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TEN LOW-MASS COMPANIONS FROM THE KECK PRECISION VELOCITY SURVEY[1]

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ABSTRACT

Ten new companions have emerged from the Keck precision Doppler velocity survey, with minimum ($M \sin i$) masses ranging from 0.8 M_{JUP} to 0.34 $M_{\odot}$. Five of these are planet candidates with $M \sin i < 12$ M_{JUP}, two are brown dwarf candidates with $M \sin i \sim 30$ M_{JUP}, and three are low-mass stellar companions. *Hipparcos* astrometry reveals the orbital inclinations and masses for three of the (more massive) companions, and it provides upper limits to the masses for the rest. A new class of extrasolar planet is emerging, characterized by nearly circular orbits and orbital radii greater than 1 AU. The planet HD 4208b appears to be a member of this new class. The mass distribution of extrasolar planets continues to exhibit a rapid rise from 10 M_{JUP} toward the lowest detectable masses near 1 M_{SAT}.

Subject headings: planetary systems — techniques: radial velocities

1. INTRODUCTION

All ~70 known extrasolar planets have been discovered by the precision Doppler technique over the last 6 yr (Marcy, Cochran, & Mayor 2000). These include four published multiple planet systems (Butler et al. 1999; Marcy et al. 2001a, 2001b; Fischer et al. 2002) and one transiting planet (Henry et al. 2000; Charbonneau et al. 2000). The mass function of giant planets is emerging (Marcy & Butler 2000; Jorissen, Mayor, & Udry 2001), and their occurrence correlates with metallicity (Butler et al. 2000; Santos, Israelian, & Mayor 2001; Gonzalez et al. 2001).

Precision Doppler surveys are biased toward finding massive companions in small orbits, as these two characteristics enhance the Doppler amplitude and allow many orbits to be observed quickly. At the current epoch, all of the confirmed extrasolar planets orbit within 4 AU of their host stars. This is primarily due to the time baseline of the active surveys, but also because the Doppler amplitude of an orbiting companion decreases with increasing orbital radii. A 1 M_{JUP} planet in a 0.05 AU orbit induces a maximum Doppler amplitude of 127 m s^{-1} on its star, but at 3 AU this is reduced to 16 m s^{-1}. While Doppler surveys with precision of 10–20 m s^{-1} can easily detect 1 M_{JUP} planets at 0.05 AU, they are hard pressed to detect similar planets at 3 AU.

Because of their larger mass, brown dwarf companions are much easier to detect than planets. A 20 M_{JUP} brown dwarf companion at 0.05 AU induces a maximum Doppler amplitude of 2500 m s^{-1}, a signal that has been in the detectable range for most of the last century. Yet no companion having mass between 10 and 80 M_{JUP} has ever been found orbiting within 0.1 AU of a star.

This paper reports the discovery of five planet candidates, two brown dwarf candidates and three low-mass stellar companions, from the Keck precision velocity survey. *Hipparcos* astrometric data is used to solve for, or set limits on, the inclination angle and maximum mass of these companions. Section 2 describes the Keck precision velocity program. The stellar properties and Keplerian orbital fits for the 10 new low-mass companions are presented in § 3. A discussion follows, including an updated substellar companion mass function.

2. THE KECK PLANET SEARCH PROGRAM

The Keck Planet Search Program makes use of the HIRES echelle spectrometer (Vogt et al. 1994) on the Keck I Telescope. The resolution of these spectra is $R \sim 80{,}000$, spanning wavelengths from 3900–6200 Å. Wavelength calibration is carried out by means of an iodine absorption cell (Marcy & Butler 1992) that superimposes a reference iodine spectrum directly on the stellar spectra (Butler et al. 1996; Valenti et al. 1995). This system currently achieves photon-limited measurement precision of 3 m s^{-1} (Vogt et al. 2000). Efforts are under way to improve the single-shot precision of this system to the 2 m s^{-1} level.

Observations from the Lick Observatory precision velocity program are combined with the Keck observations for two of the stars presented here. Lick observations are made with either the 3 m Shane Telescope or the 0.6 m Coudé Auxilliary Telescope (CAT), both of which feed the "Hamilton" echelle spectrometer (Vogt 1987). Wavelength calibration at Lick is also accomplished with an iodine absorption cell.

The Keck Planet Survey began in 1996 July and is currently surveying about 650 main-sequence dwarfs ranging in spectral type from late-F0 to mid-M. The spectrum of stars earlier than F7 do not contain enough Doppler information to achieve precision of 3 m s^{-1}, while stars later than M5 are too faint even for Keck.

[1] Based on observations obtained at Lick Observatory, which is operated by the University of California, and on observations obtained at the W. M. Keck Observatory, which is operated jointly by the University of California and the California Institute of Technology. Keck time has been granted by both NASA and the University of California.

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Nearly all suitable northern hemisphere G dwarfs within 50 pc, and K dwarfs within 30 pc, are included in either the Keck survey or the Lick 3 m survey (Fischer et al. 2002). Evolved stars have been removed from the observing list based on *Hipparcos* distances (Perryman et al. 1997; ESA 1997). The list has been further sieved to remove chromospherically active stars as these stars show velocity "jitter" of 10–50 m s^{-1}, related to rapid rotation, spots, and magnetic fields (Saar, Butler, & Marcy 1998). The Ca II H and K lines are used as a chromospheric diagnostic (Noyes et al. 1984). We measure the strength of the H and K line reversal directly from our Keck HIRES spectra. Keck H and K measurements are placed on the Mount Wilson "S" scale by calibration with previously published results (Duncan et al. 1991; Baliunas et al. 1995; Henry et al. 1996).

Stars with known stellar companions within 2″ are removed from the observing list as it is operationally difficult to get an uncontaminated spectrum of a star with a nearby companion. Known spectroscopic binaries are also removed. Otherwise there is no bias against observing multiple stars. The Keck target stars also contain no bias against brown dwarf companions.

3. NEW COMPANIONS FROM THE KECK SURVEY

Five planet-mass candidates, two brown dwarf candidates, and three stellar companions have emerged from the Keck survey. The stellar properties of the 10 host stars are given in Table 1. The first two columns provide the HD catalog number and the *Hipparcos* catalog number, respectively. Spectral types are from a calibration of $B-V$ and *Hipparcos*-derived absolute magnitudes. The stellar masses are estimated by interpolation of evolutionary tracks (Fuhrmann 1998; Fuhrmann et al. 1997). The [Fe/H] values are drawn from a variety of sources (given in § 3), including spectral synthesis matched directly to our Keck HIRES spectra.

The R'_{HK} values, a chromospheric activity indicator (Noyes et al. 1984), are measured from the Ca II H and K line cores in our Keck spectra. The level of Doppler jitter is correlated with R'_{HK} (Saar et al. 1998). Slowly rotating, chromospherically inactive stars are intrinsically stable to at least the 3 m s^{-1} level, while the Doppler jitter for young rapidly rotating stars ranges from 10 to 50 m s^{-1}.

Figure 1 shows the H line for the seven G dwarfs reported in this paper. The Sun is shown for comparison. Of these stars, HD 33636 is the most active, with $R'_{HK} = -4.81$, indicating a rotation period of 13.6 days, and expected Doppler jitter of ~7 m s^{-1}. The other six G dwarfs have R'_{HK} values similar or lower than the Sun, indicating rotation periods of 25 days or longer and intrinsic Doppler jitter of 3 m s^{-1} or less.

