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A SECOND PLANET ORBITING 47 URSAE MAJORIS[1]

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ABSTRACT

Precise Doppler velocity measurements during 13 yr at Lick Observatory reveal the presence of two planets orbiting the star 47 UMa. The previously detected inner planet is confirmed by the newer velocities that yield a revised orbital period $P_b = 1089.0 \pm 2.9$ days, $M \sin i = 2.54\ M_J$, and eccentricity $e_b = 0.061 \pm 0.014$. The residuals to that single-Keplerian fit exhibit a periodicity that is consistent with an additional planetary companion. A simultaneous fit for both planets implies that the outer planet has $P_c = 2594 \pm 90$ days, $a = 3.73$ AU, $0 < e_c < 0.2$, and $M \sin i = 0.76\ M_J$. Its semimajor axis is the largest yet found for an extrasolar planet, and its angular separation from the host star of 0.″26 makes it a good target for direct detection and astrometry. *Hipparcos* astrometry places limits on the masses of these planets at less than $\sim 10\ M_J$, and dynamical modeling places limits on both e_c and the orbital inclinations. The outer planet induces a velocity semiamplitude of $K = 11.1$ m s^{-1} in the star during its 7 yr orbit, similar to the signal induced on the sun by Jupiter.

Subject headings: planetary systems — stars: individual (47 Ursae Majoris)

1. INTRODUCTION

Since 1995, ~ 70 gas giant extrasolar planets have been discovered in Doppler surveys of solar-type stars (see Butler et al. 2001, Mayor et al. 2001; Naef et al. 2001). This ensemble of extrasolar planets is characterized by a mass distribution that rises toward the low-mass detection threshold, currently $\sim 0.2\ M_J$ (Marcy & Butler 2000; Jorissen, Mayor, & Udry 2001). The Doppler technique may be detecting only the most massive planets, missing those with masses below 0.2 M_J.

Unlike planets in our solar system, the Doppler-detected planets tend to reside either in close-in or eccentric orbits. These characteristics are presumed to result from dynamical migration and some mechanisms that have been proposed are tidal interactions between the protoplanet and the disk (Goldrich & Tremaine 1980; Lin, Bodenheimer, & Richardson 1996; Bryden et al. 1999), gravitational scattering between growing planetesimals (Rasio & Ford 1996; Weidenschilling & Marzari 1996; Levison, Lissauer, & Duncan 1998) and resonant gravitational interactions between planets and planetesimals in the disk (Murray et al. 1999; Murray, Hansen, & Holman 2001). Migrating gas giant planets have evidently suffered a more violent history of dynamical evolution than the planets in our solar system.

The maximum semimajor axis of detected extrasolar planets is currently ~ 3 AU and is set by the time baseline of Doppler surveys. As the time baselines of these surveys grow, the eccentricities of planets at larger separations will be revealed, allowing direct comparison with the giant planets in our solar system. Planetary systems with gas giant planets in circular orbits may flag analogs of our solar system.

Models of planet formation predict that multiple planets should form within the protoplanetary disk around a young star (see Lissauer 1995). This prediction constitutes a test of the true planet status of the Jupiter-mass companions found to date, and it established a testable link to our solar system architecture. The first extrasolar multiple planet system was discovered around Upsilon Andromedae (Butler et al. 1999), and since then, double planet systems have been detected around HD 83443 (Mayor et al. 2001), HD 168443 (Marcy et al. 2001a; Udry, Mayor, & Queloz 2001), and GJ876 (Marcy et al. 2001b). Residual velocity trends in known planet-bearing stars suggest that additional planetary companions may ultimately be found in more than half of the stars with one detected planet (Fischer et al. 2001). Multiple planet systems that undergo short-term gravitational perturbations offer an opportunity to constrain the companion masses (Laughlin & Chambers 2001; Rivera & Lissauer 2001; Lissauer & Rivera 2001; Chiang, Tabachnik, & Tremaine 2001).

2. STELLAR CHARACTERISTICS

47 UMa (=HR 4277, HD 95128, HIP 53721) is a G0V star with $V = 5.03$, $B-V = 0.624$, and *Hipparcos* (ESA 1997) parallax of 71.04 mas. We have carried out an LTE synthesis of its spectrum and find $T_{\rm eff} = 5780$ K, $v \sin i = 1.85$ km s^{-1}, and [Fe/H] = +0.01, consistent with published values (Gonzalez 1998). We measure Ca II H and K core emission, $S_{\rm HK} = 0.142$, on the Mount Wilson Scale (Noyes et al. 1984), which implies a ratio of the H and K flux to the bolometric flux of $\log R'_{\rm HK} = -5.12$. These values of chromospheric S and $\log R'_{\rm HK}$ agree with those of Henry et al. (1997), Baliunas et al. (1998), and Henry et al. (2000).

