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SIX NEW PLANETS FROM THE KECK PRECISION VELOCITY SURVEY[1]

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ABSTRACT

We report results of a search for planets around 530 main-sequence stars using the Keck HIRES spectrometer, which has provided Doppler precision of 3 m s^{-1} during the past 3 yr. We report six new strong planet candidates having complete Keplerian orbits, with periods ranging from 24 days to 3 yr. These are HD 10697, HD 37124, HD 134987, HD 177830, HD 192263, and HD 222582. We also provide updated orbital parameters for the previously announced planets around HD 187123, HD 195019, HD 201277, and HD 217107. Four of the six newly discovered planets have minimum $M \sin i$ masses less than 2 $M_{\rm JUP}$, while the remaining two have $M \sin i \sim 5$ $M_{\rm JUP}$. The distribution of planetary masses continues to exhibit a rise toward lower masses. The orbital eccentricities of the new planets range from 0.12 to 0.71, which also continues the ubiquity of high eccentricities. All 17 known extrasolar planets orbiting beyond 0.2 AU have eccentricities greater than $\sim$0.1. The current limiting Doppler precision of the Keck Doppler survey is 3 m s^{-1} per observation as determined from observations of both stable stars and residuals to Keplerian fits.

Subject headings: planetary systems — stars: individual (HD 10697, HD 37124, HD 134987, HD 177830, HD 187123, HD 192263, HD 195019, HD 217107, HD 222582)

1. INTRODUCTION

To date, 22 planet candidates have been identified around nearby main-sequence stars by measuring their Keplerian Doppler shifts. Four groups have contributed the bulk of the detections by surveying a total of $\sim$300 stars at a Doppler precision of $\sim$10 m s^{-1} (cf. Marcy, Cochran, & Mayor 2000; Noyes et al. 1997). These "planets" all have mass estimates, $M \sin i$, less than 7.5 $M_{\rm JUP}$, where i is the unknown orbital inclination.

Interestingly, these precision Doppler surveys, along with low-precision surveys of several thousand stars, have revealed only 11 orbiting brown dwarf candidates, $M \sin i = 8$–80 $M_{\rm JUP}$, and most are actually hydrogen-burning stars with low orbital inclination (Mayor et al. 1997; Halbwachs et al. 1999; Udry et al. 2000). This paucity of brown dwarf companions renders the planet candidates distinguishable by their high occurrence at low masses: 17 of the 22 have $M \sin i = 0.4$–4 $M_{\rm JUP}$ (cf. Fig. 6, Butler & Marcy 1997; Marcy et al. 2000).

The planet candidates detected from precision radial velocity surveys reveal a mass distribution that rises toward lower masses, from $\sim$8 to 0.4 $M_{\rm JUP}$, which is the lowest $M \sin i$ currently detected. Remarkably, all 12 planets that orbit beyond 0.2 AU reside in noncircular orbits with $e > 0.09$ and many higher than 0.3. In contrast, Earth and giant planets in our solar system have eccentricity less than 0.06. Planet formation theory is challenged to find robust mechanisms that produce these observed distributions of mass and orbital eccentricity (cf. Lissauer 1995; Weidenschilling & Marzari 1996; Lin & Ida 1996; Rasio & Ford 1996). Further, the half-dozen planets that reside within 0.2 AU offer a challenge to explain their current location (cf. Lin, Bodenheimer, & Richardson 1996).

The system of three planetary-mass companions around the main-sequence star, υ And, opens questions about the ubiquity of multiple planets and about the formation mechanisms that could explain multiple Jupiter-mass planets within 3 AU. One wonders if a Jupiter-mass planet within 3 AU is commonly accompanied by additional giant planets farther out, as demanded by dynamical evolution scenarios that involve mutual perturbations. Further Doppler measurements of existing and future planets can help ascertain the occurrence and character of multiple-planet systems.

The broad goals of the precision Doppler surveys include the following: (1) detection of several hundred planets, sufficient to construct statistically meaningful distributions of planet mass, eccentricity, and orbital distance; (2) the detection of Jupiter-mass planets beyond 4 AU to compare with our Jupiter; (3) the characterization of multiple-planet systems; (4) characterization of planet distributions down to Saturn-masses; and (5) assessment of correlations between planets and stellar properties such as metallicity (i.e., Gonzalez, Wallerstein, & Saar 1999). Toward achieving these goals, full-sky surveys of more than 1000 stars are being carried out by our group, by Mayor's group (Mayor, Udry, & Queloz 1999), and by others. Most main-sequence dwarf stars brighter than $V = 7.5$ are currently being surveyed, with a need for more surveys in different regimes of parameter space.