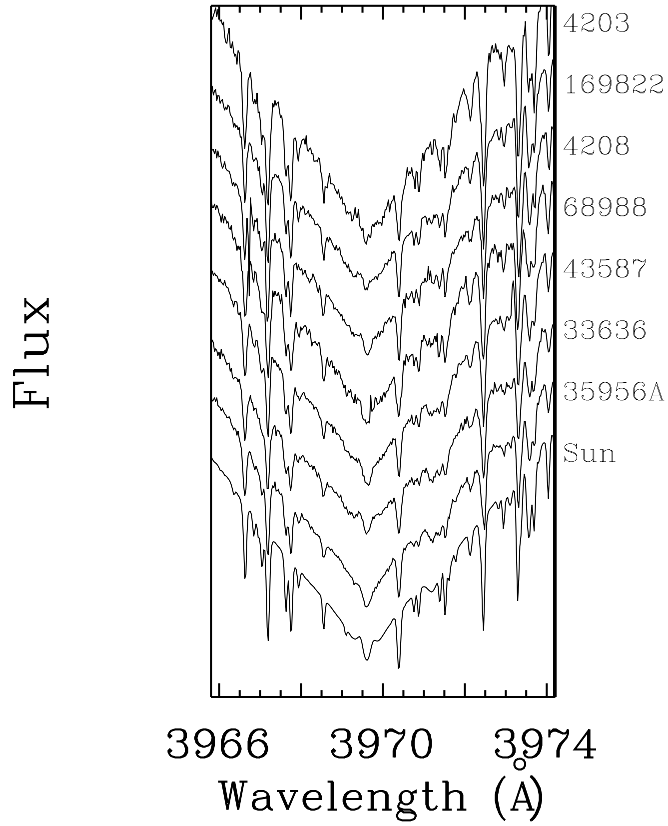

FIG. 1.—Ca II H-line cores for seven G dwarfs in ascending order of $B-V$. The HD catalog number of each star is shown along the right edge. The Sun is shown for comparison. With the exception of HD 33636, the R'_{HK} values derived from the H and K lines are similar to the Sun, indicating rotation periods of 25 days or longer and photospheric Doppler jitter of 3 m s^{-1} or less. For HD 33636 the derived rotation period is 13 days, and the expected Doppler jitter is ~7 m s^{-1}.

The H lines for the three K dwarfs reported in this paper are shown in Figure 2. All three of these stars are slow rotators. The rapid rotator HD 128311 (K0 V) is shown at the bottom for comparison. While even the slowly rotating K dwarfs show a slight line reversal in the core of the H line,

TABLE 1
STELLAR PROPERTIES

Star (HD)	Star (*Hipparcos*)	Spectral Type	M_{Star} ($M_\odot$)	V (mag)	$B-V$	$\log(R'_{HK})$	[Fe/H]	d (pc)
4203	3502	G5 V	1.06	8.70	0.771	−5.13	+0.22	77.8
4208	3479	G5 V	0.93	7.78	0.664	−4.93	−0.24	32.7
33636	24205	G0 V	0.99	7.00	0.588	−4.81	−0.13	28.7
35956A	25662	G0 V	1.00	6.71	0.582	−4.92	−0.21	28.9
43587	29860	G2 V	1.02	5.70	0.610	−4.97	−0.03	19.3
64468	38657	K2 V	0.78	7.76	0.950	−5.03	+0.00	20.0
68988	40687	G2 V	1.20	8.20	0.652	−5.07	+0.24	58.8
114783	64457	K2 V	0.92	7.56	0.930	−4.96	+0.33	20.4
169822	90355	G5 V	0.91	7.83	0.699	−4.97	−0.10	32.0
184860	96471	K2 V	0.80	8.38	1.011	−5.00	−0.13	30.3

TABLE 2
ORBITAL PARAMETERS

Star (HD)	Period (day)	K (m s^{-1})	e	ω (deg)	T_0 (JD−2,450,000)	$M \sin i$ (M_{JUP})	a (AU)	N (obs)	rms (m s^{-1})
4208	829 (36)	18.3 (2)	0.04 (0.12)	301 (84)	1774 (197)	0.80	1.7	35	5.21
114783	501 (14)	27 (2)	0.10 (0.08)	97 (40)	1840 (59)	1.0	1.2	37	4.08
4203	406 (30)	51 (5)	0.53 (0.10)	271 (50)	1882 (5)	1.6	1.1	14	3.97
68988[a]	6.276 (0.002)	187 (6)	0.14 (0.03)	186 (8)	1913.0 (0.2)	1.9	0.071	19	4.36
33636	1553 (800)	148 (15)	0.39 (0.09)	335 (8)	1196 (21)	7.7	2.6	32	8.69
169822	293.1 (0.5)	991 (87)	0.48 (0.03)	173 (1)	1919 (1)	27.2	0.84	22	5.70
184860	693 (1)	1123 (490)	0.67 (0.06)	132 (6)	1906 (9)	32.0	1.4	21	7.82
64468	161.2 (0.1)	5730 (7)	0.262 (0.002)	328.1 (0.2)	457.0 (0.2)	139	0.56	13	16.2
35956A	1427 (1)	3796 (4)	0.616 (0.002)	326.5 (0.2)	796.3 (0.3)	184	2.6	14	4.86
43587	12325 (500)	4323 (9)	0.80 (0.01)	75 (1)	0832 (1)	358	11.6	14	8.83

[a] Additional velocity slope is -26.4 ± 5.5 m s^{-1} yr^{-1}.

they are clearly distinguished from rapid rotators like HD 128311.

The orbital parameters of the 10 low-mass companions are listed in Table 2, while the individual Keck Doppler velocity measurements are listed in Tables 3–12. The host stars are discussed below.

The *Hipparcos* Intermediate Astrometric Data (ESA 1997) have been analyzed with the orbits derived from the precision velocity data, using the technique outlined by Pourbaix & Arenou (2001) to constrain, or in three cases to solve for, the orbital inclination.

3.1. *HD 4208*

Based on Stromgren photometry, Eggen (1998) finds the metallicity of HD 4208 (G5 V) to be [Fe/H] = −0.21, in good agreement with our estimate of −0.24 from spectral synthesis matched to our Keck HIRES spectra. The star is photometrically stable at the level of *Hipparcos* measurement error, ∼0.01 mag. Based on the $B-V$ color, the *Hipparcos*-derived absolute magnitude, and the metallicity, we estimate the mass of the primary to be 0.93 $M_\odot$. This star is slowly rotating and chromospherically inactive, as indicated by the R'_{HK} value.

Thirty-five Keck Doppler velocity observations have been made of HD 4208, spanning 4.9 yr, as shown in Figure 3 and listed in Table 3. These observations cover two full orbital periods. The semiamplitude (K) of the Keplerian orbital fit is 18 m s^{-1}, only the third extrasolar planet yet published with an amplitude less than 20 m s^{-1} (Marcy et al. 2000; Fischer et al. 2002). The rms of the velocity residuals to the Keplerian fit is 5.21 m s^{-1}, slightly worse than the typical internal measurement error of 4.2 m s^{-1}. The reduced

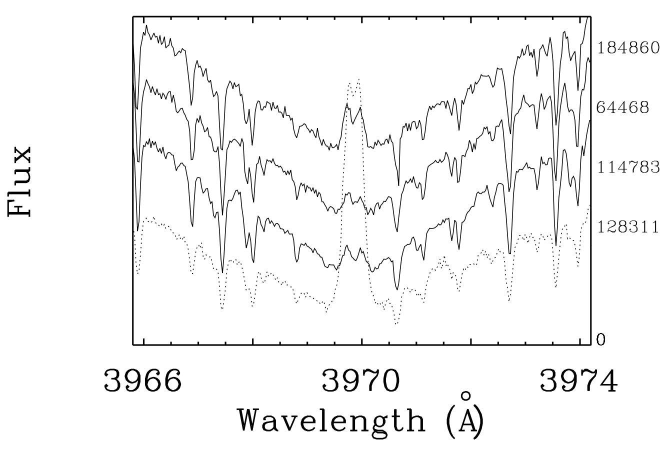

FIG. 2.—Ca II H line cores for three K dwarfs in ascending order of $B-V$. The HD catalog number of each star is shown along the right edge. The active K0 dwarf HD 128311 is shown for comparison. Even slowly rotating K dwarfs show mild line core reversal. Dramatic line core reversal is seen in the rapidly rotating, chromospherically active, K0 V star HD 128311.