These chromospheric indices correlate well with stellar rotation (Noyes et al. 1984) and age (Baliunas et al. 1995), yielding a rotation period, $P = 24$ days and an age of ~ 7 Gyr. The star shows no significant variability in either its broadband optical brightness or Ca II H and K emission (Henry et al. 1997, 2000). We are not aware of any detection of a magnetic (spot) cycle for this old star, and 3 yr of photometry have yielded no variation above 1 mmag (Henry et al. 2000).

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

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3. OBSERVATIONS

The Lick survey for extrasolar planets began in 1987 with a sample of about 100 stars. Since 1998, the sample has been expanded, and there are now a total of 360 stars on the Lick survey. This survey employs the Hamilton spectrograph (Vogt 1987) at a resolution $R \approx 50{,}000$ to obtain high-precision time series Doppler measurements. In 1995, an upgrade to the Hamilton optics resulted in an improvement in the velocity precision from 10 m s^{-1} (for *prefix* velocities) to about 3 m s^{-1} (for *postfix* velocities) for bright, chromospherically quiet stars (Butler et al. 1996).

The Hamilton spectral format spans a wavelength range of 4900–9000 Å. Our Doppler technique makes use of an iodine cell to impose a grid of sharp reference lines between 5000–6000 Å on the stellar spectrum. In the Doppler analysis, a high signal-to-noise template stellar spectrum (without iodine) is multiplied by an iodine spectrum obtained with a Fourier transform spectrometer. The resulting model is convolved with a floating instrumental broadening profile and wavelength scale to derive relative radial velocities in the spectra of the star with iodine.

4. ORBITAL SOLUTION

Butler & Marcy (1996) detected a planet with $M \sin i = 2.39\ M_J$ and orbital period, $P = 1090$ days in a nearly circular orbit, $e = 0.03$, around 47 UMa. New velocity measurements obtained through 1997 show that the "best-fit" orbital eccentricity (for the single-Keplerian solution) was increasing, indicating that the original model was not predictive of future velocities. By the year 2000, the best-fit eccentricity had increased to $e = 0.15$. Fischer et al. (2001) have noted the tenancy for single-planet solutions to absorb additional stellar wobbles as increased eccentricity and lower χ_ν^2 for the Keplerian fit.

Sixty-eight new observations of 47 UMa have been obtained since the first planet was announced, giving a total of 91 spectra to date. This star is observed at Lick with both the Shane 3 m telescope and the 0.6 m Coude Auxillary Telescope (CAT). Exposure times of 5 minutes on the 3 m and 40 minutes on the CAT yield a typical signal-to-noise ratio of 160 pixel^{-1} with an average (postfix) velocity precision of 4.65 m s^{-1}. The 91 observation dates, velocities, and errors are listed in Table 1.

A single-Keplerian fit to all velocities yields $\chi_\nu^2 = 1.75$ with a residual RMS of 9.81 m s^{-1}. However, the residual velocities (Fig. 1) are not random; they exhibit a coherent trend that is well fitted with a Keplerian. Although the additional low-amplitude signal is lost in the rms scatter of the 10 m s^{-1} precision prefix velocities, the older data are important in constraining the orbital period of the inner planet. A Lomb-Scargle floating mean periodogram of the residual velocities (Fig. 2) reveals a strong broad peak at $P = 2150$ days with a false alarm probability less than 0.001%.

The double-Keplerian solution (Fig. 3) was obtained iteratively. An initial fit was made to the larger amplitude inner planet. This provided theoretical velocities that were iteratively determined as the residual velocities were fitted with a second Keplerian. The orbital elements derived from this iterative fitting process were used as a starting point for a Marquardt least-squares minimization algorithm in which all 11 Keplerian orbital elements were fitted simultaneously. Both fitting methods independently provided orbital ele-

