TWO NEW CANDIDATE PLANETS IN ECCENTRIC ORBITS[1]

GEOFFREY W. MARCY,[2] R. PAUL BUTLER,[3] STEVEN S. VOGT,[4] DEBRA FISCHER,[2] AND MICHAEL C. LIU[5]

ABSTRACT

Doppler measurements of two G-type main-sequence stars, HD 210277 and HD 168443, reveal Keplerian variations that imply the presence of companions with masses ($M \sin i$) of 1.28 and 5.04 M_J (where M_J is the mass of Jupiter) and orbital periods of 437 and 58 days, respectively. The orbits have large eccentricities of $e = 0.45$ and $e = 0.54$, respectively. All nine known extrasolar planet candidates with $a = 0.2$–2.5 AU have orbital eccentricities greater than 0.1, higher than that of Jupiter ($e = 0.05$). Eccentric orbits may result from gravitational perturbations imposed by other orbiting planets or stars, by passing stars in the dense star-forming cluster, or by the protoplanetary disk. Based on published studies and our near-IR adaptive optics images, HD 210277 appears to be a single star. However, HD 168443 exhibits a long-term velocity trend consistent with a close stellar companion, as yet undetected directly.

Subject heading: planetary systems — stars: individual (HD 210277, HD 168443, HD 114762)

1. INTRODUCTION

Doppler surveys of main-sequence stars have revealed 15 companions to main-sequence stars that are extrasolar planet candidates. Among these candidates, 13 have $M \sin i < 5\ M_J$, where M_J is the mass of Jupiter. The host stars and associated descriptions are 51 Peg (Mayor & Queloz 1995), 47 UMa (Butler & Marcy 1996), 70 Vir (Marcy & Butler 1996), 55 Cnc, υ And, τ Boo (Butler et al. 1997), 16 Cygni B (Cochran et al. 1997), ρ CrB (Noyes et al. 1997), GJ 876 (Marcy et al. 1998a; Delfosse et al. 1998), 14 Her (Mayor et al. 1999), HD 187123 (Butler et al. 1998), HD 195019A and HD 217107 (Fischer et al. 1999), GJ 86 (Queloz et al. 1999), and HD 114762 (Latham et al. 1989). The Doppler measurements reported here suggest the presence of new planetary candidates around HD 210277 and HD 168443.

Four main-sequence stars harbor Doppler companions that have $M \sin i = 15$–75 M_J, which may represent the "brown dwarfs" (Mayor et al. 1999; Mayor et al. 1997). Indeed, the companions to 70 Vir ($M \sin i = 6.8\ M_J$) and to HD 114762 ($M \sin i = 11\ M_J$) may also represent "brown dwarfs" (Marcy & Butler 1996; Mazeh, Krymolowsky, & Rosenfeld 1997; Latham et al. 1989; Boss 1997). The distinction between "planets" and "brown dwarfs" remains cloudy and rests on two formation scenarios. Planets form out of the agglomeration of condensable material in a disk into a rock-ice core (e.g., Lissauer 1995). In contrast, brown dwarfs presumably form by a gravitational instability in gas (e.g., Boss 1998; Burrows et al. 1998). Hybrid formation scenarios remain viable in which the relative importance of solid core growth and gas accretion within a disk lead to a continuum in internal structure. Subsequent collisions may lead to further growth and dynamical evolution. The current dichotomous taxonomy may describe substellar physics no more precisely than "spiral" and "elliptical" summarize galactic physics.

The first incontrovertible subclassification within the substellar regime is revealed in the mass distribution. Companions having $M \sin i$ in the decade between 0.5 and 5 M_J outnumber those between 5 and 50 M_J by a factor of ~ 3 (e.g., Marcy & Butler 1998; Mayor et al. 1999). The poor detectability of the lowest mass companions implies that the factor of 3 is a lower limit to the cosmic ratio. This plenitude of companions having Jovian masses suggests that qualitatively distinct formation processes predominated, arguably similar to those associated with the giant planets in our solar system (Lin et al. 1998).

The extrasolar planets reveal some peculiarities that may bear on their formation. The host stars of the extrasolar planet candidates have higher mean metallicity by a factor of ~ 2 in abundance compared with field stars (Gonzalez 1998). Metallicity was not a criterion in the selection of the target stars for these planet searches. Equally interesting is the fact that seven planets reside in orbits with a radius less than 0.12 AU (sometimes termed 51 Peg planets; Mayor & Queloz 1995, Butler et al. 1998). Precision Doppler surveys are most sensitive to planets in small orbits, resulting in a selection effect. Nonetheless, these small orbits challenge us to explain their existence in a region where both the high temperatures and the small amount of protostellar material would inhibit formation in situ. The 51 Peg planets thus offer support for the prediction by Goldreich & Tremaine (1980) and Lin (1986) that Jupiters may migrate inward from farther out (Lin et al. 1996; Ward 1997; Trilling et al. 1998). Perhaps most intriguing about the planet candidates are the orbital eccentricities. The orbits of the 51 Peg planets may suffer some tidal circularization (Lin et al. 1998; Terquem et al. 1998; Ford, Rasio, & Sills 1998; Marcy et al. 1997), and indeed their orbits are all nearly circular (see Table 4). In contrast, the planets that orbit farther than 0.15 AU from their star all reside in noncircular orbits having $e > 0.1$, i.e., more eccentric than for Jupiter ($e = 0.05$). Indeed, all but two have $e > 0.2$. This high occurrence of orbital eccentricity has led to a variety of

[2] Department of Physics and Astronomy, San Francisco, CA 94132; and Department of Astronomy, University of California, Berkeley, CA 94720.

[3] Anglo-Australian Observatory, P.O. Box 296, Epping, NSW 1710, Australia; paul@aaoepp.aao.gov.au.

[4] UCO/Lick Observatory, University of California at Santa Cruz, Santa Cruz, CA, 95064.

[5] Department of Astronomy, University of California at Berkeley, Berkeley, CA 94720.

models in which Jupiter-like planets suffer gravitational interactions with (a) other planets (Weidenschilling & Marzari 1996; Rasio & Ford 1996; Lin & Ida 1997; Levison, Lissauer, & Duncan 1998), (b) the disk (Artymowicz 1993), (c) a companion star (Holman, Touma, & Tremaine 1997; Mazeh et al. 1997), and (d) passing stars in the young cluster (de la Fuente Marcos & de la Fuente Marcos 1997; Laughlin & Adams 1998).

The possibility persists that the observed noncircular orbits all stem from perturbations from a bound companion star, as proposed for 16 Cyg B (Holman et al. 1997; Mazeh et al. 1997), rather than from intrinsic dynamics of planet formation. This paper reports the detection of two new planetary candidates orbiting at 0.3 and 1.1 AU, both having large eccentricities. The observations and orbital solutions are reported in § 2. The search for stellar companions is discussed in § 3. Section 4 contains a discussion of the implications for planet formation.

2. OBSERVATIONS AND ORBITAL SOLUTIONS

2.1. Stellar Characteristics of HD 210277

The two stars described here are among 430 G-, K-, and M-type main-sequence stars currently being monitored at the Keck I telescope for Doppler variations. HD 210277 has an effective temperature of 5570 ± 50 K, the average determination from spectral synthesis of high-resolution spectra (Favata, Miccia, & Sciortino 1997; Fuhrmann 1998; Gonzalez, Wallerstein, & Saar 1998), which also yields a surface gravity of $\log g = 4.38 \pm 0.1$ (Fuhrmann 1998; Gonzalez et al. 1998). These surface values imply main-sequence status and correspond to spectral type G7 V (Gray 1992).