TABLE 3
VELOCITIES FOR HD 4208

JD (−2,450,000)	Radial Velocity (m s^{-1})	Error (m s^{-1})
366.9657	8.5	3.5
715.0257	−17.4	3.6
786.7220	−19.6	5.6
1010.1052	13.3	3.1
1014.0991	17.6	3.9
1043.0497	13.4	3.7
1044.0338	9.4	3.2
1068.9389	9.0	3.5
1172.7428	9.0	4.2
1368.0796	−13.4	3.4
1412.0645	−18.6	3.8
1438.9302	−26.6	4.0
1543.7389	−13.5	4.7
1550.7261	−10.8	4.2
1551.7132	−24.1	4.5
1552.7113	−11.8	4.2
1580.7057	−13.7	4.1
1581.7067	−29.2	4.2
1582.7244	−24.8	4.4
1583.7066	−20.8	4.2
1585.7075	−22.7	4.8
1755.0330	7.7	4.1
1756.0257	4.2	3.9
1757.0736	5.8	3.6
1793.9300	4.9	4.1
1882.7286	18.0	4.7
1883.7727	24.7	4.9
1899.7776	21.6	4.5
1900.7493	17.0	4.6
2095.1118	−4.6	4.5
2129.0961	4.2	5.0
2133.0468	−6.6	4.2
2134.0092	−4.5	4.5
2161.9285	−14.4	4.3
2187.9813	−8.7	4.7

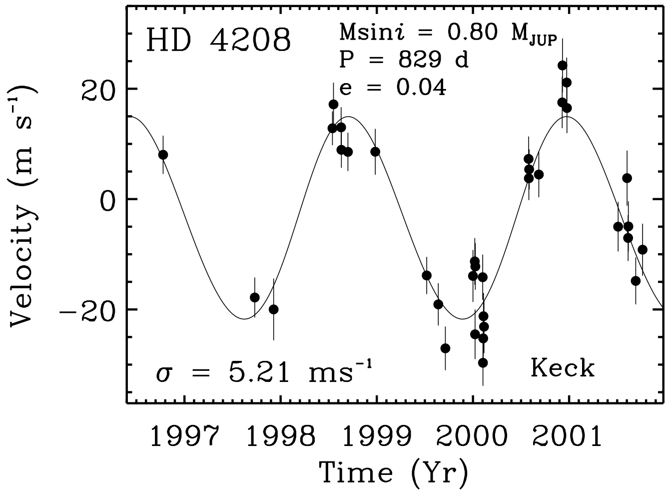

FIG. 3.—Doppler velocities for HD 4208 (G5 V). The solid line is a Keplerian orbital fit with a period of 829 days, a semiamplitude of 18.3 m s^{-1}, and an eccentricity of 0.04, yielding a minimum ($M \sin i$) of 0.80 M_{JUP} for the companion. The rms of the Keplerian fit is 5.21 m s^{-1}.

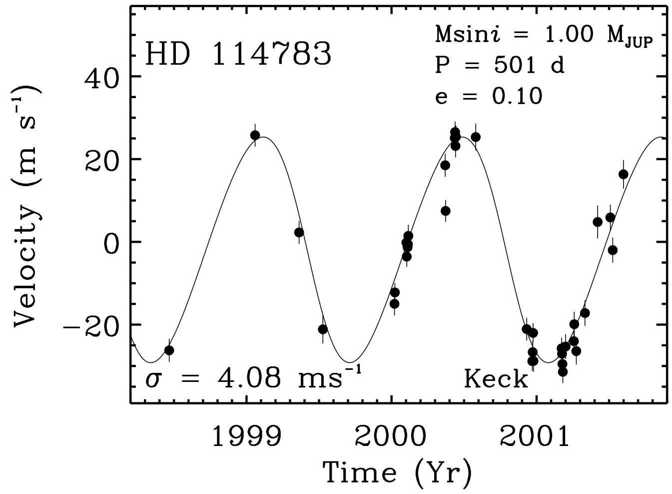

FIG. 4.—Doppler velocities for HD 114783 (K2 V). The solid line is a Keplerian orbital fit with a period of 501 days, a semiamplitude of 27 m s^{-1}, and an eccentricity of 0.10, yielding a minimum ($M \sin i$) of 1.0 M_{JUP} for the companion. The rms of the Keplerian fit is 4.08 m s^{-1}.

χ^2_ν of the Keplerian fit is 1.33. Within measurement error the orbit is circular, thus joining 47 UMa (Butler & Marcy 1996; Fischer et al. 2002) and HD 27442 (Butler et al. 2001) as the only published planets in circular orbits beyond 0.2 AU.

With a semimajor axis $a = 1.67$ AU, the maximum angular separation between planet and star for HD 4208 is 53 mas. The orbit is similar to that of Mars in the solar system. The companion is not detected in the *Hipparcos* astrometric data, thus constraining the orbital inclination to be larger than 1°.4.

Unlike most of the extrasolar planet candidates, HD 4208 is modestly metal-poor relative to the Sun.

3.2. *HD 114783*

We estimate the metallicity of HD 114783 (K2 V) to be [Fe/H] = +0.33 based on *uvby* photometry. Strassmeier et al. (2000) report that the star is chromospherically inactive, in agreement with our Keck-derived value of $\log(R'_{HK}) = -4.96$. HD 114783 is photometrically stable at the level of *Hipparcos* measurement error, ~0.01 mag.

A total of 37 Keck observations have been obtained between 1998 June and 2001 August, as shown in Figure 4 and Table 4. These observations cover slightly more than two full orbital periods of 501 days. The semiamplitude (K) of the Keplerian orbital fit is 27 m s^{-1}, with an eccentricity of 0.10. The rms to the Keplerian fit is 4.08 m s^{-1}, with a reduced χ^2_ν of 1.48. There is 5 σ discrepant point near 2000.35. A periodogram of the Keplerian residuals reveal no other periodicities with a false alarm probability under 5%.

At a distance of 20.4 pc, HD 114783 is an attractive astrometric target. With a semimajor axis of 1.2 AU, the maximum separation between the planet and the host star is 65 mas. The astrometric amplitude of the star due to the planet is 61 mas/sin i, which should be easily within the capabilities of both ground and space-based interferometry within a few years. The orbital inclination is constrained to be greater than 1°.26 by the *Hipparcos* astrometric data.

TABLE 4
VELOCITIES FOR HD 114783

JD (−2,450,000)	Radial Velocity (m s^{-1})	Error (m s^{-1})
983.7917	−22.9	2.8
1200.0942	29.1	2.8
1310.9285	5.6	2.8
1370.8121	−17.8	3.4
1551.1677	−11.6	2.8
1552.1549	−8.9	2.3
1581.1187	3.2	2.5
1582.0853	−0.2	2.5
1583.0644	2.9	2.8
1584.1043	2.1	2.5
1585.0266	2.8	1.7
1586.0245	4.8	2.7
1678.8802	21.9	2.8
1679.8972	10.8	2.6
1702.9153	28.5	2.6
1703.8098	29.9	2.5
1704.8819	26.5	2.8
1705.8815	28.8	2.7
1755.7586	28.7	3.3
1884.1633	−17.7	2.7
1898.1701	−25.5	2.4
1899.1755	−23.3	2.7
1900.1717	−18.6	2.3
1901.1800	−25.4	2.6
1972.1100	−22.4	2.5
1973.1352	−23.7	2.9
1974.1353	−26.1	2.8
1975.1449	−28.0	2.7
1982.1079	−21.9	3.0
2002.9808	−20.6	3.0
2003.8969	−16.5	3.0
2009.0445	−23.0	3.2
2030.9115	−13.8	3.1
2062.8241	8.2	4.0
2094.7722	9.3	3.1
2100.7892	1.4	3.0
2127.7826	19.7	3.4

TABLE 5
Velocities for HD 4203

JD (−2,450,000)	Radial Velocity (m s^{-1})	Error (m s^{-1})
757.1224	−26.2	3.6
792.9725	−32.4	3.8
882.8351	5.3	3.4
883.8483	11.6	3.9
900.8378	45.6	3.4
1063.1258	2.8	4.0
1065.1288	10.6	4.6
1096.1144	−7.7	3.7
1097.0676	−3.3	4.6
1128.1161	−5.0	3.8
1133.0558	−8.6	3.6
1133.9261	−19.5	3.6
1162.9185	−26.6	3.8
1187.9624	−32.6	3.6

3.3. *HD 4203*

HD 4203 (G5 V) is photometrically stable at the level of *Hipparcos* measurement error, and chromospherically quiet, with a measured $R'_{\rm HK}$ value of −5.13. At 77.8 pc, this is one of the most distant stars on this project. This star was added to the Keck project in 2000 July based on the suggestion of Laughlin (2000), who noted the star is metal-rich ([Fe/H] = +0.22). From interpolation of isochrones, Prieto & Lambert (1999) estimate the mass of the HD 4203 to be 0.98 $M_\odot$. This estimate does not take into account the extreme metallicity of the star. Based on its similarity to 51 Peg (Marcy et al. 1997), we estimate the mass of HD 4203 to be 1.06 $M_\odot$.