This paper reports the discovery of six new planet candidates from the Keck extrasolar planet survey. Section 2 describes the Keck precision velocity program including technique, the stellar sample, and the current level of precision. The stellar properties and Keplerian orbital fits for the

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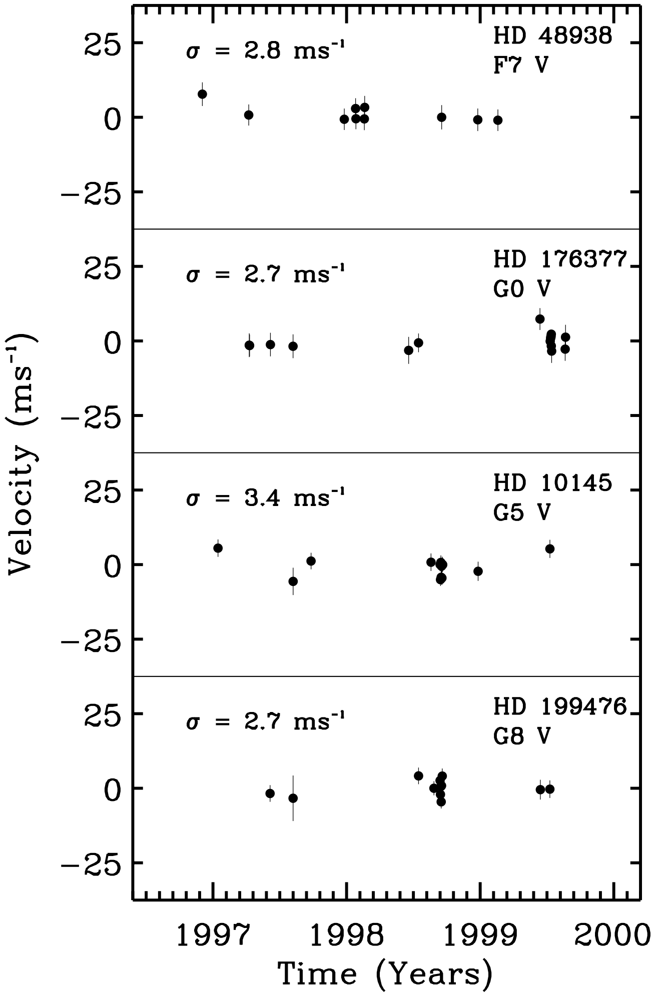

FIG. 1.—Keck/HIRES velocities of a representative subset of F and G dwarfs from our planet search, chosen to be chromospherically quiet (age > 3 Gyr). The typical velocity scatter is 3 m s^{-1}, which represents the sum of measurement errors and intrinsic photospheric variability. The observations span the 2–3 yr duration of our Keck planet search.

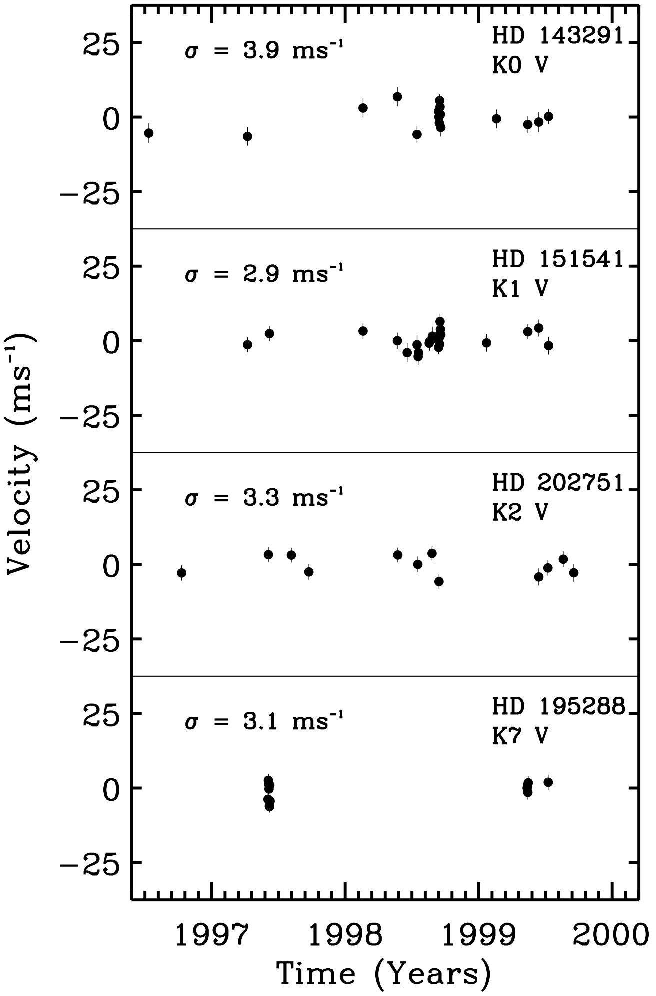

FIG. 2.—Velocities of a representative set of K dwarfs, showing typical scatter of 3–4 m s^{-1} that represent errors and intrinsic variability.

six new planet candidates are presented in § 3. Section 4 provides an update on the orbital parameters for several previously announced planets. A discussion follows.