The metallicity of HD 210277 is measured to be [Fe/H] $= +0.24 \pm 0.02$, considerably higher than the average value for field stars, $\langle$[Fe/H]$\rangle = -0.23$, in the solar neighborhood (Gonzalez et al. 1998; Favata et al. 1997; Fuhrmann 1998). Thus, HD 210277 appears to be rich by a factor of 3 in its abundance of heavy elements, normalized to hydrogen, placing its metallicity within the upper 5% of nearby stars. We measure a radial velocity of -21.1 ± 2 km s^{-1}, which agrees with that of Duquennoy & Mayor (1991), -21.44 km s^{-1}. Its parallax of $0''047$ (Perryman et al. 1997) implies an absolute visual magnitude of $M_V = 4.90 \pm 0.05$ and a luminosity, $L = 0.93 L_\odot$. These stellar parameters permit placement of HD 210277 on evolutionary tracks, which yield a mass $M = 0.92 \pm 0.02 M_\odot$ and an age of 12 ± 2 Gyr (Gonzalez et al. 1998).

One stellar characteristic that bears on the Doppler detectability of planets is the magnetic field and chromosphere. Spots on a rotating star can produce spurious Doppler shifts, and chromospheric emission correlates with spurious Doppler "noise" presumably caused by surface magnetohydrodynamics (Saar, Butler, & Marcy 1998). Our spectra contain the chromospheric H and K emission lines from which stellar rotation and stellar age can be estimated (Noyes et al. 1984). This emission yields the chromospheric index known as the "Mount Wilson S-Value" of $S = 0.155$, implying $R'(HK) = -5.06$, measured from 36 spectra obtained from 1996.5 through 1998.7 (Shirts & Marcy 1998). See Baliunas et al. (1998) for a detailed discussion of the S-value. No trend or periodicity is apparent in the S-values of HD 210277, and the rms is 0.006, all of which indicates that HD 210277 is chromospherically quiet. The implied rotation period is $P_{rot} = 40.8$ days, and the age is

6.9 Gyr. In conjunction with the aforementioned age of 12 Gyr from tracks, we conclude that HD 210277 has an age in the range 7–10 Gyr, but not evolved into the subgiant regime. Such a chromospherically inactive star may produce spurious Doppler shifts of no more than ~ 3 m s^{-1} (Saar et al. 1998; Butler et al. 1998).

2.2. Stellar Characteristics of HD 168443

No detailed LTE analysis of HD 168443 has been carried out to our knowledge. A photometric analysis was done by Carney et al. (1994) giving $T_{eff} = 5430$ and m/H $= -0.14$. The metallicity is apparently slightly subsolar, similar to the mean for nearby field stars. Its parallax of 26.4 mas (Perryman et al. 1997) implies an absolute visual magnitude of $M_V = 4.03 \pm 0.07$ and a luminosity $L = 2.1 L_\odot$, which places it ~ 1.5 mag above the main sequence at its T_{eff}. These stellar parameters suggest a subgiant status and spectral type G8 IV. Apparently HD 168443 is similar to 70 Vir in mass, surface characteristics, and metallicity (Marcy & Butler 1996; K. Apps 1998, private communication).

Our spectra of HD 168443 yield a chromospheric S-value of $S = 0.147$, with an rms of 0.009 during 30 observations from 1996 to 1998.5, implying $R'(HK) = -5.08$. No trend or periodicity are apparent in the S values. The implied rotation period is $P_{rot} = 37$ days, and the implied age is 7.8 Gyr, from the calibration by Noyes et al. (1984). In conjunction with its possible subgiant status from above, we conclude that HD 168443 has an age of 7–10 Gyr, slightly evolved toward subgiant status. We caution that the subgiant status remains in question, pending spectroscopic assessment of surface gravity.

A mass determination for HD 168443 is given by Carney et al. (1994), who find $M = 0.84 M_\odot$. This mass determination may warrant revision because it preceded the Hipparcos parallax and because it did not include revisions to the metallicity dependence of evolutionary tracks (Bertelli et al. 1994). Based on the Hipparcos data and new tracks, along with available narrowband photometry for HD 168443, K. Apps (1998, private communication) estimates a mass of $1.05 \pm 0.10 M_\odot$ for HD 168443. We adopt here the straight average of the two mass estimates to yield $M = 0.945 \pm 0.1 M_\odot$.

We measure a radial velocity of -49.0 ± 2 km s^{-1} (on 1998 August 26), which, along with its high transverse velocity of 44 km s^{-1}, suggests a kinematic association with the old disk population. Such an old, chromospherically inactive star may produce spurious Doppler shifts of ~ 3 m s^{-1} of photospheric origin (Saar et al. 1998; Butler et al. 1998).

2.3. Details of the Doppler Measurements

For both HD 210277 and HD 168443, spectra were obtained from 1996.5 through 1998.7 with the HIRES echelle spectrometer on the Keck I telescope (Vogt et al. 1994). We used slit B1, which has a width of $0''57$ and a height of $3''5$. The resolution for these spectra was $R = 87,000$, based on the measured FWHM of the spectrometer instrumental profile. The spectra span wavelengths from 3900 to 6200 Å. The wavelength scale and instrumental profile were determined for each 2 Å chunk of spectrum for each exposure by using iodine absorption lines superimposed on the stellar spectrum (Butler et al. 1996). The measured velocities are relative, with an arbitrary zero point.

The typical exposure times were ~ 5 minutes, depending on seeing, for both stars, yielding a signal-to-noise ratio of

300 pixel[-1] (one-half of one resolution element). Such spectra are expected to carry photon-limited Doppler precision of 2–3 m s^{-1} (Butler et al. 1996). Indeed, the uncertainty in the mean velocity of the 400 spectral chunks is typically 2.5 m s^{-1}. However, our results from 430 stars on the survey reveal a median rms velocity of 6 m s^{-1}, which we interpret as the actual scatter that limits planet detection. Intrinsic photospheric noise of ~ 3 m s^{-1} accounts for some of the 6 m s^{-1} scatter (Saar et al. 1998). This intrinsic stellar effect may be added in quadrature to the photon-limited errors of 2.5 m s^{-1} to establish an expected Doppler scatter of 3.9 m s^{-1}. Thus, we infer that unidentified errors of ~ 4 m s^{-1} persist in our Doppler results, which presumably stem from inadequacies in our spectral modeling, improvements to which are in progress.

2.4. Keplerian Velocities for HD 210277

The 34 measured velocities of HD 210277 are listed in Table 1 along with the Julian Date. Again, the true uncertainty of each measurement is ~ 6 m s^{-1}. A plot of the velocities for HD 210277 is shown in Figure 1. It is apparent that the velocities for HD 210277 scatter with a peak-to-

peak variation of ~ 80 m s^{-1}, and the velocities are correlated in time. A periodogram analysis revealed no significant peak because too few cycles have transpired during the 2 years of observations and because a Lomb-Scargle periodogram is not robust for nonsinusoidal variations that result from eccentric orbits.

A suggestive period of 1.2 yr is evident in the velocities for HD 210277, although less than two periods have transpired. The best-fit Keplerian model yields an orbital period of 437 ± 25 days, a semiamplitude $K = 41.0 \pm 5$ m s^{-1}, and an eccentricity $e = 0.45 \pm 0.08$. The complete set of orbital parameters is given in Table 3. The rms to the Keplerian fit is 7.1 m s^{-1}, similar to the uncertainty and similar to the velocity rms, 7.6 m s^{-1}, for the orbital fit to a previously discovered Keck survey planet HD 187123 (Butler et al. 1998). Thus, the rms of 7 m s^{-1} for HD 210277 implies that a single companion provides a model that plausibly explains the velocities.