A total of 14 Keck observations have been obtained between 2000 July and 2001 October. These observations are listed in Table 5 and graphically displayed in Figure 5. The best-fit Keplerian orbit to these data has a period of 406 days, a semiamplitude (K) of 51 m s^{-1}, and an eccentricity of 0.53. The minimum ($M \sin i$) mass of the companion is 1.6 $M_{\rm JUP}$. The rms to the Keplerian fit is 3.97 m s^{-1}, consistent with measurement uncertainty.

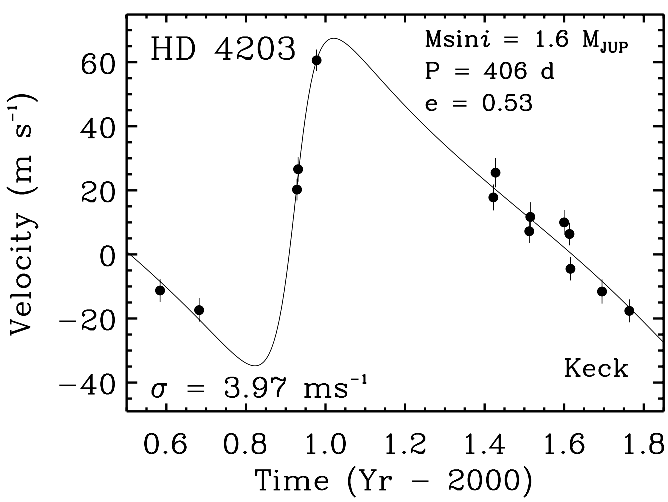

Fig. 5.—Doppler velocities for HD 4203 (G5 V). The solid line is a Keplerian orbital fit with a period of 406 days, a semiamplitude of 51 m s^{-1}, and an eccentricity of 0.53, yielding $M \sin i = 1.6\ M_{\rm JUP}$ for the companion. The rms of the Keplerian fit is 3.97 m s^{-1}.

As only one orbit has been observed, the orbital period and amplitude remain somewhat uncertain. Only a few observations have been obtained near the velocity maximum. The next passage through maximum velocity will occur in spring 2002. The orbital inclination is constrained to be greater than 0°.44 by *Hipparcos* astrometry.

3.4. *HD 68988*

Based on Stromgren photometry, Laughlin (2000) finds the metallicity of HD 68988 (G2 V) to be [Fe/H] = +0.36, consistent with the estimate of Feltzing & Gustafsson (1998) but somewhat higher than the +0.24 derived from matching spectral synthesis to our Keck HIRES spectra. HD 68988 is photometrically stable at the level of *Hipparcos* measurement error, ~0.01 mag. We estimate the mass of the primary to be 1.2 $M_\odot$. This star is slowly rotating and chromospherically inactive, as indicated by our measurement of the Ca II line cores, $\log(R'_{\rm HK}) = -5.07$. The age of the star is estimated to be approximately 6 Gyr based on the chromospheric diagnostic.

Thirteen Keck Doppler observations and six Lick observations have been made of HD 68988 spanning 1.4 yr, as shown in Figure 6 and listed in Table 6. The orbital period is 6.276 days, the semiamplitude (K) is 187 m s^{-1}, and the eccentricity is $e = 0.14$. The rms of the velocity measurements to the best-fit Keplerian is 4.36 m s^{-1}, yielding a reduced χ^2_ν of 1.05. The minimum mass of this companion is 1.9 $M_{\rm JUP}$. In addition, there is a linear trend of −0.072 m s^{-1} day^{-1}, indicating a second companion with an orbital period much greater than 4 yr.

All of the published planets with orbital periods of less than 1 week[7] have circular orbits. It is therefore surprising that the orbit of HD 68988, with an eccentricity of 0.14

[7] HD 46375 (Marcy et al. 2000), HD 179949 (Tinney et al. 2001), HD 187123 (Butler et al. 1998), τ Boo (Butler et al. 1997), BD −10°3166 (Butler et al. 2000), HD 75289 (Udry et al. 2000; Butler et al. 2001), HD 209458 (Henry et al. 2000), 51 Peg (Mayor & Queloz 1995; Marcy et al. 1997), and υ And b (Butler et al. 1997, 1999).

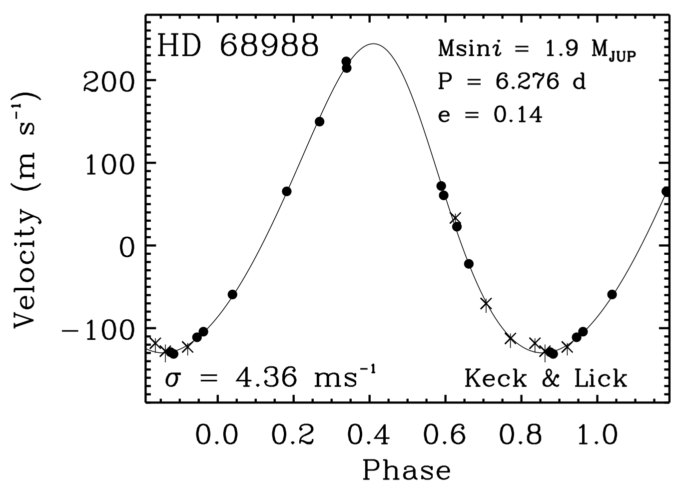

Fig. 6.—Phased Doppler velocities for HD 68988 (G2 V). The filled dots are the Keck 10 m observations, while the Lick 3 m observations are indicated by the crosses. The solid line is the best-fit Keplerian orbit to the combined data sets. The period is 6.276 days, the semiamplitude is 187 m s^{-1}, and the eccentricity is 0.14, yielding ($M \sin i$) = 1.9 $M_{\rm JUP}$ for the companion. The rms of the Keplerian fit is 4.36 m s^{-1}. A linear trend of −26.4 m s^{-1} yr^{-1} has been removed. This linear trend suggests a second companion with an orbital period much longer than 4 yr.

TABLE 6
Velocities for HD 68988

JD (−2,450,000)	Radial Velocity (m s^{-1})	Error (m s^{-1})	Survey
552.0229.........	−102.4	4.0	Keck
582.8602.........	−129.4	4.4	Keck
899.1245.........	126.6	3.5	Keck
901.1357.........	48.6	3.5	Keck
913.9219.........	6.2	8.0	Lick
914.8319.........	−139.6	8.8	Lick
915.7716.........	−150.0	7.5	Lick
927.7894.........	−146.3	8.8	Lick
945.8093.........	−99.5	8.5	Lick
946.7834.........	−157.2	10.8	Lick
972.0226.........	−159.7	3.9	Keck
972.9965.........	−87.9	4.3	Keck
973.8936.........	36.8	3.2	Keck
974.8776.........	193.9	3.5	Keck
982.9828.........	−6.5	3.8	Keck
1003.7900.......	−141.8	3.9	Keck
1007.8684.......	29.5	4.5	Keck
1062.7491.......	179.6	3.8	Keck
1064.7680.......	−57.4	3.8	Keck

($\pm$0.03) is markedly noncircular. This system is similar to the companion orbiting HD 217107 (Fischer et al. 1999) with its period of 7.12 days, $M \sin i = 1.25\ M_{\rm JUP}$, and eccentricity of 0.134. HD 68988 and HD 217107 are both markedly metal-rich.