2. THE KECK PLANET SEARCH PROGRAM

The Keck Doppler planet survey began in 1996 July using Keck I with the HIRES echelle spectrometer (Vogt et al. 1994). The spectra have resolution, $R = 80{,}000$ and span wavelengths from 3900 to 6200 Å. Wavelength calibration is carried out by means of an iodine absorption cell (Marcy & Butler 1992; Butler et al. 1996), which superimposes a reference iodine spectrum directly on the stellar spectra.

The stellar sample contains 530 main-sequence stars from F7 to M5. Stars hotter than F7 contain too few spectral features to achieve precision of 3 m s^{-1}, while stars later than M5 are too faint ($V > 11$) for the Keck telescope to achieve 3 m s^{-1} precision in our nominal 10 minute exposure time. The G and K dwarfs are mostly within 50 pc and are selected from the *Hipparcos* catalog (Perryman et al. 1997), while M dwarfs have been selected from both *Hipparcos* and the Gliese catalog. Evolved stars have been removed from the observing list based on *Hipparcos* distances.

The list has been further sieved to remove chromospherically active stars as these stars show velocity "jitter" of 10 to 50 m s^{-1}, related to rapid rotation, spots, and magnetic fields (Saar, Butler, & Marcy 1998). The Ca II H and K line reversals are used as a chromospheric diagnostic (Noyes et al. 1984) and are measured directly from our Keck HIRES spectra. The 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). Based on their "*S*" index, stars with ages less than 2 Gyr are either excluded from our sample, or are given shorter exposure times.

Stars with known stellar companions within 2″ (including known spectroscopic binaries) are removed from the observing list as it is operationally difficult to get an uncontaminated spectrum of a star with a nearby companion. Otherwise, there is no bias against observing multiple stars. Further, the list of Keck program stars has no bias against brown dwarf companions. Stars with known or suspected brown dwarf companions have not been excluded from the Keck target list.

Doppler measurement errors from our Keck survey were previously reported to be 6–8 m s^{-1} (Butler et al. 1998; Marcy et al. 1999). However, we have since made improvements to the data analysis software. We now achieve a pre-

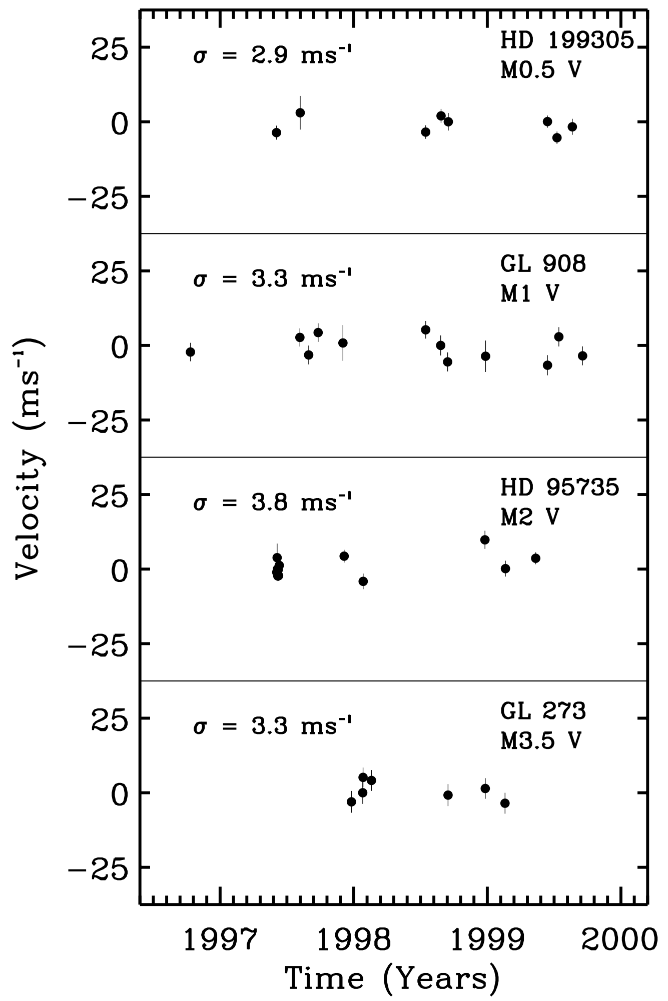

FIG. 3.—Velocities of a representative set of M dwarfs, showing typical scatter of 3–4 m s^{-1} that represent errors and intrinsic variability.