Using the stellar mass of 0.92 $M_\odot$, the companion mass is constrained as $M \sin i = 1.28$ M_J, and the semimajor axis is $a = 1.10$ AU. With periastron and apastron distances of 0.61 and 1.60 AU, HD 210277 is unlikely to harbor additional companions within that range.

2.5. Keplerian Velocities for HD 168443

The 30 velocity measurements for HD 168443 are listed in Table 2 along with the Julian Date. As with HD 210277, the true uncertainty of each measurement is ~ 6 m s^{-1}. A plot of the velocities for HD 168443 is shown in Figure 2. The velocities for HD 168443 scatter with a peak-to-peak variation of 650 m s^{-1}, with clear temporal correlations and trends among measurements. A periodogram reveals two dominant peaks, at $P = 20$ days and $P \approx 55$ days.

We carried out nonlinear least-squares fits of Keplerian models to the velocities, starting with trial periods ranging from 3 to 600 days. For trial periods near 20 days, the lowest velocity rms was 69 m s^{-1}, which is clearly inconsistent with the expected scatter of 6 m s^{-1}. For trial periods near 55 days, we found two nearby minima in χ^2, corresponding to two slightly different orbital periods, $P = 64$ days (rms = 23 m s^{-1}) and $P = 59$ days (rms = 36 m s^{-1}). Figure 3 shows the velocities as a function of orbital phase for the better of those fits ($P = 64$ days). That Keplerian fit

TABLE 1

VELOCITIES FOR HD 210277

JD −2,450,000	Radial Velocity (m s^{-1})	JD −2,450,000	Radial Velocity (m s^{-1})
277.0404......	15.8	983.0511......	−8.4
366.7926......	22.7	984.0878......	0.0
418.7591......	26.2	1010.0261......	−40.2
462.7062......	53.3	1011.1015......	−36.4
605.0940......	−23.3	1011.9692......	−39.2
665.9876......	−11.5	1013.0816......	−39.0
688.9457......	0.9	1014.0859......	−39.6
689.9833......	0.6	1043.0057......	−35.4
713.8792......	6.1	1043.9942......	−32.0
714.9728......	12.3	1050.9159......	−24.7
715.9286......	16.6	1051.9839......	−35.0
783.7130......	24.6	1068.8670......	−14.0
784.7205......	46.4	1069.9748......	−18.0
785.6995......	38.3	1070.9566......	−20.2
805.7146......	14.2	1071.8706......	−16.6
806.7038......	30.6	1072.9307......	−17.2
956.0877......	25.3	1074.8716......	−3.8

FIG. 1.—Measured radial velocities for HD 210277. The solid line shows the best-fit Keplerian curve.

TABLE 2

VELOCITIES FOR HD 168443

| JD −2,450,000	Radial Velocity (m s^{-1})	JD −2,450,000	Radial Velocity (m s^{-1})
276.9089......	−305.1	1010.8508......	21.4
603.0118......	−50.7	1011.8608......	22.9
665.8678......	−82.7	1012.9541......	13.6
713.7377......	−88.4	1013.0670......	22.4
714.7665......	−89.8	1013.8279......	7.8
955.0104......	−22.4	1013.9298......	6.3
955.9586......	−16.3	1042.9556......	−344.1
957.0711......	−7.5	1043.9560......	−287.2
981.8801......	−578.4	1050.8141......	−92.9
982.8913......	−505.7	1068.7704......	39.1
983.0769......	−483.6	1069.7860......	47.5
983.8223......	−412.4	1070.7981......	40.2
984.0614......	−406.0	1071.7700......	37.9
1009.8701......	8.1	1072.7627......	33.3
1010.0599......	28.0	1074.7851......	41.8
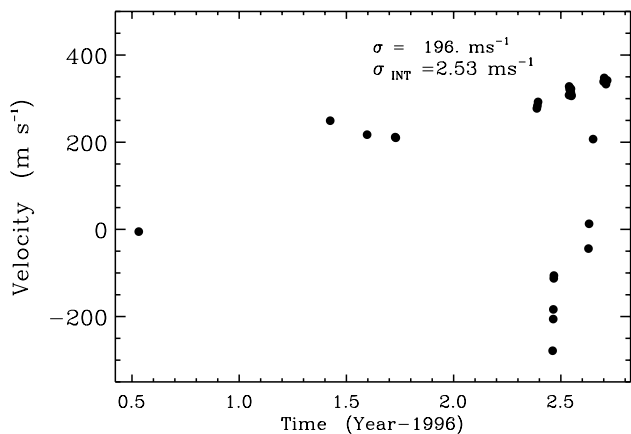
FIG. 2.—Measured radial velocities for HD 168443. The points exhibit obvious correlations in time, with a hint of periodicity.

carries an implied eccentricity of $e = 0.69$, $K = 292$ m s^{-1}, and a companion minimum mass of $M \sin i = 4.0\ M_J$.

However, the scatter to that fit, rms = 23.3 m s^{-1}, clearly exceeds the expected scatter of 6 m s^{-1}, implying that this fit carries a reduced χ^2 greater than 4 and hence this model is inadequate. Indeed, two telltale points located at phase ~ 0.95 (see Figure 3) were obtained on consecutive nights. The second velocity was 58 m s^{-1} higher, and yet according to the Keplerian curve it should reside lower by 60 m s^{-1}. We consider this dubious orbital fit to imply that the Keplerian model fails in some important way.

We modified the model by simply adding a variable linear trend to Keplerian velocities. Such a model incorporates the possibility of a long-period companion in addition to the shorter period companion. This slope introduces only one additional free parameter, as the "y-intercept" of the slope is subsumed within the arbitrary zero point of the velocities.

The Keplerian-plus-slope model is shown in Figure 4 and yields a best-fit orbital period of, $P = 57.8$ days, $K = 350$ m s^{-1}, $e = 0.54$, and $M \sin i = 5.04\ M_J$. The rms of the residuals, 12.8 m s^{-1}, is considerably reduced from the rms of 23.3 m s^{-1} that results from a model without a trend. The reduced χ^2 for this solution is 2.3. All orbital parameters are
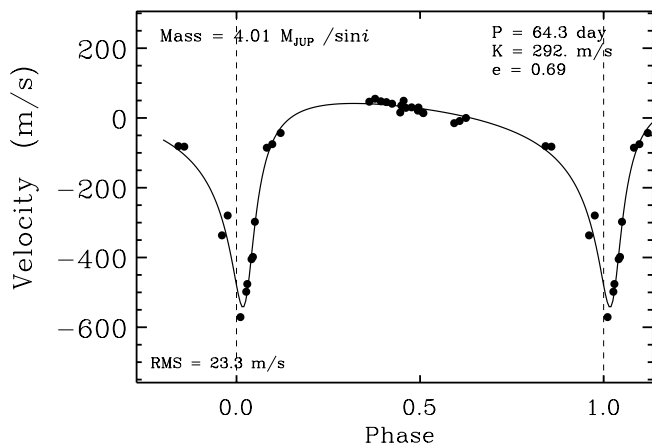