The timescale for orbital circularization due to tidal dissipation within a planet of mass m and radius R_p, orbiting a star of mass M with an orbital period of $P_{\rm orb}$, is given by Marcy et al. (1997):

$$t_{\rm circ} \approx \frac{4Q}{63} \frac{m}{M} \frac{P_{\rm orb}}{2\pi} \left(\frac{a}{R_p}\right)^5 . \quad (1)$$

Assuming a radius 1.3 $R_{\rm JUP}$ for the companion to HD 68988, this reduces to $5000Q/\sin i$ yr, where Q is the tidal quality factor (Goldreich & Soter 1966). For Q values less than $\sim 10^6/\sin i$, the orbit of HD 68988 should have circularized. The Q-value for Jupiter is inferred to be, $10^5 < Q < 10^6$ (Goldreich & Soter 1966; Yoder 1979; Yoder & Peale 1981). The Q-value for solid planets is in the range of 100–1000 (Marcy et al. 1997). The planet orbiting HD 68988 is thus likely to be a gas giant. Three possibilities exist to explain the observed orbital eccentricity: the planet has a higher Q-value than is inferred for Jupiter; it has only recently arrived in its current orbit; or it is being perturbed by another body.

3.5. *HD 33636*

Spectral synthesis matched to our Keck spectra yields [Fe/H] $= -0.13$ for HD 33636 (G0 V). The star is photometrically stable at the level of *Hipparcos* measurement error, and mildly active with $\log(R'_{\rm HK}) = -4.81$. The Doppler velocity jitter associated with this level of activity for a G0 V star is $\sim$7 m s^{-1} (Saar et al. 1998). The *Hipparcos*-derived distance of HD 33636 is 28.7 pc.

A total of 21 observations of HD 33636 have been made at Keck between 1998 January and 2001 October. A further 11 observations were made at Lick with the 3 m Shane Telescope and the 0.6 m CAT between 1998 January and 2001 February. These observations are listed in Table 7 and graphically displayed in Figure 7. The best-fit Keplerian orbit to the combined Keck and Lick data sets has a period of 1553 days, a semiamplitude (K) of 148 m s^{-1}, and an eccentricity of 0.39. The minimum ($M \sin i$) mass of the companion is 7.7 $M_{\rm JUP}$. The rms to the Keplerian fit is 8.69 m s^{-1}, consistent with the expected Doppler jitter due to activity.

TABLE 7
Velocities for HD 33636

JD (−2,450,000)	Radial Velocity (m s^{-1})	Error (m s^{-1})	Survey
831.7357.........	−87.6	30.1	Lick
838.7594.........	−82.1	4.5	Keck
1051.1034.......	38.1	3.9	Keck
1073.0403.......	61.9	3.6	Keck
1154.7925.......	150.9	11.3	Lick
1171.8449.......	167.4	3.3	Keck
1228.8034.......	200.0	3.9	Keck
1412.1067.......	112.1	4.3	Keck
1447.0323.......	101.4	10.5	Lick
1543.8997.......	28.5	4.2	Keck
1550.8857.......	19.7	2.9	Keck
1580.8356.......	15.2	4.7	Keck
1581.8678.......	11.6	4.0	Keck
1582.7846.......	10.3	4.1	Keck
1607.6845.......	8.5	12.8	Lick
1628.6289.......	22.9	12.0	Lick
1793.1197.......	−38.1	4.6	Keck
1859.9447.......	−65.5	9.3	Lick
1860.9068.......	−64.6	10.2	Lick
1882.9336.......	−69.1	4.3	Keck
1884.0852.......	−67.0	4.0	Keck
1898.0322.......	−73.2	3.9	Keck
1899.0454.......	−71.6	3.6	Keck
1900.0648.......	−63.7	3.7	Keck
1901.0137.......	−60.9	3.4	Keck
1913.7822.......	−86.2	6.1	Lick
1914.8443.......	−87.5	7.9	Lick
1915.8011.......	−82.7	8.0	Lick
1945.7179.......	−80.6	5.7	Lick
1973.7486.......	−90.4	5.8	Keck
2003.7459.......	−83.0	4.1	Keck
2188.1390.......	−91.2	4.4	Keck

The Keck and Lick observations of HD 33636 cover nearly the full amplitude of the velocity variation, but slightly less than one orbital period, leading to a large uncertainty in the derived orbital period. *Hipparcos* astrometry is not able to place limits on the orbital inclination of this system because the orbital period is much longer than the duration of the *Hipparcos* mission.

3.6. *HD 169822*

Spectral synthesis matched to our Keck spectra yield [Fe/H] $= -0.10$ for HD 169822 (G5 V). The star is chromospherically quiet with $R'_{\rm HK} = -4.97$, and photometrically stable at the level of *Hipparcos* measurement error.

We have obtained a total of 22 Keck observations between 1999 July and 2001 October. The measured Doppler velocities are shown in Figure 8 and listed in Table 8. The best-fit Keplerian to these velocities yields a period of 293 days, an eccentricity of 0.48, and a semiamplitude (K)

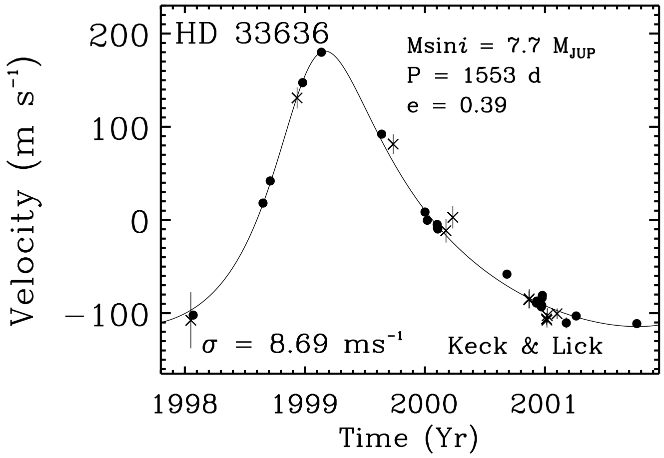

FIG. 7.—Doppler velocities for HD 33636 (G0 V). The filled dots are the Keck 10 m observations, while the Lick 3 m observations are indicated by the crosses. The solid line is a Keplerian orbital fit with a period of 1553 days, a semiamplitude of 188 m s^{-1}, and an eccentricity of 0.67, yielding a minimum ($M \sin i$) of 11.5 $M_{\rm JUP}$ for the companion. The rms of the Keplerian fit is 8.75 m s^{-1}. Nearly the full amplitude of the velocity variation has been observed, but only a faction of the total orbit. Large uncertainties therefore remain in the orbital period and minimum mass of the companion.

TABLE 8

VELOCITIES FOR HD 169822

JD (−2,450,000)	Radial Velocity (m s^{-1})	Error (m s^{-1})
372.8809.........	−554.1	3.5
373.8011.........	−529.2	3.9
411.8501.........	14.6	3.0
679.0826.........	−292.6	3.3
680.1159.........	−274.4	2.8
703.0212.........	−10.2	2.7
703.9911.........	5.3	2.7
705.0419.........	13.3	4.4
705.9615.........	25.1	3.0
707.0839.........	28.1	4.8
755.9132.........	239.8	4.6
793.8101.........	291.8	3.8
973.1655.........	−283.7	4.5
982.1650.........	−150.0	3.6
1004.1285.......	64.0	3.3
1009.1085.......	93.0	3.4
1030.9853.......	210.0	3.6
1061.9457.......	293.2	3.9
1062.9627.......	278.2	3.8
1094.8889.......	276.3	4.4
1128.8559.......	174.4	3.8

of 991 m s^{-1}. The minimum ($M \sin i$) mass of the companion is 27.2 $M_{\rm JUP}$. The rms to the Keplerian is 5.70 m s^{-1}.