TABLE 1

Radial Velocities for 47 UMa

JD-2440000	Radial Velocity (m s^{-1})	Uncertainties (m s^{-1})
6959.737	−60.48	14.00
7194.912	−53.60	7.49
7223.798	−38.36	6.14
7964.893	0.60	8.19
8017.730	−28.29	10.57
8374.771	−40.25	9.37
8647.897	42.37	11.41
8648.910	32.64	11.02
8670.878	55.45	11.45
8745.691	51.78	8.76
8992.061	4.49	11.21
9067.771	−14.63	7.00
9096.734	−26.06	6.79
9122.691	−47.38	7.91
9172.686	−38.22	10.55
9349.912	−52.21	9.52
9374.964	−48.69	8.67
9411.839	−36.01	12.81
9481.720	−52.46	13.40
9767.918	38.58	5.48
9768.908	36.68	5.02
9802.789	37.93	3.85
10058.079......	15.82	3.45
10068.980......	15.46	4.63
10072.012......	21.20	4.09
10088.994......	1.30	4.25
10089.947......	6.12	3.70
10091.900......	0.00	4.16
10120.918......	4.07	4.16
10124.905......	0.29	3.74
10125.823......	−1.87	3.79
10127.898......	−0.68	4.10
10144.877......	−4.13	5.26
10150.797......	−8.14	4.18
10172.829......	−10.79	4.43
10173.762......	−9.33	5.43
10181.742......	−23.87	3.28
10187.740......	−16.70	4.67
10199.730......	−16.29	3.98
10203.733......	−21.84	4.92
10214.731......	−24.51	3.67
10422.018......	−56.63	4.23
10438.001......	−39.61	3.91
10442.027......	−44.62	4.05
10502.853......	−32.05	4.69
10504.859......	−39.08	4.65
10536.845......	−22.46	5.18
10537.842......	−22.83	4.16
10563.673......	−17.47	4.03
10579.697......	−11.01	3.84
10610.719......	−8.67	3.52
10793.957......	37.00	3.78
10795.039......	41.85	4.80
10978.684......	36.42	5.01
11131.066......	13.56	6.61
11175.027......	−3.74	8.17
11242.842......	−21.85	5.43
11303.712......	−48.75	4.63
11508.070......	−51.65	8.37
11536.064......	−72.44	4.73
11540.999......	−57.58	5.97
11607.916......	−43.94	4.94
11626.771......	−39.14	7.03
11627.754......	−50.88	6.21

TABLE 1—*Continued*

JD-2440000	Radial Velocity (m s^{-1})	Uncertainties (m s^{-1})
11628.727......	−51.52	5.87
11629.832......	−51.86	4.60
11700.693......	−24.58	5.20
11861.049......	14.64	5.33
11874.068......	14.15	5.75
11881.045......	18.02	4.15
11895.068......	16.96	4.60
11906.014......	11.73	4.07
11907.011......	22.83	4.38
11909.042......	23.42	3.78
11910.955......	18.34	4.33
11914.067......	15.45	5.37
11915.048......	24.05	3.82
11916.033......	23.16	3.67
11939.969......	27.53	5.08
11946.960......	21.44	4.18
11969.902......	30.99	4.58
11971.894......	38.36	5.01
11998.779......	33.82	3.93
11999.820......	27.52	3.98
12000.858......	23.40	4.07
12028.740......	37.08	4.95
12033.746......	26.28	5.24
12040.759......	31.12	3.54
12041.719......	34.04	3.45
12042.695......	31.38	3.98
12073.723......	21.81	4.73

ments that agreed within the Monte Carlo derived errors (Table 2). The double-Keplerian model yields a solution for the inner planet of $P_b = 1089.0 \pm 2.9$ days and $K_b = 49.3 \pm 1.2$ m s^{-1}. The eccentricity for the inner planet converged robustly to $e_b = 0.061 \pm 0.014$ in agreement with the original published value of 0.03. The solution for the outer planet is $P_c = 2594 \pm 90$ days and $K_c = 11.1 \pm 1.1$ m s^{-1}.

The eccentricity for the low-amplitude outer planet is poorly constrained with the existing observations; the same low χ_ν^2 is obtained for a range of e_c between 0 and 0.2.