cision of 3 m s^{-1} with HIRES by treating readout electronics and CCD charge diffusion in the model that determines the instrumental point-spread function (PSF) of each observation (Valenti, Butler, & Marcy 1995). We routinely achieve precision of 3 m s^{-1} for $V = 8$ stars in 10 minute exposures, as shown in Figures 1, 2, and 3, which cover stars of spectral types late F and G, K, and M respectively. The observed velocity precision, $\sigma_{\rm obs}$, is the quadrature sum of the instrumental errors, $\sigma_{\rm inst}$, and random velocity variations intrinsic to the program stars, $\sigma_{\rm star}$. Saar et al. (1998) have shown that, for the slowest rotating G, K, and M stars, $\sigma_{\rm star} \sim 2$ m s^{-1}. Thus, our instrumental precision is presently $\sigma_{\rm inst} \sim 2$ m s^{-1} per observation. All previous HIRES data have also been reprocessed to bring their precision to this level. With further improvements, we expect to achieve photon-limited precision of ~ 2 m s^{-1} with this system, and thus our exposures are nominally taken at a S/N sufficient for this goal.

3. NEW PLANET CANDIDATES FROM THE KECK SURVEY

Six new planet candidates have recently emerged from the Keck survey. For HD 192263, the discovery of its planet was announced during the writing of this paper (Santos et al. 1999).

The stellar properties of the six host stars are given in Table 1. The first three columns provide the common name, the HD catalog number, and the *Hipparcos* catalog number, respectively. Spectral types are from the Simbad database. The stellar masses are estimated by interpolation of evolutionary tracks (Fuhrmann, Pfeiffer, & Bernkopf 1997, 1998). The values of $R'_{\rm HK}$, a measure of the ratio of chromospheric to bolometric flux (Noyes et al. 1984), are measured from the Ca II H and K line cores in the Keck spectra. Distances are from *Hipparcos* (Perryman et al. 1997).

The [Fe/H] values are based on a calibration of the Hauck & Mermilliod (1997) catalog of *uvby* photometry and 60 [Fe/H] determinations from high-resolution spectroscopy (Favata, Micela, & Sciortina 1997; Gonzalez & Vanture 1998; Gonzalez et al. 1999; Gonzalez 1997, 1998). From the scatter in the calibration relationship, the uncertainty in [Fe/H] is estimated to be 0.07 dex for stars from G0 V to K0 V.

Astrophysical effects that can mimic Keplerian Doppler velocity signals include radial and nonradial pulsations and rotational modulation caused by stellar surface features (i.e., spots, plages). Five of the new Keck candidates are chromospherically inactive, with $R'_{\rm HK}$ values similar to that of the Sun or lower. In contrast, the sixth star, HD 192263, is extremely active with $R'_{\rm HK} = -4.37$ (Santos et al. 1999).

The orbital parameters for the six new Keck planet candidates are listed in Table 2. The quantities in parentheses are the formal uncertainties in each orbital parameter, as determined by Monte Carlo simulations. The individual Keck Doppler velocity measurements are listed in Tables 3 through 8. The host stars are discussed below.

3.1. *HD 10697*

HD 10697 (HR 508) is assigned a spectral type of G5 IV by the Bright Star Catalog (Hoffleit 1982). From its spectral type, $B-V$ color, and the *Hipparcos*-derived absolute magnitude, we find a stellar mass of 1.10 $M_\odot$ for HD 10697 based on placement on standard evolutionary tracks. This star is a slow rotator and is chromospherically inactive, as

TABLE 1

STELLAR PROPERTIES

Star	Star (HD)	Star (Hipp)	Spectral Type	$M_{\rm Star}$ ($M_\odot$)	V (mag)	$R'_{\rm HK}$	[Fe/H]	d (pc)
109 Psc......	10697	8159	G5 IV	1.10	6.27	−5.02	+0.15	32.6
	37124	26381	G4 V	0.91	7.68	−4.90	−0.32	33.2
23 Lib	134987	74500	G5 V	1.05	6.47	−5.01	+0.23	25.6
	177830	93746	K0 IV	1.15	7.18	−5.28		59.0
	192263	99711	K0 V	0.75	7.79	−4.37	−0.20	19.9
	222582	116906	G5 V	1.00	7.68	−5.00	−0.01	41.9