The *Hipparcos* catalog assigned a stochastic solution for HD 169822 because none of the investigated models gave a satisfactory solution at that time. The *Hipparcos* data has been reinvestigated in light of the Doppler velocity signal and now clearly yields a periodicity of 292.7 days, in excellent agreement with the Doppler velocity data. The new *Hipparcos* solution, taking into account the orbital motion, changes the measured parallax to this system from 37.04 to 31.2 mas, increasing the distance of this system from 27 to 32 pc. The *Hipparcos*-derived orbital inclination of 175° yields a companion mass of 0.30 $M_{\odot}$. The companion is thus stellar, presumably with a spectral type around M3 V. With a semimajor axis of 0.84 AU, the maximum separation between the companion and the primary is 39 mas. The M dwarf companion is expected to be ∼5.5 *V* magnitudes fainter than the primary.

3.7. *HD 184860*

The metallicity of HD 184860 (K2 V), determined by spectral synthesis matched to our Keck spectra, is [Fe/H] = −0.13. The star is chromospherically quiet, with $R'_{\rm HK} = -5.00$. *Hipparcos* *V*-band photometric scatter is 0.016 mag.

A total of 21 Keck observations of HD 184860 have been made between 1996 July and 2001 August. These observations are shown graphically in Figure 9 and in tabular form in Table 9. The best-fit Keplerian yields an orbital period of

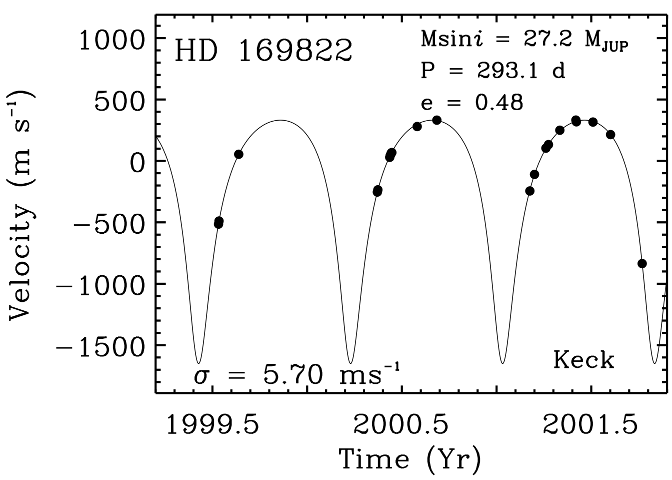

FIG. 8.—Doppler velocities for HD 169822 (G5 V). The solid line is a Keplerian orbital fit with a period of 293 days, a semiamplitude of 991 m s^{-1}, and an eccentricity of 0.48, yielding a minimum ($M \sin i$) of 27.2 $M_{\rm JUP}$ for the companion. The rms of the Keplerian fit is 5.92 m s^{-1}. *Hipparcos* astrometry finds the inclination $i = 175°$, and the true mass of the companion to be 0.30 $M_{\odot}$. The companion is therefore an M dwarf in a nearly face-on orbit.

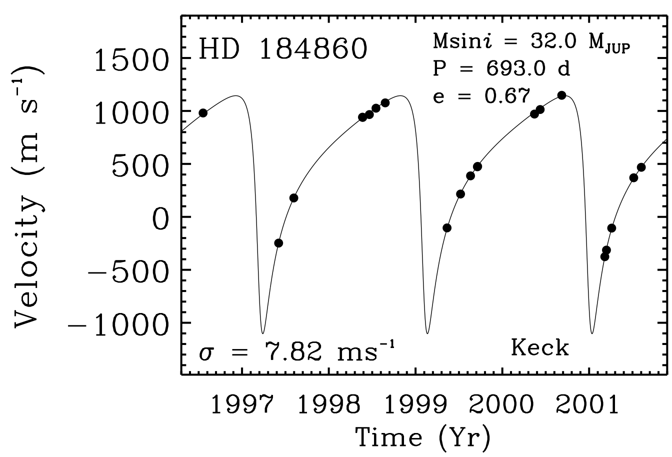

FIG. 9.—Doppler velocities for HD 184860 (K2 V). The solid line is a Keplerian orbital fit with a period of 693 days, a semiamplitude of 1123 m s^{-1}, and an eccentricity of 0.67, yielding a minimum ($M \sin i$) of 32 $M_{\rm JUP}$ for the companion. The rms of the Keplerian fit is 7.82 m s^{-1}. *Hipparcos* astrometry is unable to constrain sin *i* owing to a known nearby stellar companion. This companion may well be an M dwarf in a modestly inclined orbit.

TABLE 9
Velocities for HD 184860

JD (−2,450,000)	Radial Velocity (m s^{-1})	Error (m s^{-1})
283.9812.........	480.9	4.2
602.0837.........	−747.4	3.1
665.9255.........	−321.5	3.1
955.0729.........	441.1	2.8
955.9625.........	439.2	3.8
984.0518.........	466.1	6.4
1011.8909.......	526.0	7.9
1050.8529.......	576.5	5.0
1311.0711.......	−604.0	4.6
1367.8866.......	−284.3	4.8
1409.8883.......	−112.6	4.8
1438.7611.......	−26.9	5.0
1439.7771.......	−23.5	5.7
1679.0771.......	470.6	6.5
1703.0113.......	513.6	6.7
1793.8075.......	647.8	6.2
1975.1678.......	−876.1	4.3
1982.1679.......	−813.8	6.0
2004.1326.......	−606.1	4.5
2096.9296.......	−130.8	9.4
2128.8532.......	−31.8	5.4

693.0 days, a semiamplitude $K = 1123$ m s^{-1}, eccentricity $e = 0.67$, and $M \sin i = 32\ M_{\rm JUP}$. As no observations have been made near minimum velocity, the semiamplitude is poorly constrained. Minimum velocity will next occur in 2002 December.

With a semimajor axis of 1.44 AU, the companion to HD 184860 is separated from the primary by 47.5 mas. The minimum astrometric semiamplitude of the primary is ~1.8 mas. Unfortunately, HD 184860 has a stellar companion separated by 5″.1. This stellar companion shows up in the *Hipparcos* Intermediate Astrometric Data, making it impossible to search for the astrometric signal that is caused by the brown dwarf candidate. It is thus not possible to derive an upper limit for the orbital inclination of the brown dwarf candidate. Moderate values of sin *i* would render this an M dwarf.

3.8. *HD 64468*

Spectral synthesis matched to our Keck spectra yield [Fe/H] = +0.00 for HD 64468 (K2 V). The star is chromospherically quiet, with $R'_{\rm HK} = -5.03$, and photometrically stable within *Hipparcos* measurement error.

Thirteen observations of HD 64468 have been made at Keck between 1997 Jan and 2001 April. These observations are listed in Table 10 and graphically displayed in Figure 10. The best-fit Keplerian orbit to this data has a period of 161 days, a semiamplitude (K) of 5730 m s^{-1}, and an eccentricity of 0.26. The minimum ($M \sin i$) mass of the companion is 0.13 $M_\odot$. As the companion is clearly stellar, we will drop this star from our observing program.

The orbital inclination of this system was derived from the *Hipparcos* astrometric data by freezing the orbital parameters from the Doppler velocities, yielding an inclination of 64° ± 13° and a true mass for the companion of 0.14 $M_\odot$. The companion is likely to be an M6 dwarf. With a semimajor axis of 0.56 AU, the maximum separation between the companion and the primary is 28 mas. The M dwarf companion is expected to be ~7.5 V magnitudes fainter than the primary.