FIG. 3.—Velocities of HD 168443, plotted as a function of orbital phase for the best-fit Keplerian model (without an ad hoc velocity trend). This orbit has rms residuals of 23.3 m s^{-1}, exceeding the expected scatter by a factor of 4. This model appears inadequate to explain the velocities.
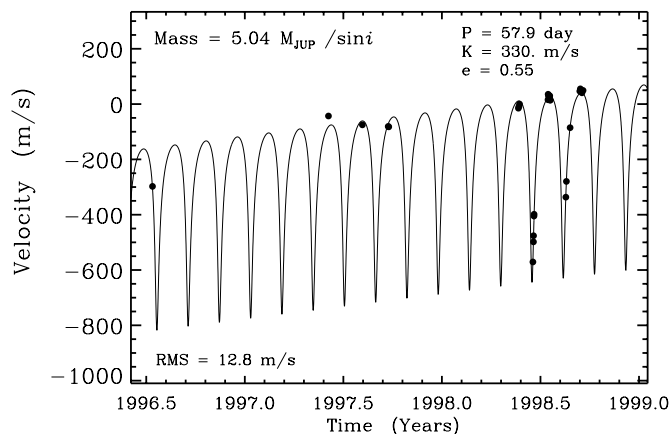

FIG. 4.—Velocities of HD 168443 plotted against time. The solid line shows the best-fit Keplerian model with an added linear trend in velocity. This ad hoc model yields residuals with rms = 13 m s^{-1}, which is about twice the expected scatter but a clear improvement over the model without a trend in Fig. 3.

given in Table 3. Thus, it appears that the introduction of an ad hoc slope into the Keplerian model for HD 168443 significantly improves the fit. However, the rms of 12.8 m s^{-1} remains larger than the expected scatter of 6 m s^{-1}, implying that the addition of a velocity slope is too simple. Introducing an ad hoc parabolic term in the velocity trend reduces the rms to 8 m s^{-1} ($\chi^2 = 1.5$), superior to that of a linear trend. However, we feel that introducing this parabolic free parameter carries only marginal statistical justification. A proper model that contained a second orbiting companion would require the introduction of an additional set of Keplerian parameters, for which we have inadequate constraints. Thus, the only model supported by the current data is that containing the linear trend.

We tested the predictability of this model with two additional velocity measurements obtained with the 0.6 m coudé auxiliary telescope (CAT) at Lick Observatory. We obtained spectra on two consecutive nights, centered on JD 2,451,100.644 and JD 2,451,101.645, for which the model containing the Keplerian and linear trend offered a prediction of an increase in velocity of 52.4 m s^{-1}. On both nights we obtained four consecutive spectra, each lasting 30 minutes. Each spectrum was analyzed separately to derive a Doppler shift. The four velocities were averaged, to yield the final velocity for each night. The uncertainty in the mean was computed from the standard deviation of the four separate measurements, giving an internal error for each night.

TABLE 3

ORBITAL PARAMETERS OF HD 21 0277 AND HD 168443

Parameter	HD 210277	HD 168443[a]
P (days)...........	437 (25)	57.9 (1)
T_p (JD).............	2,450,993 (20)	2,450,979.35 (2)
e....................	0.45 (0.08)	0.55 (0.04)
ω (deg).............	124 (20)	170 (5)
K_1 (m s^{-1})........	41.5 (5)	330 (23)
$a_1 \sin i$ (AU)	1.49×10^{-3}	1.56×10^{-3}
$f_1(m)$ $(M_\odot)$.........	2.29×10^{-9}	1.51×10^{-7}
$M_2 \sin i$ (M_J)......	1.28 (0.4)	5.04 (0.4)
N_{obs}	34	30

[a] Additional velocity slope is 89 ± 9 m s^{-1} yr^{-1}.

These two Lick velocities were -24.2 ± 6.2 m s^{-1} and $+24.1 \pm 3$ m s^{-1} on the two nights, respectively, implying that the velocity of HD 168443 increased by $+48.3 \pm 7$ m s^{-1}. This velocity increase agrees with the prediction of the model (Keplerian plus trend) of $+52.4$ m s^{-1}. These Lick velocities were obtained 26 days after the last Keck measurements were made, on JD 2,451,1074.785, shown in Figure 4. The alternative model without an imposed velocity trend has a longer period of $P = 64.3$ days, and its predicted change in velocity is -60 m s^{-1}, clearly in conflict (wrong sign) with the observed rise of 48 m s^{-1}. Thus, both the lower velocity rms and the Lick measurements favor the model that contains a Keplerian with $P = 57.8$ days and a velocity trend.

The best-fit velocity trend has a slope of 89.4 m s^{-1} yr^{-1}, which could be caused by a second more distant companion. If so, its minimum orbital period is ~ 4 yr. As a benchmark, Jupiter causes a trend of ~ 4 m s^{-1} yr^{-1} in the Sun during 6 yr. Thus, if the period of the hypothetical second companion to HD 168443 were ~ 12 yr, its mass would be at least ~ 25 M_J. For the shortest possible period of 4 yr, the companion mass would be at least 15 M_J. In both cases, the companion would be considered a "brown dwarf" and quite possibly a hydrogen-burning star, depending on the actual period and sin i. Prospective stellar companions are discussed in § 3.2

2.6. Velocities for HD 114762

We have obtained 33 velocity measurements for HD 114762 since 1994 November. They are plotted against orbital phase in Figure 5. The unseen companion to this star has been described by Latham et al. (1989), Mazeh, Latham, & Stefanik (1996), Cochran, Hatzes, & Hancock (1991), and Hale (1995). Our velocities offer new measurements of the orbital parameters, $P = 84.03 \pm 0.1$ days, $e = 0.334 \pm 0.02$, $K = 618 \pm 6$ m s^{-1}, $\omega = 201° \pm 3°$, and $T_p = $ JD 2,450,225.30 ± 0.6. A revised mass for HD 114762 has been measured by Ng & Bertelli (1998) and Gonzalez (1998), giving $M = 0.82 \pm 0.03$ $M_\odot$, based on its Hipparcos distance ($d = 40.57$ pc; Perryman et al. 1997) and new stellar evolution models. This stellar mass and the orbital parameters imply that the companion has M sin $i = 11.02 \pm 0.5$ M_J.

If the companion mass is truly small compared to the primary star, then the semimajor axis is $a = 0.35$ AU. However, Cochran et al. (1991) and Hale (1995) provide
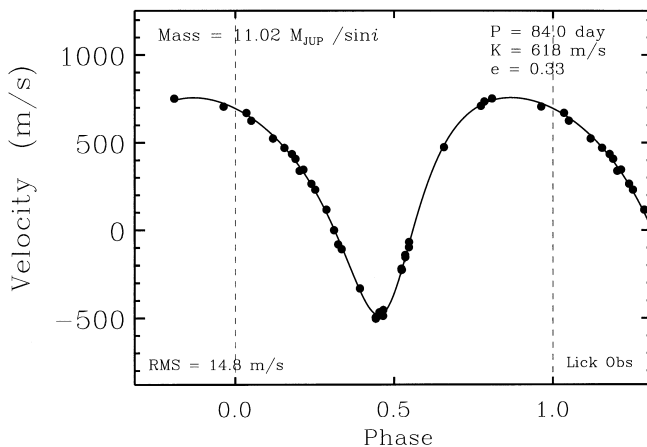
arguments that the companion mass may be large, possibly stellar. Since that work, several additional considerations have emerged regarding its status as a candidate planet. HD 114762 is the only planet candidate found with modest velocity precision rather than with high precision of ~ 10 m s^{-1}. That precision, along with the large survey size (Latham et al. 1989), makes the discovery of a face-on system more likely. Further, HD 114762 has [Fe/H] $= -0.6$, substantially more metal-poor than any other planet candidate (Gonzalez 1998). The standard model of planet formation requires heavy elements to form the dust which was presumably not abundant in the protoplanetary disk around HD 114762. Finally, the value of M sin i (11.02 M_J) is much higher than that for all other planet candidates, the highest of which is M sin $i = 7.4$ M_J (70 Vir). Nonetheless, we include HD 114762 as a candidate planetary object in this complete compilation.