TABLE 2

ORBITAL PARAMETERS

Star (HD)	Period (days)	K (m s^{-1})	e	ω (deg)	T_0 (JD $-$2,450,000)	M sin i ($M_{\rm JUP}$)	a (AU)	N Obs	rms (m s^{-1})
10697	1072.3 (9.6)	119 (3)	0.12 (0.02)	113 (14)	1482 (39)	6.35	2.12	35	7.75
37124	155.7 (2.0)	43 (7)	0.19 (0.12)	73 (52)	1219 (33)	1.04	0.55	15	2.82
134987......	259.6 (1.1)	50 (1)	0.24 (0.03)	353 (10)	1364 (6)	1.58	0.81	43	2.99
177830......	391.6 (11)	34 (14)	0.41 (0.13)	5 (35)	1333 (14)	1.22	1.10	29	5.18
192263......	24.36 (0.07)	68 (11)	0.22 (0.14)	153 (18)	1380.9 (1)	0.78	0.15	15	4.52
222582......	575.9 (3.6)	184 (52)	0.71 (0.05)	306 (12)	1310 (17)	5.29	1.35	24	3.36

indicated by $R'_{\rm HK} = -5.02$, by its photometric stability (Lockwood, Skiff, & Radick 1997), and by its low X-ray flux (Hunsch, Schmitt, & Voges 1998). Relative to the Sun, HD 10697 is modestly metal rich, [Fe/H] $= +0.15$.

We have made 35 velocity observations of HD 10697, spanning 3 yr, as shown in Figure 4 and listed in Table 3. These observations barely cover one orbital period of the new planet candidate, accounting for the relatively large uncertainty in the derived orbital period. The amplitude (K) of the Keplerian orbital fit is 119 m s^{-1}, while the rms of the velocity residuals to the Keplerian fit is 7.8 m s^{-1}. This scatter is twice that of our present known errors, for reasons not yet known. The eccentricity of the orbit, $e = 0.12$, is about twice as large as that of Jupiter, as is common for extrasolar planet candidates that orbit beyond 0.2 AU. Its minimum mass, M sin i, is 6.35 $M_{\rm JUP}$, placing it among the most massive companions found from precision velocity surveys.

The semimajor axis of the orbit is $a = 2.12$ AU, yielding a maximum angular separation between planet and star of 73 mas. The amplitude of the astrometric wobble of the star is 373/sin i μas, making this a prime target for interferometric astrometry. The expected effective temperature of the planet due to stellar insolation (assuming an albedo of 0.3) is 264 K (Saumon et al. 1996), and internal heating may increase this by 10–20 K. Direct detection would be difficult at present.

3.2. *HD 37124*

HD 37124 (G4 V) is a slowly rotating, chromospherically inactive star with $R'_{\rm HK} = -4.90$. As listed in Table 4 and shown in Figure 5, 15 velocity measurements have been made, spanning 2.7 yr, revealing six complete orbits with a derived orbital period of 155.7 days. The semiamplitude (K) is 43 m s^{-1}, and the eccentricity is 0.19, giving the companion a minimum mass of 1.04 $M_{\rm JUP}$. The rms of the observations to the Keplerian fit is 2.82 m s^{-1}

The semimajor axis of the companion orbit is $a = 0.55$ AU, yielding a maximum angular separation between planet and star of 20 mas. The planet is expected to have $T_{\rm eff} = 327$ K (Saumon et al. 1996). HD 37124 has low metallicity, [Fe/H] $= -0.32$, relative to the Sun, but its metal-

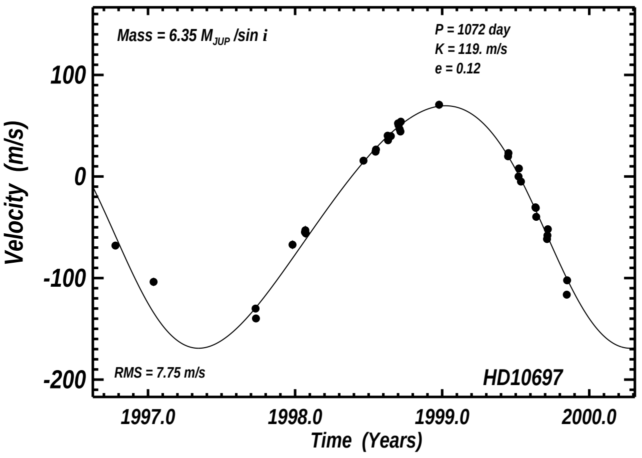

FIG. 4.—Velocities for HD 10697 (G5 IV) spanning 3 yr. The solid line is a Keplerian orbital fit with orbital parameters, $P = 1072$ days, $K = 119$ m s^{-1}, and $e = 0.12$, yielding a minimum mass, M sin $i = 6.35$ $M_{\rm JUP}$ for the companion. The rms of the residuals to the Keplerian fit is 7.8 m s^{-1}