TABLE 10
Velocities for HD 64468

JD (−2,450,000)	Radial Velocity (m s^{-1})	Error (m s^{-1})
462.9003.........	7537.9	3.0
545.8154.........	−3502.0	4.5
807.0220.........	4765.3	3.1
839.0313.........	−897.6	4.7
861.9171.........	−3106.4	5.0
1170.9913.......	−2030.9	4.5
1226.9085.......	−2685.2	5.0
1550.9977.......	−2413.7	4.8
1552.9947.......	−2112.1	5.8
1581.9092.......	5895.1	4.7
1898.1031.......	3965.0	3.1
1973.8651.......	−1665.3	6.0
2003.7708.......	−3750.1	5.0

3.9. *HD 35956A*

Based on Stromgren photometry, Eggen (1998) reports the metallicity of HD 35956A (G0 V) to be [Fe/H] = −0.14, in reasonable agreement with our photometric estimate of −0.21. The star is photometrically stable at the level of *Hipparcos* measurement error, ~0.01 mag, and chromospherically quiet with $R'_{\rm HK} = -4.92$. The *Hipparcos*-derived distance of this star is 28.9 pc. We estimate the mass of the primary to be 1.0 $M_\odot$.

We have obtained a total of 14 Keck observations between 1996 October and 2001 October. The measured Doppler velocities are shown in Figure 11 and listed in Table 11. The best-fit Keplerian orbit to these velocities yields a period of 1427 days, an eccentricity $e = 0.62$, and a semiamplitude, $K = 3796$ m s^{-1}. The rms to the Keplerian fit is 4.89 m s^{-1}. The minimum ($M \sin i$) mass of the com-

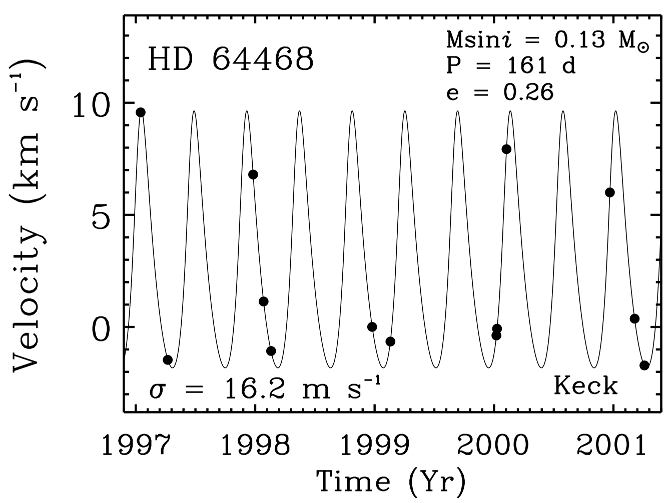

Fig. 10.—Doppler velocities for HD 64468 (K2 V). The solid line is a Keplerian orbital fit with a period of 161 days, a semiamplitude of 5730 m s^{-1}, and an eccentricity of 0.26, yielding a minimum ($M \sin i$) of 0.13 $M_\odot$ for the companion. The rms of the Keplerian fit is 16.2 m s^{-1}. The *Hipparcos*-derived orbital inclination is 64°, yielding a true mass of 0.14 $M_\odot$. The companion is thus an M dwarf.

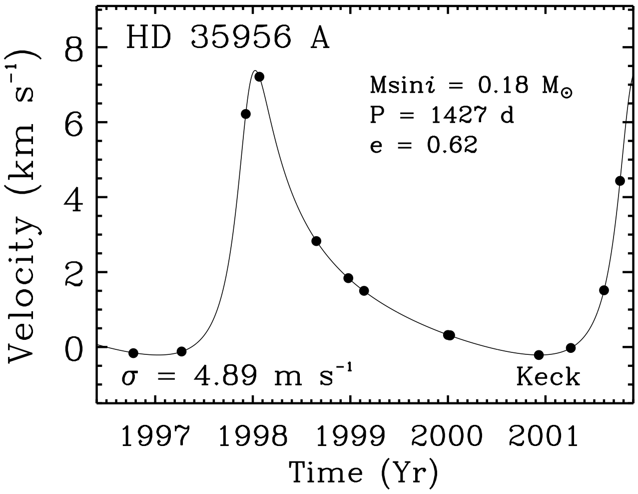

FIG. 11.—Doppler velocities for HD 35956 A (G0 V). The solid line is a Keplerian orbital fit with a period of 1427 days, a semiamplitude of 3796 m s^{-1}, an eccentricity of 0.62, and $(M \sin i) = 0.18\ M_\odot$ for the companion. The rms of the Keplerian fit is 4.86 m s^{-1}. The *Hipparcos*-derived orbital inclination is 78°, thus the true mass is only 2% larger than the minimum $(M \sin i)$ mass. The companion is an M dwarf.

panion is 0.18 $M_\odot$. As this companion is stellar, we will drop this star from our target list.

Although the orbital period of this binary is about 50% longer than the duration of the *Hipparcos* mission, the astrometric signature of the companion was detected. Freezing the orbital elements from the precision velocities yields an orbital inclination of $78° \pm 4°$. The true mass of the companion is thus only 2% larger than the minimum mass. The spectral type of the companion is expected to be roughly M6, with V magnitude ~16, separated from the $V = 6.7$ primary by 0."1.

3.10. *HD 43587*

HD 43587 is assigned a spectral type of F9 V by Simbad and G0.5 by *Hipparcos*. The $B-V$ color of 0.61 is consistent with G1 or G2 spectral type. Spectral synthesis matched to our Keck spectra yields $T_{\rm eff} = 5795$ K, [Fe/H] $= -0.03$, and $V \sin i = 2.7$ km s^{-1}. The $R'_{\rm HK}$ value measured from the H and K lines in the Keck spectra is -4.97. The star is photometrically stable at the level of *Hipparcos* measurement error. HD 43587 is thus a near solar twin.

TABLE 11
VELOCITIES FOR HD 35956A

JD (−2,450,000)	Radial Velocity (m s^{-1})	Error (m s^{-1})
366.1155.........	−2018.8	3.9
546.7296.........	−1974.0	3.8
786.9244.........	4363.6	4.8
837.8768.........	5357.2	3.3
1051.1210.......	972.3	3.9
1170.9331.......	−16.7	3.9
1229.7433.......	−354.8	4.3
1543.9305.......	−1533.8	4.6
1550.8895.......	−1544.7	4.3
1551.8912.......	−1540.9	4.2
1884.0873.......	−2068.4	4.7
2003.7483.......	−1879.5	4.8
2128.1349.......	−340.6	4.2
2188.1412.......	2578.7	3.5

TABLE 12
VELOCITIES FOR HD 43587

JD (−2,450,000)	Radial Velocity (m s^{-1})	Error (m s^{-1})
366.1316.........	5052.2	3.2
545.7812.........	5586.7	4.5
787.0277.........	3819.9	3.7
807.0639.........	3252.6	3.4
838.9376.........	2236.4	3.6
861.7638.........	1481.6	3.7
1069.0974.......	−2481.5	4.0
1171.8867.......	−2895.6	4.4
1227.8236.......	−2943.0	5.1
1544.0042.......	−2810.6	3.9
1552.9211.......	−2788.6	3.9
1582.8475.......	−2752.9	4.3
1884.0956.......	−2446.7	4.5
2003.7636.......	−2310.7	6.3

Fourteen observations of HD 43587 have been made at Keck between 1996 Oct and 2001 April. These observations are listed in Table 12 and graphically displayed in Figure 12. The best-fit Keplerian to this data has a period of 33.7 yr, a semiamplitude (K) of 4323 m s^{-1}, and an eccentricity of 0.80. The minimum $(M \sin i)$ mass of the companion is 0.34 $M_\odot$. Given the long orbital period, we were fortunate to observe the extreme velocity drop of 1998. As the companion is clearly stellar, we will drop this star from our observing program. *Hipparcos* was unable to astrometrically detect the companion owing to the short duration of the *Hipparcos* mission.