3. SEARCH FOR STELLAR COMPANIONS

3.1. HD 210277

We examined HD 210277 for companion stars as follows. Duquennoy & Mayor (1991) made eight radial velocity measurements spanning 6 yr, which exhibited no variation above 220 m s^{-1}. Ground-based astrometry from 1989 to1993 revealed no motion at a level of 0".01 (Heintz 1994). Lunar occultation measurements revealed no companion to HD 210277, with detection thresholds of $\Delta V_{mag} < 2$ within 3 mas (Meyer et al. 1995) . The above measurements, especially those of Duquennoy & Mayor (1991), jointly rule out stellar companions with masses as low as 0.1 $M_\odot$ within 10 AU. A 0.1 $M_\odot$ dwarf orbiting 10 AU from HD 210277 would induce velocity variations with semiamplitude of 700 m s^{-1} ($\times$ sin i) and a period of 30 yr, detectable as a trend in velocities of Duquennoy & Mayor (1991) but not observed. The astrometry of Heintz similarly rules out a stellar companion with mass down to the substellar limit within 5 AU, which would have induced astrometric wobbles of 0".02.

To search for possible stellar companions beyond 10 AU, we observed HD 210277 on 1998 September 8 UT using the Lawrence Livermore National Laboratory adaptive optics system (Max et al. 1997), which is mounted at the f/17 Cassegrain focus of the Lick Observatory Shane 3 m telescope. The adaptive optics system performs real-time compensation of atmospheric seeing using a Shack-Hartmann type wave-front sensor with a 127 actuator deformable mirror. In its current configuration, 61 of the actuators are actively controlled. For these observations, image compensation was done with a sampling frequency of 250 Hz using HD 210277 ($V = 6.54$) itself as a wave-front reference, achieving a closed-loop bandwidth of 20 Hz.

We acquired images using the Lick facility near-IR camera LIRC2 (Gilmore, Rank, & Temi 1994). The camera has a 256 × 256 pixel HgCdTe NICMOS3 detector and, when coupled with the adaptive optics system, a plate scale of 0".12 pixel^{-1}. We used both a narrowband ($\Delta\lambda/\lambda = 0.01$) filter centered on Br$\gamma$ (2.166 μm) and the broadband K' filter (1.95–2.35 μm; Wainscoat & Cowie 1992) to span a wide range in radii with good sensitivity and dynamic range. The star was dithered to four positions on the detector, with total integrations of 240 s in each filter. Images were reduced in a standard fashion for near-IR images—bias subtraction, flat-fielding, and sky subtraction using a

FIG. 5.—Phased radial velocities of HD 114762 from Lick Observatory

master sky frame constructed from all the images. The angular resolution as measured by the full width at half-maximum (FWHM) of the Brγ images is 0″.18, and the images have a mean Strehl ratio of 0.45. The Brγ data are most sensitive to companions inside of 0″.5, and the K′-images are more sensitive at larger radii.

Figure 6 presents our 4 σ upper limits to any stellar companions to HD 210277 combined with K-band flux ratios for main-sequence companions derived from Kirkpatrick & McCarthy (1994). Only the inner radii are shown for clarity; the deepest portion of our images cover 12″ in radius. Our adaptive optics data are nearly diffraction-limited, ruling out any main-sequence dwarf companions earlier than spectral type M0 from 0.2 to 12″ (4.2–250 AU). In addition, the high Strehl ratio means the images are very sharply peaked and sensitive to even the lowest mass M dwarfs outside of 0″.5 (11 AU). We rule out any main-sequence companion with a separation of 0″.8 (17 AU) to 12″ (250 AU).

We further rule out any stellar companions out to ≈ 1′ separations using 2″.5 FWHM J and K′ images obtained from the Lick 3 m telescope with the UCLA two-channel infrared camera known as Gemini (McLean et al. 1994). The J and K′ data were taken simultaneously on 1998 October 9 UT with two 256 × 256 pixel detectors, a Rockwell HgCdTe NICMOS3 detector for J and a Hughes SBRC InSb detector for K′. There are a handful of $K \approx 14$–17 unresolved sources in these images; the majority of these also appear on the Palomar Sky Survey. Their $J - K$ colors are consistent with background stars or galaxies, and their numbers are in accord with field K-band galaxy counts (Szokoly et al. 1998). Comparing our images with those on the Palomar Sky Survey, the only source that shows noticeable proper motion is HD 210277 itself, which exhibits a magnitude and direction consistent with its nominal proper motion.

3.2. HD 168443

We have searched for stellar companions to HD 168443 in several ways. A literature search turned up no known companions. We searched for superimposed spectral lines from a secondary star in the 8400 Å region of our Lick spectra (near the Ca II IR triplet). No such lines were found at a threshold of a few percent of the continuum. This non-
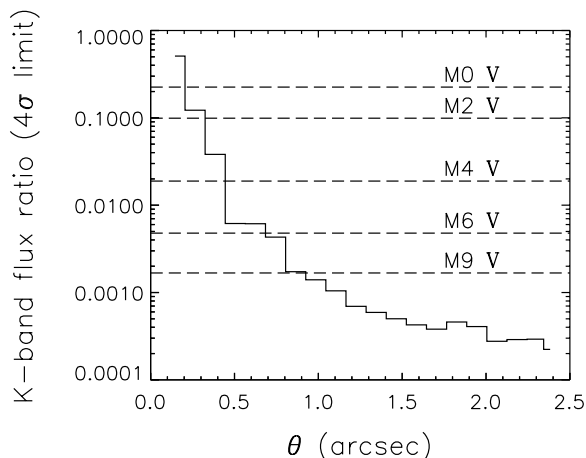
detection rules out any main-sequence companions more massive than 0.5 $M_\odot$ within 2″.5 (95 AU) of HD 168443, as we use a slit width of 5″ with the Lick Observatory CAT.

Carney et al. (1994) obtained eight radial velocity measurements of HD 168443 spanning 5 yr and detected no variation above the errors of 400 m s⁻¹. Any stellar companion more massive than 0.1 $M_\odot$ orbiting within 5 AU would have been revealed, except for extreme values of sin i. The Hipparcos astrometry of HD 168443 recorded no astrometric motion at a level of 2 mas during several years (Perryman et al. 1997). A stellar companion having 0.1 $M_\odot$ at 5 AU would induce a (curved) astrometric reflex motion of 16 mas during ~3 yr (¼ orbital period), as viewed from a distance of 38 pc. Such a wobble evidently did not occur, thus ruling out stellar companions within 5 AU, consistent with the velocity data. Hipparcos would not easily detect stellar companions orbiting beyond 5 AU, as the (more linear) reflex motion could be absorbed into the assessment of proper motion. Thus, stellar companions orbiting beyond 5 AU might escape detection by both the Carney et al. velocities and the Hipparcos astrometry.