TABLE 3

VELOCITIES FOR HD 10697

JD ($-$2,450,000)	RV (m s^{-1})	Error (m s^{-1})
367.0617	-63.0	2.8
461.8056	-98.8	4.2
715.0682	-125.1	3.0
716.0976	-134.8	2.8
806.8627	-62.2	4.5
837.7322	-49.8	5.1
838.7081	-48.0	4.6
839.7260	-51.0	4.6
983.1289	20.6	2.6
1013.0972......	29.5	3.0
1014.0916......	31.5	2.7
1043.0700......	45.2	3.3
1044.0879......	40.7	2.9
1051.0464......	44.8	2.7
1068.9138......	57.3	2.9
1070.0916......	55.5	2.8
1070.9763......	56.8	2.9
1071.9868......	57.3	3.0
1072.9530......	51.5	3.1
1074.8834......	49.3	2.9
1075.8794......	59.0	2.6
1170.8261......	75.7	4.1
1342.1172......	24.9	3.1
1343.1171......	28.0	2.7
1368.1185......	5.0	3.1
1369.0795......	12.9	3.1
1374.1286......	0.0	3.0
1410.1192......	-25.3	2.9
1411.0250......	-25.9	3.1
1412.0736......	-34.7	3.2
1438.8873......	-56.6	3.1
1439.9187......	-53.0	3.0
1440.9339......	-46.9	3.2
1487.9494......	-111.4	3.7
1488.8072......	-97.2	3.7

TABLE 4

Velocities for HD 37124

JD (−2,450,000)	RV (m s^{-1})	Error (m s^{-1})
420.0466	47.8	3.7
546.7365	30.7	2.8
837.7662	1.2	2.8
838.9487	4.0	3.1
861.8046	23.7	3.3
1069.0362......	−1.7	2.7
1070.1319......	0.7	2.6
1071.1149......	0.0	3.3
1072.1295......	−4.2	3.0
1073.0296......	−8.0	3.1
1172.8957......	32.6	3.3
1226.7806......	−2.3	3.1
1227.7817......	−6.0	3.2
1228.7429......	−10.8	2.8
1412.1416......	−38.0	4.3

licity is nearly typical for field GK dwarfs. This is the lowest metallicity star known to have a planet. Most previous planet candidates have been found around metal rich host stars.

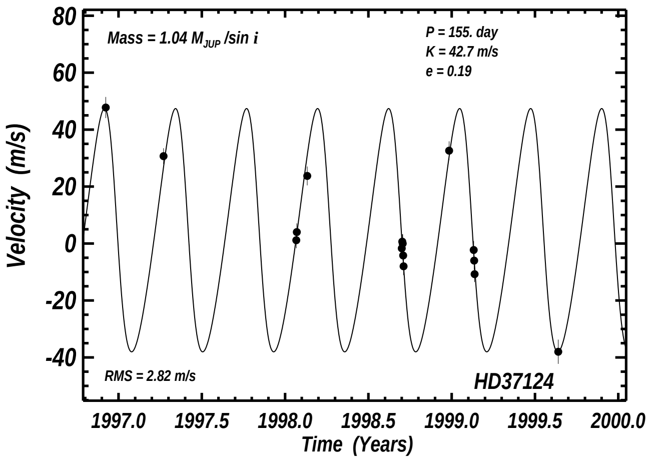

Fig. 5.—Velocities for HD 37124 (G4 V). The solid line is a Keplerian orbital fit, giving $P = 155.7$ days, $K = 43$ m s^{-1}, and $e = 0.19$, yielding $M \sin i = 1.04$ $M_{\rm JUP}$. The rms of the residuals 2.82 m s^{-1}.

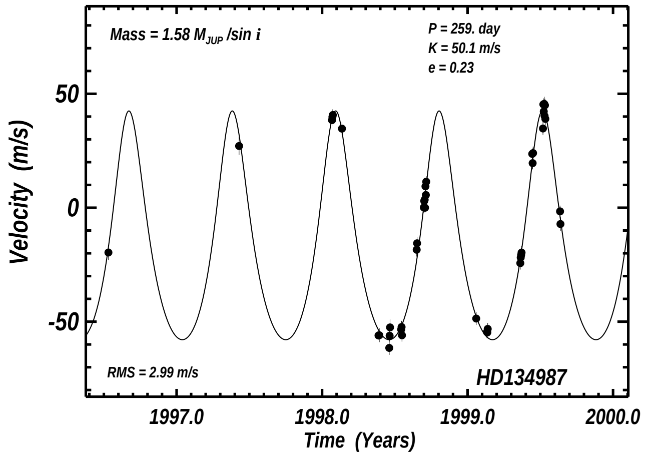

Fig. 6.—Velocities for HD 134987 (G5 V). The solid line is a Keplerian orbital fit, giving $P = 260$ days, $K = 50$ m s^{-1}, and $e = 0.24$, yielding $M \sin i = 1.58$ $M_{\rm JUP}$. The rms of the residuals 3.0 m s^{-1}.

