motion resonance, in establishing the web of parameter space within which these two planets could plausibly survive against disruption for the lifetime of the star. The existence and nature of any web of stability remains to be thoroughly explored.

We have performed numerical simulations of the dynamical evolution of the GJ 876 planetary system using the procedure developed by Lissauer & Rivera (2001). As a diagnostic effort to determine whether the system could plausibly be stable, we chose planet masses to be either their minimum values, $M \sin i$, or twice their minimum values (i.e., $\sin i = \frac{1}{2}$). We assumed that the measured Keplerian element corresponded to the osculating Jacobi elements of the system at the initial epoch (see Lissauer & Rivera 2000).

We tried about two dozen different values of the initial epoch of the integration. Many of these systems self-destructed within 4 million years of integration. However, 16 systems remained stable over the entire 240–500 million year interval that they were simulated. Several of the stable systems had $\sin i = \frac{1}{2}$. The initial epoch for the integrations was a key factor in determining system stability; this indicates that mutual perturbations of the planets are substantial on orbital timescales. For these stable systems, the ratio of the orbital periods oscillated about the value 2.0. Thus it appears that some domain of orbital parameters may render the system stable for the lifetime of the M dwarf. Dynamical simulations of the two planets by Laughlin & Chambers (2001) also reveal a mean-motion resonance and suggest a secular resonance.

5. DISCUSSION

Roughly 50% of the stars for which we have detected a single planet show evidence of additional companions, as seen in coherent variations of the residuals to the Keplerian fit (Fischer et al. 2001). This detection of a second planet to GJ 876 further supports the growing abundance of second companions to stars that harbor a known planet. It appears that stars with planets have a high occurrence rate, at least 50%, of harboring more distant substellar companions, planetary or otherwise (Fischer et al. 2001; Marcy et al. 2001b).

The 2:1 resonance rendered the less massive planet much more difficult to detect. The Fourier components of Keplerian motion show that two planets with nearly commensurate orbital periods can masquerade, within uncertainties, as a single planet with a larger orbital eccentricity. Clearly, most of the eccentric orbits found to date are immune to this danger, as the residuals are consistent with measurement errors. Nonetheless, for Keplerian fits in which the residuals are larger than errors ($\chi_\nu^2 > 2$), we should be alert to such possible masquerades.

The two planets around GJ 876 reside in orbits with periods of 61.0 and 30.1 days, nearly in the ratio 2:1. The resulting semimajor axes are 0.21 and 0.13 AU and their masses are at least 0.56 and 1.89 M_J, respectively. This near 2:1 ratio of periods and their physical proximity, along with their substantial masses, implies that mutual gravitational perturbations must affect their subsequent motion. One likely outcome is a stable resonant lock.

The likely mean-motion and possible secular resonances may play roles in the stability of the system. Early simulations reveal periodicities of the instantaneous orbital periods and show suggestions of libration of the pericenters, both by our group and by Laughlin & Chambers (2001). Simulations of the system are warranted to understand its origin and dynamics. Indeed, upper limits to the masses of the planets may be established by such simulations, by imposing the constraint of dynamical stability and by detectable perturbations between the planets.

The orbital alignment of axes in GJ 876 is reminiscent of that in the υ And system of three planets in which interactions between the outer two planets seem to enhance stability owing to a similar periapse alignment. These alignments among extrasolar planets suggest a rich formational and dynamical environment in which multiple planets play a significant role in the final orbits. We suspect that the eccentric orbits of some planets that appear single were similarly shaped by interactions with planets as yet unseen. A catalog of single extrasolar planets is provided by Butler et al. (2000).[7]

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[7] Updates to orbital elements are also available at http://www.exoplanets.org.

The likely resonance lock between the two planets suggests that the planetary orbits migrated during or subsequent to the accretion epoch (Goldreich 1965). Resonance locks are more stable to migration if the bodies would have been moving closer to one another (the ratio of orbital periods approaching unity) in the absence of the resonant interaction (Peale 1976), although diverging planets on eccentric orbits can become, and temporarily remain, in resonant lock under some circumstances (Kary & Lissauer 1995). Most migration scenarios (e.g., Ward 1986, 1997; Lin & Papaloizou 1986) predict that the planets would be diverging, as the inner planet should move inward faster since it is closer to the star (and possibly also because it is less massive). However, if planetary migration is stopped by stars clearing their protoplanetary disks from the inside outward (Lissauer 2001), then the planets would be converging prior to encountering resonance, and the lock would be more stable.

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