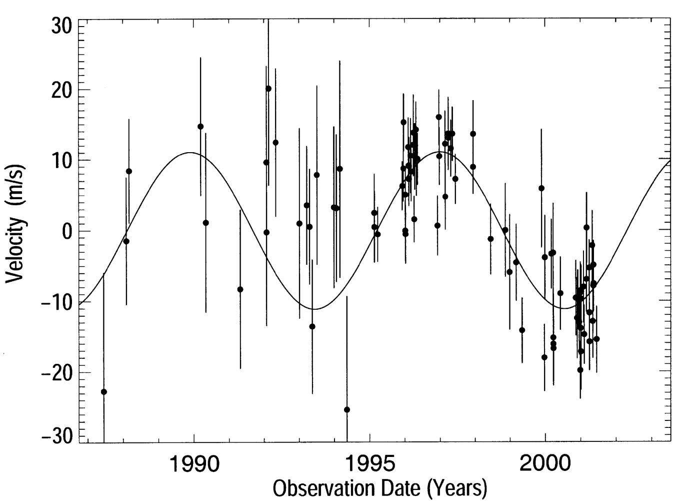

FIG. 1.—Residual radial velocities after subtracting off the 1089.5 day theoretical velocities for the planetary companion to 47 UMa. These residuals are well-fitted with a Keplerian with $P = 2594 \pm 90$ days and $K = 11.1 \pm 1.1$ m s^{-1}. The poorly constrained eccentricity was fixed to 0.005. The stellar mass of 1.03 $M_\odot$ implies a second companion with $M \sin i = 0.76\ M_J$ at an orbital radius of 3.73 AU.

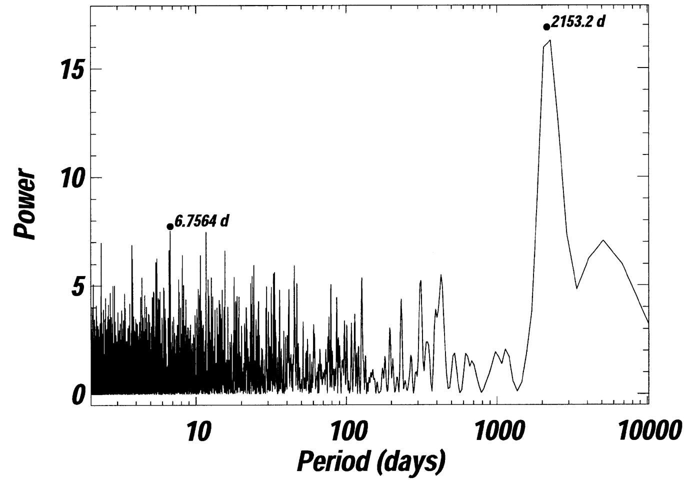

FIG. 2.—Periodogram of the residual velocities for 47 UMa shows a strong, broad peak at $P = 2153$ days, indicating the presence of a second companion.

Several years of higher precision velocities will be needed to derive a more precise eccentricity solution for the outer planet. The double-Keplerian fit has $\chi_\nu^2 = 1.08$ and an rms of 7.53 m s^{-1}, consistent with the median of the velocity measurement errors (from 1987 to 2001) for this star. Assuming a mass of 1.03 $M_\odot$ (consistent with the spectral type and metallicity), we derive $M_b \sin i = 2.54\ M_J$ with a semimajor axis of 2.09 AU and $M_c \sin i = 0.76\ M_J$ with a semimajor axis of 3.73 AU.

A good test of an orbital solution is its ability to predict future velocities. To compare the predictive power of the single- and double-Keplerian models, we considered only the data obtained before 1999 May. By that time, the single-Keplerian fit was already beginning to fail, as evidenced by the coherent residuals. We fit the data before 1999 May with both a single- and a double-Keplerian model. The single-Keplerian fit yields $\chi_\nu^2 = 1.33$ and rms = 9.7 m s^{-1} and the double-Keplerian yields $\chi_\nu^2 = 1.05$ with an rms fit of 8.1 m s^{-1}. Both of these appear to be reasonable fits to the velocities obtained from 1987 to 1999 May velocities. We then ran these theoretical fits forward in time without fitting