This star was observed seven times during 5.3 yr around epoch 1987 by the CORAVEL Doppler velocity survey (Duquennoy & Mayor 1991), and found to be constant,

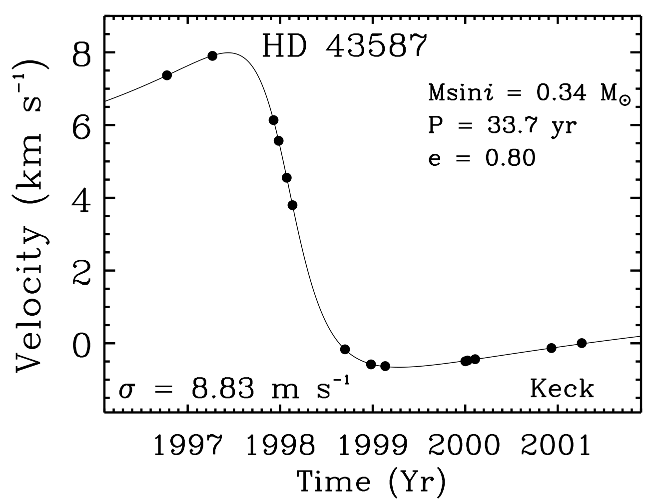

FIG. 12.—Doppler velocities for HD 43587 (G2 V). The solid line is a Keplerian orbital fit with a period of 33.7 yr, a semiamplitude of 4323 m s^{-1}, and an eccentricity of 0.80, yielding a minimum $(M \sin i)$ of 0.34 $M_\odot$ for the companion. The rms of the Keplerian fit is 8.83 m s^{-1}. While only 10% of the orbital period has been covered, the full amplitude was observed between 1997 and 1999. *Hipparcos* astrometry is unable to detect binaries with such long orbital periods.

with standard deviation of 0.36 km s^{-1}. That constant velocity is consistent with our results. The present best-fit Keplerian predicts the last epoch of rapid velocity change would have been in 1964. During the epoch when CORAVEL measurements were made, the velocity of the star would have changed by only 0.2 km s^{-1} yr^{-1}. We expect that in retrospect, the CORAVEL velocities should reveal a trend just above the errors. The absolute velocity reported by Duquennoy & Mayor was 9.6 km s^{-1}. We find that on 1997 December 2 (JD = 2,450,785) the velocity of HD 43587 was 12.3 ± 0.1 km s^{-1} (Nidever et al. 2002). Thus, the measured change in the velocity of the star from 1987 to 1997 December 2 was +2.7 km s^{-1}. In comparison, our orbital solution predicts a change of +2.4 km s^{-1} during that 10 yr period, in good agreement within errors.

With a semimajor axis $a = 11.6$ AU, the companion orbits about 0″.6 from the primary. For a minimum mass companion ($\sin i = 1$), the primary would be about 5.5 *V* magnitudes brighter than the companion. The value of $\sin i$ is likely greater than 0.5, as smaller values would yield a companion with an expected difference in *V* magnitude of 3 or less, which would be detectable in our Keck spectra. This binary thus makes an interesting adaptive optics (AO) target.

4. DISCUSSION

A total of 1200 stars are currently being surveyed by the Keck, Lick, and Anglo-Australian precision velocity surveys. All three of these programs use the iodine cell technique, and all three have demonstrated long-term precision of 3 m s^{-1} (Butler & Marcy 1997; Vogt et al. 2000; Butler et al. 2001). These three surveys have no selection bias against stars with brown dwarf companions.

A total of 48 substellar candidates ($M \sin i < 80\ M_{JUP}$) have been uncovered from these surveys, of which 44 are planet candidates with plausible masses below the Deuterium burning limit ($M \sin i < 12\ M_{JUP}$). All of these companions have either been published or are currently submitted to refereed journals, including three new companions from the Anglo-Australian Telescope (AAT) survey (Tinney et al. 2002; Jones et al. 2002).

Two of the four brown dwarf candidates from these surveys, HD 169822 and HD 164427 (Tinney et al. 2001), have been revealed by *Hipparcos* astrometry to be M dwarfs. *Hipparcos* is able to place upper limits on the masses of the remaining 49 companions (Pourbaix & Arenou 2001; Perryman et al. 1996).

The mass function of the 46 surviving substellar candidates from the Keck, Lick, and Anglo-Australian surveys is shown in Figure 13. All but three of these companions orbit within 3 AU. The mass function is flat and sparsely populated above 10 M_{JUP}, and then begins rising abruptly below 10 M_{JUP}.

Within 3 AU these surveys are complete for companions having $M \sin i > 10\ M_{JUP}$. Incompleteness is greatest for the smallest mass bin, $M \sin i < 1\ M_{JUP}$. Companions with $M \sin i < 1\ M_{SAT}$ are detectable only if they orbit within 1 AU. These selection effects strongly favor the detection of companions with $M \sin i > 10\ M_{JUP}$ at the expense of companions with $M \sin i < 1\ M_{JUP}$. In spite of this, 15 companions having $M \sin i < 1\ M_{JUP}$ have been detected, while only two have been found with $M \sin i > 10\ M_{JUP}$.

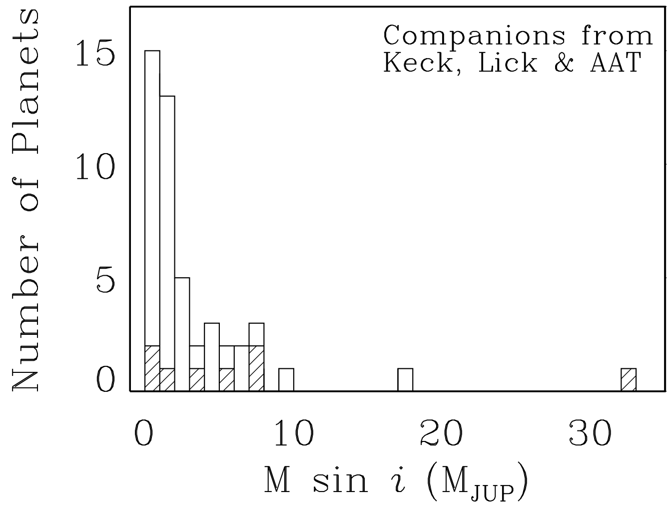

FIG. 13.—Substellar mass function found from the Keck, Lick, and AAT precision Doppler surveys. These are the only surveys sensitive to 1 M_{JUP} planets orbiting beyond 3 AU. Out to 3 AU these surveys are complete for companions of more than 5 M_{JUP}. Incompleteness is greatest for the smallest mass bin. The discontinuous and abrupt rise in the mass function below 10 M_{JUP} empirically motivates setting the upper mass limit of planets near 10 M_{JUP}. Planets orbiting stars with [Fe/H] < +0.0 are indicated by cross hatching. About one-third of field stars are metal-rich relative to the Sun, but roughly 88% of the planets found from these surveys orbit metal-rich stars.

The abrupt and discontinuous jump in the mass function below 10 M_{JUP} empirically sets the threshold between planets and brown dwarfs at ~10 M_{JUP}. Coincidentally, the deuterium-burning limit resides near this limit at 12 M_{JUP}.

The two companions with the largest mass in Figure 13 are HD 168443c ($M \sin i = 17\ M_{JUP}$) and HD 184860 ($M \sin i = 32\ M_{JUP}$). As described in the previous section, *Hipparcos* cannot put an upper limit on the mass of the companion to HD 184860 because of a nearby stellar companion. A moderate inclination of 23° would be sufficient to push this brown dwarf candidate into the M-dwarf mass range. For the case of HD 168443c, *Hipparcos* astrometry is able to put an upper limit on the mass of the companion of 42 M_{JUP} (Marcy et al. 2001a). Brown dwarf companions orbiting within 3 AU of main-sequence stars are rare, with at most about 1 such companion per 500 stars. In contrast, planetary mass companions are common.

Relatively few planets have been found orbiting metal-poor stars (Butler et al. 2000, Santos et al. 2001). Planets orbiting stars of less than solar metallicity ([Fe/H] < +0.00) are indicated in Figure 13 by the crosshatched area. They constitute about 12% of the planets found in the Keck, Lick, and Anglo-Australian surveys (even though two-thirds of the field stars have metallicity less than solar). If planets are common around metal-poor stars, these planets must either have smaller masses or larger orbital radii than the planets found to date.

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