We have not obtained an adaptive optics image of the star, leaving us little information about stellar companions farther than 5 AU. However, we were compelled to include a velocity slope of 89 m s⁻¹ yr⁻¹ in the model of our velocities (Fig. 4). This slope could indicate a stellar companion beyond 5 AU, or a brown dwarf somewhat closer. As a benchmark, a 0.1 $M_\odot$ companion orbiting at 10 AU would induce a typical velocity slope of 100 m s⁻¹ yr⁻¹ (× sin i). Our Keck velocities are consistent with such a stellar companion as well as more distant and correspondingly more massive ones. The upper mass limit of 0.5 $M_\odot$, imposed by the lack of secondary lines, implies that the companion must reside within ~30 AU in order to induce the observed velocity slope of 89 m s⁻¹ yr⁻¹.

A consistency check on the putative companion is provided by comparing the absolute velocities obtained by Carney et al. (1994) to those found here. Carney et al. obtained eight velocity measurements centered at epoch ~1990 that exhibited an average of −48.9 km s⁻¹, with σ = 0.4 km s⁻¹. Our observation on 1998 August 25 gave a velocity of −49.0 ± 2 km s⁻¹, which agrees with the Carney measurement within the 2 km s⁻¹ uncertainty. This implies an upper limit to the velocity trend of 2 km s⁻¹ per 8 year period, which is indeed larger than the trend we actually detect of 89 m s⁻¹ yr⁻¹.

In summary, any stellar companion must reside beyond 5 AU but not beyond 30 AU to explain the observed velocity trend, and its mass must be less than 0.5 $M_\odot$ to explain the lack of stellar secondary lines. A direct search for a stellar companion located 0″.15–1″ from HD 168443 seems warranted.

4. DISCUSSION

The two extrasolar planet candidates suggested by the data in this paper bring the total number of such candidates to 17. These candidates all have $M \sin i \lesssim 5$ M_J except 70 Vir ($M \sin i = 7.4$ M_J) and HD 114762 ($M \sin i = 11$ M_J) which some would place in the "brown dwarf" class (Black 1998). Table 4 lists the basic orbital parameters and $M \sin i$ of all 17 known planetary candidates. A few of the orbital parameters have been slightly modified, based on our own recent measurements and orbital fits. The typical uncertainty in the orbital eccentricity is 0.03, based on Monte

FIG. 6.—Detectability of stellar companions near HD 210277, based on K-band (2.2 μm) adaptive optics images. All main-sequence companions between 17 and 250 AU (0″.8–12″) would have been detected, but none was found. The data rule out an M0 V dwarf as close as 0″.2 (4.2 AU).

TABLE 4
ORBITAL PARAMETERS OF PLANET CANDIDATES

Star	$M_{\rm star}$ $(M_\odot)$	a (AU)	P (days)	e	$M \sin i$ $(M_{\rm J})$
HD 187123......	1.00	0.042	3.097	0.03	0.57
τ Boo	1.20	0.047	3.3126	0.00	3.66
51 Peg	0.98	0.051	4.2308	0.01	0.44
υ And	1.10	0.054	4.62	0.15	0.61
HD 217107......	0.96	0.072	7.11	0.14	1.28
55 Cnc..........	0.90	0.110	14.656	0.04	0.85
GJ 86	0.79	0.114	15.84	0.04	4.90
HD 195019......	0.98	0.136	18.3	0.05	3.43
GJ 876..........	0.32	0.210	60.9	0.27	2.10
ρ CrB	1.00	0.230	39.6	0.11	1.10
HD 168443......	0.84	0.277	57.9	0.54	5.04
HD 114762......	0.82	0.351	84.0	0.334	11.02
70 Vir...........	1.10	0.480	116.7	0.40	7.42
HD 210277......	0.92	1.097	437.	0.45	1.28
16 Cyg B	1.00	1.61	803	0.69	1.67
47 UMa	1.03	2.09	1086	0.11	2.45
14 Her	0.85	>2.50	>2000	0.36	3.35

Carlo simulations of the Keplerian fits to data with artificial noise

Table 4 shows that all nine planet candidates that have $a > 0.2$ AU have eccentricities above 0.1, larger than that for both Jupiter ($e = 0.048$) and Saturn ($e = 0.055$). Figure 7 shows a plot of orbital eccentricities as a function of the semimajor axis. All extrasolar planets orbiting closer than 0.1 AU have small eccentricities. While possibly primordial, these near-circular orbits for close planets may have been induced by tidal circularization (see Rasio et al. 1996; Marcy et al. 1997; Terquem et al. 1998).

Apparently, Jupiter-mass companions orbiting from 0.2 to 2.5 AU, immune to tides, have large orbital eccentricities. Apparently, some mechanism commonly produces eccentric orbits in Jupiter-mass companions that reside from 0.2 to 2.5 AU in main-sequence stars. These eccentric planets represent a general property of 0.3–1.2 $M_\odot$ stars.

Figure 8 shows orbital eccentricities as a function of $M \sin i$. No trend is apparent at first glance, suggesting that

orbital eccentricity is not correlated with planet mass, within the mass range 0.5–5 $M_{\rm J}$. However, all five planets with $M \sin i < 1.1$ $M_{\rm J}$ reside in nearly circular orbits. This correlation may be a selection effect, as the lowest mass planets are more easily detected close to their host stars in order to induce a detectable Doppler reflex signal. These close planets are all subject to tidal circularization. Thus, the low eccentricities among the lowest mass giant planets may not be considered intrinsic to planet formation.

Figure 9 shows $M \sin i$ versus the semimajor axis for all 17 planet candidates. The detectability of planetary companions is shown as the curved line near the bottom (Cumming, Marcy, & Butler 1999). Apparently, the distribution of planet masses is not a strong function of the semimajor axis from 0.05 to 2.5 AU for the range of detectable masses, 1–6 $M_{\rm J}$. There is no paucity of either the most or the least massive companions at either extreme of the semimajor axis. Of course there may be some blurring in mass due to $\sin i$. Nonetheless, we conclude that if orbital migration within a gaseous disk brings the giant plants
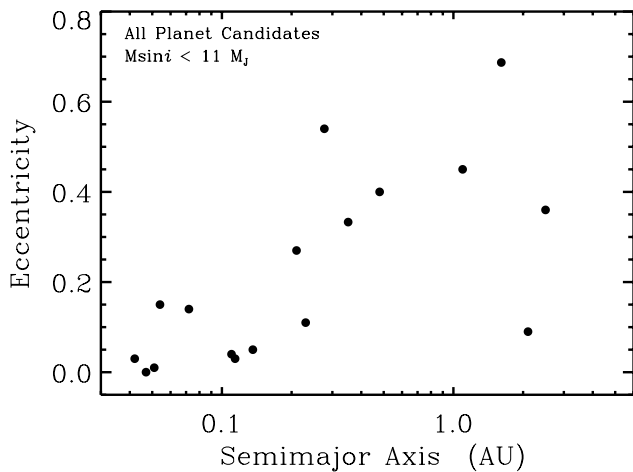

FIG. 7.—Orbital eccentricity vs. semimajor axis for all 17 known extrasolar planet candidates ($M \sin i < 11$ $M_{\rm J}$). All small orbits are nearly circular, but all planet candidates that have $a > 0.2$ AU have eccentricities above that of Jupiter ($e = 0.05$).
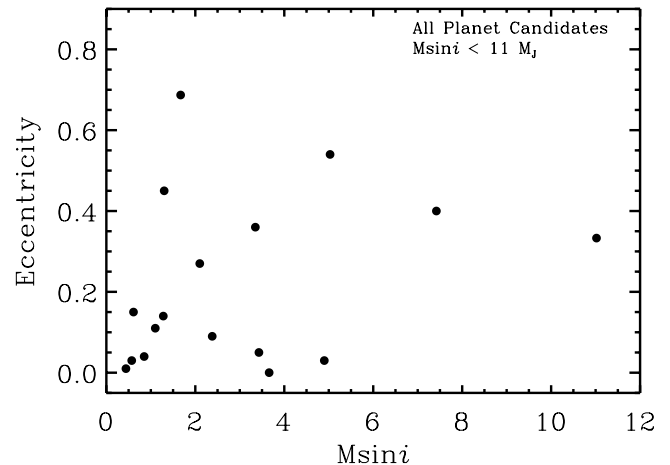