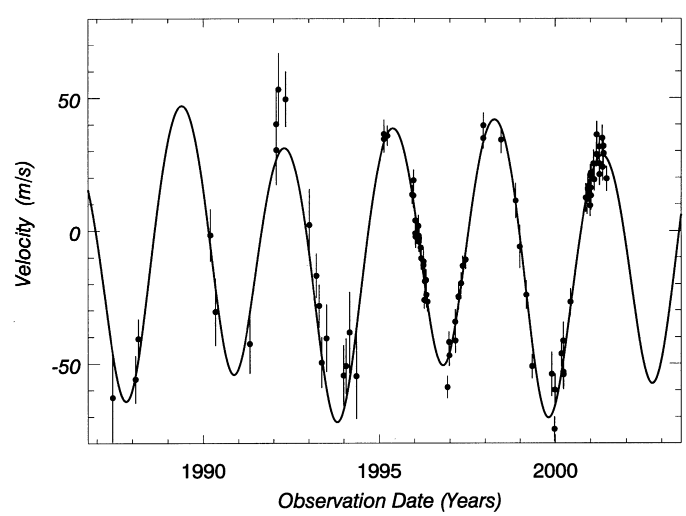

FIG. 3.—Radial velocities for HR 4277 with a double-Keplerian fit to the data. $P_b = 1089.0$ days, $M_b \sin i = 2.54\ M_J$, $e_b = 0.061$. $P_c = 2594$ days, $M_c \sin i = 0.76\ M_J$, and $e_c = 0.005$ (fixed).

TABLE 2

ORBITAL PARAMETERS

Parameter	47 UMa b	47 UMa c
P (day)	1089.0 (2.9)	2594 (90)
T_p (JD)	2450356.0 (33.6)	2451363.5 (495.3)
e	0.061 (0.014)	0.005 (0.115)
ω (deg)	171.8 (15.2)	127.0 (55.8)
K_1 (m s^{-1})	49.3 (1.2)	11.1 (1.1)
a (AU)	2.09	3.73
$a_1 \sin i$ (AU)	4.94×10^{-3}	2.64×10^{-3}
$f_1(m)$ ($M_\odot$)	1.35×10^{-8}	3.67×10^{-10}
$M_2 \sin i$ (M_J)	2.54	0.76
[1]Nobs	90	
rms (m s^{-1})	7.4	
χ^2	1.06	

the velocities after 1999 May. The two orbital solutions diverge with time and we expect the correct model to predict future velocities. In Figure 4 we show the two models fitted to the pre–1999 May data. A dotted line indicates where we stopped fitting and simply let the theoretical curves roll forward in time. Finally, we overplotted the post–1999 May velocities. *The single-Keplerian fit clearly fails, while the double-Keplerian curve passes through the new velocities.*

Finally, we note that short-term perturbations among massive planets in multiple planet systems can result in radial velocity variations of the central star that differ substantially from velocity variations derived assuming that the planets are executing independent Keplerian motions. This effect is important for GJ 876, and, to a lesser extent, for Upsilon Andromedae. We have checked the importance of this effect for the 47 UMa system by comparing the synthetic radial velocity curve generated by the dual-Keplerian reflex motion with one generated by a three-body integration starting at epoch JD 2446959.737. Over the 14 yr epoch of observation these curves are identical to within 0.3 m s^{-1}, which is much smaller than the intrinsic error of the Doppler technique.

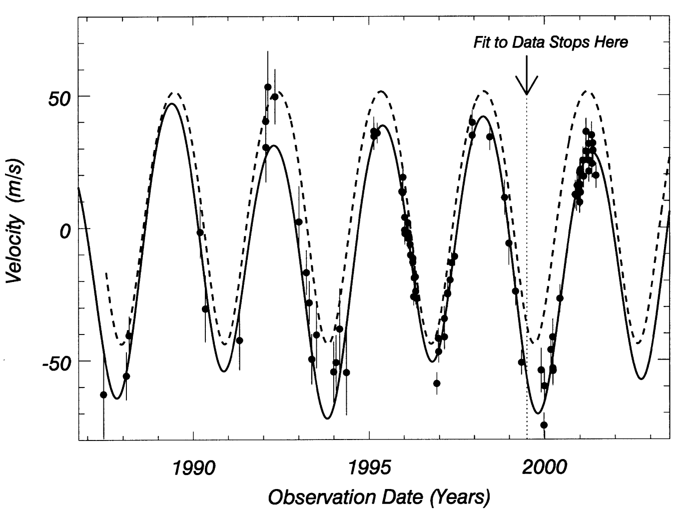

FIG. 4.—Data predating 1999 May were used to construct a theoretical two-Keplerian model (*solid line*) and a theoretical single-Keplerian model (*dashed line*). The vertical dotted line shows where the fit to the data stopped. Velocities after 1999 May are not included in the fit but are simply overplotted. The two-Keplerian model is a good predictor of subsequent velocities, while the single Keplerian is inadequate.