3.3. *HD 134987*

HD 134987 (HR 5657, G5 V) is similar to 51 Peg in its spectral type, enhanced metallicity, and low chromospheric activity. But its planet has $P = 259$ days and $M \sin i = 1.58$ $M_{\rm JUP}$. We have made 43 Doppler observations spanning 3 yr, as shown in Figure 6 and listed in Table 5. The eccentricity is 0.24, quite noncircular as with all extrasolar planet candidates orbiting beyond 0.2 AU. The rms of the Keplerian fit to the measured velocities is 3.0 m s^{-1}, consistent with measurement errors.

The semimajor axis of the planetary orbit is $a = 0.81$ AU, yielding a maximum angular separation between planet and star of 39 mas. We expect a planet temperature of $T_{\rm eff} = 315$ K (Saumon et al. 1996). The amplitude of the associated astrometric wobble is 45/sin i μas.

3.4. *HD 177830*

HD 177830 is an evolved subgiant of spectral type K0 IV, with photometry placing it close to giant status, $M_V = 3.32$. It is difficult to estimate [Fe/H] of subgiants from photometry, and we are not aware of a spectroscopic analysis of metallicity. The stellar mass estimate of 1.15 ± 0.2 $M_\odot$ is based on placement on evolutionary tracks but is similarly suspect. Figure 7 shows a spectroscopic comparison of HD 177830 (*dotted line*) and the chromospherically inactive K dwarf σ Dra (*light solid line*) in the core of the Ca II H line. The heavy solid line is the chromospherically active K2 V star HD 192263, which will be discussed in the next subsection. Even slowly rotating, chromospherically inactive, main-sequence K dwarf stars, such σ Dra, show mild core reversal in Ca II H & K lines, while evolved K subgiants, like HD 177830, have "flat-bottomed" line cores.

We have made 29 velocity measurements of HD 177830 spanning 3 yr, as shown in Figure 8 and listed in Table 6. The orbital fit yields $P = 391.6$ days, $K = 34$ m s^{-1}, and $e = 0.41$, yielding $M \sin i = 1.22$ $M_{\rm JUP}$. The rms of the velocity residuals to the Keplerian fit is 5.2 m s^{-1}, again larger than our known errors.

The somewhat elevated rms of 5.2 m s^{-1} is probably related to the subgiant status of HD 177830. This star is a

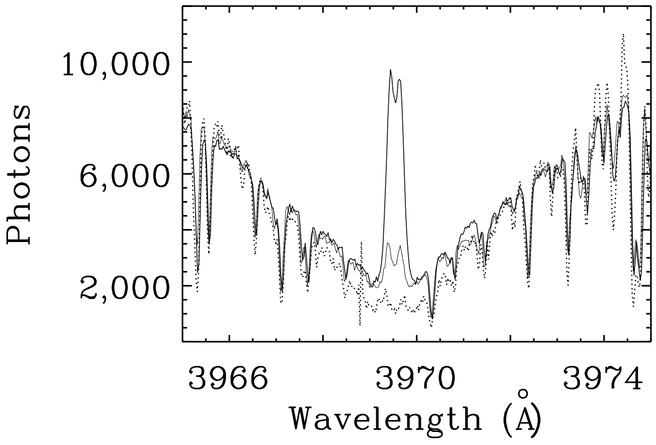

Fig. 7.—Comparison of Ca II H line core of HD 177830 (*dotted line*) with a chromospherically quiet K2 V star σ Draconis (*light solid line*). Slowly rotating K dwarfs show a mild core reversal, unlike the more evolved subgiants such as HD 177830, which have flat-bottomed cores. Dramatic line core reversal is seen in the rapidly rotating, chromospherically active, K2 V star HD 192263 (*heavy solid line*).