FIG. 8.—Orbital eccentricity vs. $M \sin i$ for all 17 known extrasolar planet candidates that have $M \sin i < 11$ $M_{\rm J}$. No trend with planet mass is apparent.
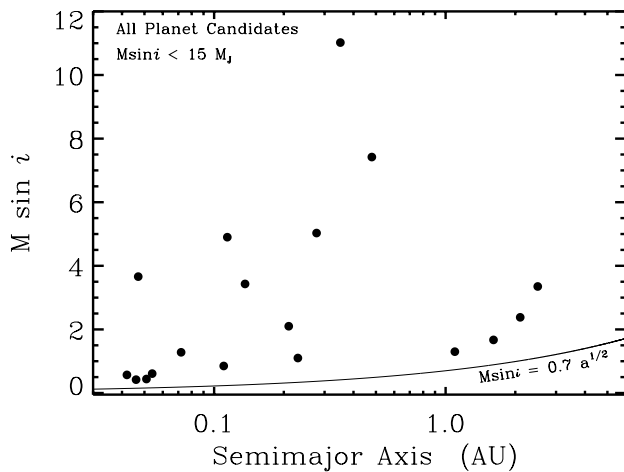
FIG. 9.—$M \sin i$ vs. semimajor axis for all 17 extrasolar planet candidates. The lowest detectable values of $M \sin i$ are shown as the solid curve near the bottom (Cumming et al. 1999). Planet candidates are found at all values of the semimajor axis from 0.05 to 2.5 AU. The mass distribution exhibits a cutoff at $\sim 6\,M_J$, possibly the end of the planetary mass function. HD 114762 appears above that prospective mass limit.

inward, neither that process nor the halting mechanism seems to depend on planet mass.

Figure 10 shows a histogram of $M \sin i$ within the range $0 < 15\,M_J$ for known companions to main-sequence stars. The distribution of $M \sin i$ shows a rapid decline at roughly $4\,M_J$. There are no companions having $M \sin i = 7.5$–11 M_J, and those massive companions would have been easily detected. This absence seems statistically significant relative to the 14 companions having $M \sin i = 0.4$–5 M_J. All selection effects favor detection of the high-mass companions, and thus the apparent drop in the $M \sin i$ histogram from 4 to 7 M_J must be real. This drop implies that the distribution of companion masses, dN/dM, must indeed exhibit a decline at $\sim 5\,M_J$ with increasing mass, within 2.5 AU.

The highest value of $M \sin i$ among planet candidates (Fig. 10) is for HD 114762, which has $M \sin i = 11.02\,M_J$, which is well above the decline at $\sim 5\,M_J$. Its unknown $\sin i$
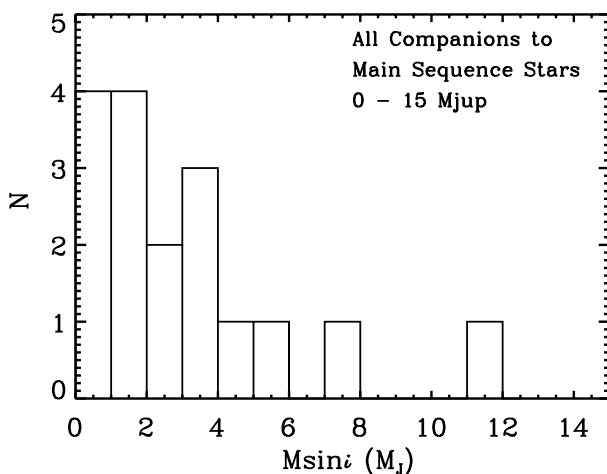
leaves an important question unanswered regarding its true mass and hence any affiliation with "planets." With that possible exception of HD 114762, the planetary mass distribution certainly declines rapidly for masses above 5 M_J.

The origin of the distribution of semimajor axes and eccentricities now presents a puzzle. In the standard paradigm, giant planets form outside 4 AU (Boss 1995; Lissauer 1995). Inward orbital migration (Lin et al. 1996; Trilling et al. 1998) within the gaseous protoplanetary disk has been suggested to explain the small orbits detected to date among extrasolar planets. Such migration makes two predictions that appear testable. First, orbital migration in a viscous, gaseous environment is expected to preserve circular orbits under most circumstances (but see Artymowicz 1993). In contrast, all nine planet candidates orbiting between 0.2 and 2.5 AU have noncircular orbits. Second, the orbital migration timescale is proportional to the orbital period, which leads to rapid orbital decay for successively smaller orbits. In contrast, the observed orbital semimajor axes are spread throughout 0.1–2.5 AU (although not necessarily distributed uniformly). No obvious mechanism is known to halt the migration for these orbits.

Apparently, the orbits with sizes of ~ 1 AU and large eccentricities ($e > 0.1$) require physical processes that are not explicitly included within the context of quiescent migration in a dissipative medium. Scattering of orbits by other planets, companion stars, or passing stars in the young star cluster offer mechanisms for producing eccentric orbits (Rasio & Ford 1996; Lin & Ida 1997; Weidenschilling & Marzari 1996; Laughlin & Adams 1998). However, these mechanisms do not explicitly predict small orbits of $\lesssim 1$ AU, because significant energy must be lost from the original orbits of ~ 5 AU.

One possibility is that planet scattering continues to occur during the final era of the remnant gaseous protoplanetary disk. If the disk remains intact within the inner few AU where the original gas density was highest, the disk can serve as the reservoir into which the planet's orbital energy can be deposited, either by dynamical friction or by tidal interaction between planet and disk. In this scenario, scattered planets would reside in eccentric orbits subjecting them to dissipation during periastron passages. Clearly detailed models are required that include both planet scattering and the dissipative effects of a weak inner gaseous disk to determine the resulting planetary orbits.

In any case, we currently have little information about giant planets that orbit beyond 3 AU. We expect to obtain such information in the coming years as Doppler programs extend their time baseline. Planets beyond 3 AU may well reside in predominantly circular orbits. A population of giant planets that never suffered significant scattering or migration could comprise these Jupiter analogs. The lack of main-sequence stars having reflex Doppler periodicities with amplitudes above 30 m s^{-1} already indicates a paucity of planets having $M > 3\,M_J$ within 5 AU (Cumming et al. 1999). It remains to be determined whether the planet mass function rises rapidly for smaller masses.

FIG. 10.—Histogram of $M \sin i$ in the range 0–15 M_J for all known companions to main-sequence stars. The mass distribution exhibits a steep drop for $M \sin i > 4\,M_J$, indicating a drop in the underlying companion mass function for $M \gtrsim 5\,M_J$.