5. ASTROMETRIC CONSTRAINTS

The inner and outer planets around 47 UMa will cause stellar displacements of $a_1 \sin i = 0.0049$ AU and $a_1 \sin i = 0.0026$, respectively, corresponding to angular motion of 0.35 and 0.18 mas. *Hipparcos* astrometry for 47 UMa reveals no significant astrometric displacements (beyond proper motion and parallax) above 1 mas (Perryman et al. 1996,1997). Because the inner planet has larger $a_1 \sin i$ and a shorter period, *Hipparcos* astrometry sets a more stringent constraint on its orbital inclination of $\sin i < 0.33$ (Perryman et al. 1996). Thus, the actual mass of the inner companion is less than 3 $M \sin i$, i.e., $M_b < 7.6$ M_J. If the orbits are coplanar, the upper limit for the second companion mass is similarly constrained to $M_c < 2.25\ M_J$.

Pourbaix (2001) has searched the *Hipparcos* Intermediate Astrometric Data for stars with known extrasolar planets. For 47 UMa, he finds a best fit at inclination $i \approx 45°$. However he notes a low F-test probability, indicating that this inclination is quite uncertain. Pourbaix concludes that *Hipparcos* precision is not sufficient to confidently determine inclinations in any of the extrasolar planet systems, in agreement with Halbwachs et al. (2000).

6. DYNAMICAL SIMULATIONS

The two-planet fit to the radial velocity measurements of 47 UMa bears an interesting resemblance to the Jupiter-Saturn pair in our own solar system. In both cases, the orbital period ratio is close to 5:2 (2.35:1 for 47 UMa, 2.49:1 for Jupiter-Saturn), and the mass ratios are also similar (3.39:1 for 47 UMa, 3.34:1 for Jupiter-Saturn). The major difference is one of overall scale. The orbital period of 47 UMa b is less than one-fourth that of Jupiter, and the nominal mass is $\sim$2.5 times greater. We thus expect that the planets in the 47 UMa system will experience more significant mutual perturbations than do Jupiter and Saturn. Indeed, the system poses a very interesting dynamical problem. Stability issues can restrict the allowed parameter space of the system, and at the same time, the analytic secular theory developed for Jupiter and Saturn by Laplace and Lagrange (e.g., Murray & Dermott 1999) can be brought directly to bear.

For situations involving two planets on circular orbits (which is very nearly the case in the best-fit system shown in Table 1) Gladman (1993) has derived a criterion that gives the minimum separation that two planets on initially circular orbits require for stability:

$$\Delta_{\min} = 2.4(\mu_b + \mu_c)^{1/3} ,$$

where μ_b and μ_c are the ratios of the planet masses to the stellar mass, and Δ is the fractional orbital separation of the two planets $(a_c - a_b)/a_b$. For the two companions to 47 UMa, $\Delta = 0.7655$, which is considerably larger than the minimum separation, $\Delta = 0.357$, required for stability given the minimum masses of the companions. The Gladman criterion suggests that the system will become unstable for a mass factor $\sin(i)^{-1} = 9.7$. Such a small value of $\sin i$ (nearly face-on) is ruled out by the astrometry, as described above. The numerical integrations described below indicate that the maximum mass factor for coplanar systems is actually $\sin(i)^{-1} = 6$, owing to the nonzero eccentricity of the inner planet.

As is also the case with the planetary system surrounding Upsilon Andromedae, numerical experiments can be used

TABLE 3

HIGHEST ECCENTRICITY FOR 47 UMa c IN 100 MYR

	e_c					
$\sin(i)^{-1}$	0.005	0.05	0.10	0.15	0.20	0.25
1.00......	0.09	0.08	0.11	0.16	0.22	Unstable
1.25......	0.09	0.08	0.11	0.16	Unstable	Unstable
1.50......	0.09	0.09	0.11	0.16	Unstable	Unstable
1.75......	0.10	0.09	0.12	0.17	Unstable	Unstable
2.00......	0.10	0.09	0.12	0.17	Unstable	Unstable
2.50......	0.10	0.10	0.12	0.17	Unstable	Unstable
3.00......	0.10	0.10	0.12	0.17	Unstable	Unstable
4.00......	0.10	0.13	0.14	Unstable	Unstable	Unstable
5.00......	0.10	0.14	0.16	Unstable	Unstable	Unstable
6.00......	Unstable	Unstable	Unstable	Unstable	Unstable	Unstable

to constrain the unknown inclination angles and other orbital parameters (see e.g., Laughlin & Adams 1999; Laughlin & Chambers 2000; Lissauer & Rivera 2001; Rivera & Lissauer 2000; Chiang et al. 2001). The constraints are imposed by the dynamical survivability of the system despite the gravitational interactions among the planets.