REFERENCES

Artymowicz, P. 1993, ApJ, 419, 166
Baliunas, S. L., Donahue, R. A., Soon, W., & Henry, G. W. 1998, in ASP Conf. Ser. 154, Tenth Cambridge Workshop on Cool Stars, Stellar Systems, and the Sun, ed. R. A. Donahue & J. A. Bookbinder (San Francisco: ASP), 153
Bertelli, G., Bressan, A., Chiosi, C., Fagotto, F., & Nasi, E. 1994, A&AS, 106, 275
Black, D. C. 1998, ApJ, 490, L171
Boss, A. P. 1995, Science, 267, 360
———. 1997, Science, 276, 1836
———. 1998, ApJ, 503, 923
Burrows, A., Hubbard, B., Lunine, J., Marley, M., & Saumon, D. 1998, in Protostars and Planets IV, ed. V. Manning, A. Boss, & S. Russell (Tucson: Univ. Arizona Press)
Butler, R. P., & Marcy, G. W. 1996, ApJ, 464, 153
Butler, R. P., Marcy, G. W., Vogt, S. S., & Apps, K. 1998, PASP, 110, 1389
Butler, R. P., Marcy, G. W., Williams, E., Hauser, H., & Shirts, P. 1997, ApJ, 474, L115
Butler, R. P., Marcy, G. W., Williams, E., McCarthy, C., Dosanjh, P., & Vogt, S. S. 1996, PASP, 108, 500
Carney, B. W., Latham, D. W., Laird, J. B., & Aguilar, L. A. 1994, AJ, 107, 2240
Cochran, W. D., Hatzes, A. P., Butler, R. P., & Marcy, G. M. 1997, ApJ, 483, 457
Cochran, W. D., Hatzes, A. P., Hancock, T. J. 1991, ApJ, 380, L35
Cumming, A., Marcy, G. W., & Butler, R. P. 1999, ApJ, submitted
de la Fuente Marcos, C., & de la Fuente Marcos, R. 1997, A&A 326, L21
Delfosse, X., Forveille, T., Mayor, M., Perrier, C., Naif, D., & Queloz, D. 1998, A&A, 338, L67
Duquennoy, A., & Mayor, M. 1991, A&A, 248, 485
Favata, F., Miccla, G., & Sciortino, S. 1997, A&A, 323, 809
Fischer, D. A., Marcy, G. W., Butler, R. P., Vogt, S. S., & Apps, K. 1999, PASP, 111, 50
Ford, E. B., Rasio, F. A., & Sills, A. 1998, ApJ, submitted
Fuhrmann, K. 1998, A&A, 338, 161
Gilmore, D. K., Rank, D. M., & Temi, P. 1994, in Instrumentation in Astronomy VIII, ed. D. L. Crawford & E. R. Craine (Proc. SPIE, Vol. 2198), 744
Goldreich, P., & Tremaine, S. 1980, ApJ, 241, 425
Gonzalez, G. 1998, A&A, 334, 221
Gonzalez, G., Wallerstein, G., & Saar, S. 1998, ApJ, 511, L111
Gray, D. F. 1992, in The Observation and Analysis of Stellar Spectra (2d ed.; Cambridge: Cambridge Univ. Press), 431
Hale, A. 1995, PASP, 107,22
Heintz, W. 1994, AJ, 108, 2338
Holman, M., Touma, J., & Tremaine, S. 1997, Nature, 386, 264
Kirkpatrick, J. D., & McCarthy, D. W., Jr. 1994, AJ, 107, 333
Latham, D. W., Mazeh, T., Stefanik, R. P., Mayor, M., & Burki, G. 1989, Nature, 339, 38
Laughlin, G., & Adams, F. C. 1998, ApJ, 508, L171
Levison, H. A., Lissauer, J. J., & Duncan, M. J. 1998, AJ, 116, 1998
Lin, D. N. C. 1986, in The Solar System: Observations and Interpretation, ed. M. G. Kivelson (Englewood Cliffs: Prentice-Hall), 68

Lin, D. N. C., Bodenheimer, P., & Richardson, D. C. 1996, Nature, 380, 606
Lin D. N. C., & Ida, S. 1997, ApJ, 477, 781
Lin, D. N. C., Papaloizou, J. C. B., Bryden, G., Ida, S., & Terquem, C. 1998, in Protostars and Planets IV, ed. V. Manning, A. Boss, & S. Russell (Tucson: Univ. Arizona Press)
Lissauer, J. J. 1995, Icarus, 114, 217
Marcy, G. W., & Butler, R. P. 1996, ApJ, 464, L147
———. 1998, ARA&A, 36, 57
Marcy, G. W., Butler, R. P., Vogt, S. S., Fischer, D., & Lissauer, J. J. 1998a, ApJ, 505, L147
Marcy, G. W., Butler, R. P., Williams, E., Bildsten, L., Graham, J. R., Ghez, A., & Jernigan, G. 1997, ApJ, 481, 926
Max, C. E., et al. 1997, Science, 277, 1649
Mayor, M., Beuzit, J. L., Mariotti, J. M., Naef, D., Perrier, C., Queloz, D., & Sivan, J. P. 1999, in ASP Conf. Ser., IAU Colloq. 170, Precise Stellar Radial Velocities, ed. J. B. Hearnshaw & C. D. Scarfe (San Francisco: ASP)
Mayor, M., & Queloz, D. 1995, Nature, 378, 355
Mayor, M., Queloz, D., Udry, S., & Halbwachs, J.-L. 1997. in Proc. Fifth Int. Conf. on Bioastronomy (Capri), IAU Colloq. 161, Astronomical and Biochemical Origins and the Search for Life in the Universe, ed. C. Cosmovici, S. Bowyer, & D. Werthimer (Bologna: Editrice Compositori), 313
Mazeh, T., Latham, D. W., & Stefanik, R. P. 1996, ApJ, 466, 415
Mazeh, T., Krymolowsky, Y., & Rosenfeld, G. 1997, ApJ, 477, L103
McLean, I. S., et al. 1994, in Instrumentation in Astronomy VIII, ed. D. L. Crawford & E. R. Craine (Proc. SPIE, Vol. 2198), 457
Meyer, C., Rabbia, Y., Froeschle, M., Helmer, G., & Amieux, G. 1995, A&AS, 110, 107
Ng, Y. K., & Bertelli, G. 1998, A&A, 329, 943
Noyes, R. W., Hartmann, L., Baliunas, S. L., Duncan, D. K., & Vaughan, A. H. 1984, ApJ, 279, 763
Noyes, R. W., Jha, S., Korzennik, S. G., Krockenberger, M., Nisenson, P., Brown, T. M., Kennelly, E. J., & Horner, S. D. 1997, ApJ, 483, L111
Perryman, M. A. C., et al. 1997, A&A, 323, L49. (The *Hipparcos* Catalog)
Queloz, D., et al. 1999, preprint
Rasio, F. A., & Ford, E. B. 1996, Science, 274, 954
Rasio, F. A., Tout, C. A., Lubow, S. H., & Livio, M. 1996, ApJ, 470, 1187
Saar, S. H., Butler, R. P., & Marcy, G. W. 1998, ApJ, 403, L153
Shirts, P., & Marcy, G. W. 1998, preprint
Szokoly, G. P., Subbarao, M. U., Connally, A. J., & Mobasher, B. 1998, ApJ, 492, 452
Terquem, C., Papaloizou, J. C. B., Nelson, R. P., & Lin, D. N. C. 1998, ApJ, 502, 788
Trilling, D., Benz, W., Guillot, T., Lunine, J. I., Hubbard, W. B., & Burrows, A. 1998, ApJ, 500, 428
Vogt, S. S., et al. 1994, Proc. Soc. Photo-Opt. Instr. Eng., 2198, 362
Wainscoat, R. J., & Cowie, L. L. 1992, AJ, 103, 332
Ward, W. R. 1997, ApJ, 482, L211
Weidenschilling, S. J., & Marzari, F. 1996, Nature, 384, 619