Using a Bulirsch-Stoer integrator, we have made a number of trial 100 million yr integrations of the 47 UMa system, which are summarized in Table 3. In these calculations, we have used the orbital parameters listed in Table 2. The parameters are considered as osculating elements, and all simulations are started from epoch JD 2451293.70. We assume that the planets are initially very close to coplanar configurations, with $|i_b - i_c| \leq 1.0 \times 10^{-5}$ (in order to give the integrator access to all three spatial dimensions).

We systematically investigate the result of varying the overall initial inclination angle of the system (parameterized by the mass factor $\sin(i)^{-1}$) and the initial eccentricity, e_c, of planet c. The parameter e_c is not well determined by the radial velocity data, yet it is seen to play a crucial role in determining the overall stability of the system. The simulations conserve energy to a high degree. Time-step accuracy is required to be better than one part in 10^{14}, and the overall energy accuracy during the course of a simulation is typically $\Delta E/E = 1.0 \times 10^{-8}$ or better.

In Table 3 we report the largest value of e_c achieved during the course of each 100 million yr integration. For $\sin(i)^{-1} > 5.0$ or $e_c > 0.20$, the system is always unstable, as indicated in Table 3. In all cases where instability was observed, the destruction of the system occurs via ejection of planet c. We note that while collisions between the planets or between the planets and the star are also possible, these outcomes were not observed in any of the simulations.

Figure 5 shows the difference in periapse angles ($\omega_b - \omega_c$) and the eccentricities e_b and e_c of the planets as a function of

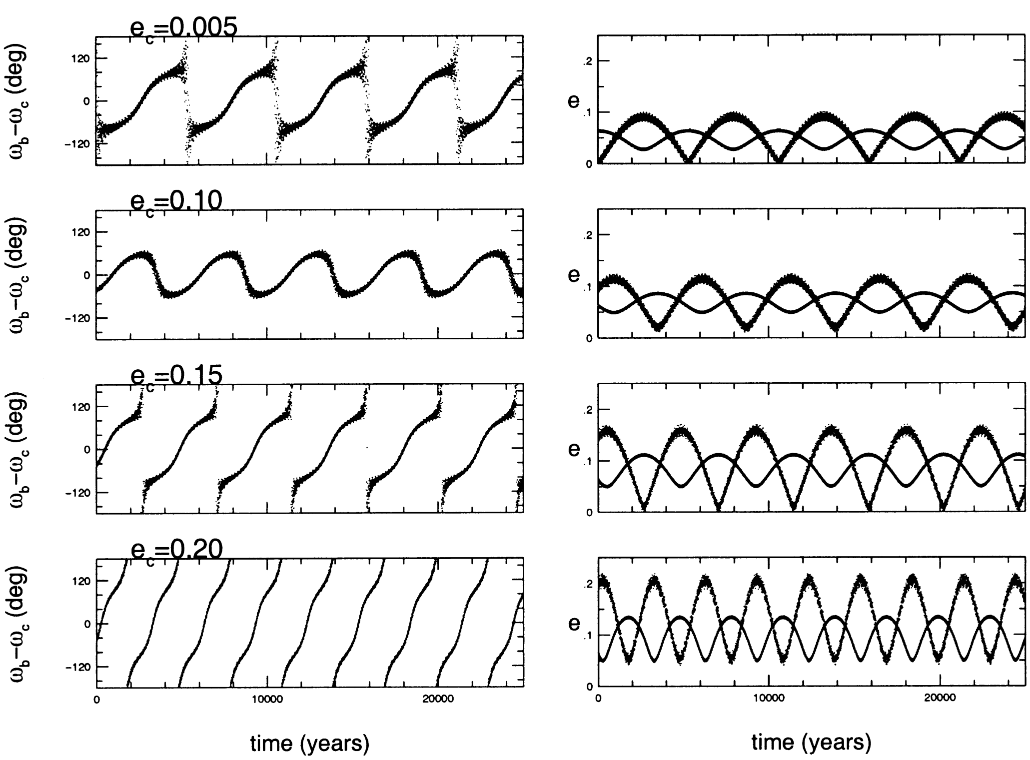

FIG. 5.—Differences in periapse longitude (*left panels*) and eccentricities (*right panels*) in numerical integrations of the 47 UMa system listed in Table 2, with initial eccentricities of planet c listed on the figure.

time for coplanar systems with sin $(i) = 1$ and initial eccentricities $e_{ci} = 0.005$, 0.10, 0.15, and 0.20. (All other starting parameters are given in Table 2.) When $e_{ci} < 0.15$, the planets are participating in a secular resonance involving libration around apsidal alignment. The planets also undergo periodic exchange of eccentricity on characteristic secular timescales of several thousand years. Libration of the apsidal alignment is likely to aid the stability of the system, since it prevents the close encounters which could otherwise occur when the periapse longitudes are antialigned.

Most randomly selected configurations within 2 σ bounds on the orbital parameters of Table 2 participate in libration about apsidal alignment. If, however, the period of the outer planet falls in the range 2715 days $< P_c <$ 2729 days, so that the system is very close to 5:2 commensurability, then the librations about apsidal alignment are replaced by free precession of the periapses, as is observed for Jupiter and Saturn.

7. DISCUSSION

Doppler measurements from Lick Observatory reveal two planets orbiting the star 47 UMa. This is the first system with two planets of roughly Jupiter-mass that reside beyond 2 AU from the host star. In contrast to other detected extrasolar planets, the low eccentricity of these orbits together with the large orbital semimajor axes lead us to wonder if this system may have followed a gentler dynamical history, possibly similar to our own solar system.

The star 47 UMa is similar to our sun as a middle-aged, chromospherically inactive G0V star with solar metallicity of [Fe/H] = 0.01 and a rotation period of about 24 days (per chromospheric activity indicators). Indeed, 47 UMa had been considered a good solar analog even prior to the discovery of its planets (Cayrel de Strobel 1996).

One concern is that the velocity variations with a period of 7 yr (leading to the outer planet) may instead be caused by a photspheric periodicity. Stellar magnetic cycles can exhibit periods of $\sim$ 7 yr (Baliunas et al. 1998). During the past 3 yr, *V*-band photometry has revealed no brightness variations above 1 mmag (Henry et al. 2000), indicating that the number of spots has not changed significantly. Since 1985 the Mount Wilson survey has detected remarkably little variation in the *S* index of Ca II H and K emission. There is weak evidence of an upward trend during the past 6 yr (see Fig. 2 of Henry et al. 2000). But the variation is small, $\sigma S/S = 2.8\%$, and no cyclic behavior is apparent. Thus the *V*-band photometry and the chromospheric indicators suggest that the photosphere is too quiet to result in the observed velocity variations of $\sim$ 11 m s^{-1}. Nonetheless, continued chromospheric monitoring is important to verify the planet nature of the 7 yr periodicity.

The inner planet has $M_b \sin i = 2.54\ M_J$ and orbits with semimajor axis of 2.09 AU and an orbital period of 2.99 yr. The outer planet has $M_c \sin i = 0.76\ M_J$, a semimajor axis of 3.73 AU and an orbital period of 7 yr.

The eccentricity of the outer planet is not well constrained by Keplerian fitting to the single orbital period of high-precision radial velocity observations. However, numerical three-body simulations show that e_c and the orbital inclination play critical roles in the overall dynamical stability of the system. For $\sin i < 0.2$ or $e_c > 0.2$ the system is dynamically unstable. From this dynamical consideration and the astrometric constraints, both planets likely have masses less than 7.5 M_J, and most probably have masses within a factor of 2 of their values of $M \sin i$.

Jones, Sleep, & Chambers (2001) tested the dynamical stability for terrestrial mass planets of the habitable zones around stars with detected gas giant planets. Without knowledge of the second planet presented in this paper, they concluded that 47 UMa was the best candidate to host terrestrial planets in orbits that could remain confined to the habitable zone for biologically significant lengths of time. With the detection of a second planet, we have investigated the effect of placing an Earth mass planet at various regions in the habitable zone. In the presence of a second planet, most test particles survive within the habitable zone over 10^6 yr timescales. The analogue of the ν_6 secular resonance in our own solar system, however, may lead to difficulty in allowing large terrestrial planets to form in 47 UMa's habitable zone via the usual accretion scenario (see Jones et al. 2001). These points are deserving of further investigation, and this star remains an interesting target for future searches with space missions such as *SIM* and *TPF* that have the sensitivity to detect earth-mass planets.

The star 47 UMa is one of only $\sim$20 stars observed at Lick Observatory with both sufficient precision and time baseline to permit detection of a Jupiter analogs orbiting beyond 3 AU. During the upcoming years this survey will provide an early measure of the occurrence rate of planetary systems with giant planets at $\sim$ 5 Au.

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