TABLE 5

VELOCITIES FOR HD 134987

JD (−2,450,000)	RV (m s^{-1})	Error (m s^{-1})
276.8020	−18.0	3.3
604.8935	28.7	3.9
838.1755	40.1	2.6
839.1727	41.5	2.7
840.1707	42.3	2.6
863.1203	36.3	2.8
954.9159	−54.4	1.8
956.9547	−54.4	3.0
981.8126	−59.9	3.0
982.8190	−54.6	2.5
983.8498	−50.9	3.5
1011.8011......	−51.8	2.6
1012.8005......	−50.7	2.7
1013.8006......	−54.4	2.8
1050.7730......	−16.8	3.0
1051.7547......	−14.0	2.6
1068.7306......	1.7	2.5
1069.7193......	4.6	2.2
1070.7242......	5.1	2.2
1071.7229......	1.6	2.1
1072.7204......	11.0	2.6
1073.7196......	7.2	3.4
1074.7070......	13.0	2.4
1200.1581......	−47.0	2.8
1227.0883......	−52.9	2.7
1228.1038......	−53.1	2.5
1229.1161......	−51.6	2.6
1310.8892......	−22.7	2.8
1311.9101......	−20.3	2.8
1312.9239......	−19.2	3.1
1314.0005......	−18.1	2.9
1340.8393......	25.2	2.4
1341.8853......	21.2	2.7
1342.8787......	25.6	2.9
1367.7877......	36.4	2.8
1368.7558......	47.0	2.6
1369.7821......	43.8	3.1
1370.8677......	47.2	3.1
1371.7599......	41.9	2.6
1372.7678......	46.6	2.8
1373.7712......	40.6	2.7
1410.7258......	0.0	2.5
1411.7251......	−5.5	3.0

very evolved subgiant, with $M_v = 3.32 \pm 0.1$. True K III giants often show complex velocity variability with periods ranging from less than a day to several hundred days. β Oph, a K2 III giant, shows evidence of multiple periodicities with timescales of less than 1 day and velocity amplitudes of ∼40 m s^{-1} (Hatzes & Cochran 1994). Velocity variations with periods of several hundred days have been observed in π Her (Hatzes & Cochran 1999) and Aldebaran and β Gem (Hatzes & Cochran 1993). Arcturus (Hatzes & Cochran 1993, 1994) shows both short- and long-period Doppler velocity variations with amplitudes of order 150 m s^{-1}. In contrast Horner (1996) surveyed four late-type giants with spectral types ranging from G8 III to K2 III and found these stars to be stable at the 25 m s^{-1} level.

Little is known about the intrinsic velocity stability of subgiants. The three stars on the Keck precision velocity program that most closely match the $B-V$ and absolute magnitude of HD 177830 are HD 136442, HD 208801, and HD 23249. These stars are stable at the 4–6 m s^{-1} level. It is thus probable that the observed velocity variations of HD 177830 are due to Keplerian orbital motion, but we cannot rule out intrinsic photospheric variations. This star should be followed up with precision photometry and line bisector studies.

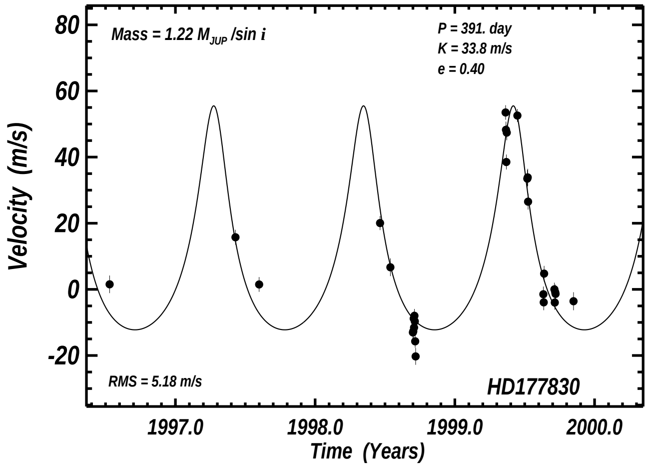

FIG. 8.—Velocities for HD 177830 (K0 IV). The solid line is a Keplerian orbital fit with $P = 391.6$ days, $K = 34$ m s^{-1}, and $e = 0.41$, yielding $M \sin i = 1.22\ M_{\rm JUP}$. The rms of residuals is 5.2 m s^{-1}.

The semimajor axis of the planetary orbit is $a = 1.10$ AU, yielding a maximum separation between planet and star of 27 mas. The planet is expected to have $T_{\rm eff} = 362$ K (Saumon et al. 1996), with some increase due to internal heating.

3.5. *HD 192263*

A planet around this star was recently announced by Santos et al. (1999) during the writing of this paper. They found the following orbital parameters: $P = 23.87 \pm 0.14$ days, $K = 65$ m s^{-1}, and a small but uncertain orbital eccentricity. Here we find $P = 24.4 \pm 0.07$ days, and $K = 68 \pm 11$ m s^{-1}, as listed in Table 2. Our 15 Keck velocity measurements are shown in Figure 9 and are listed in Table 7. The eccentricity, 0.03, derived from 40 observations of Santos et al. is somewhat lower than that derived from

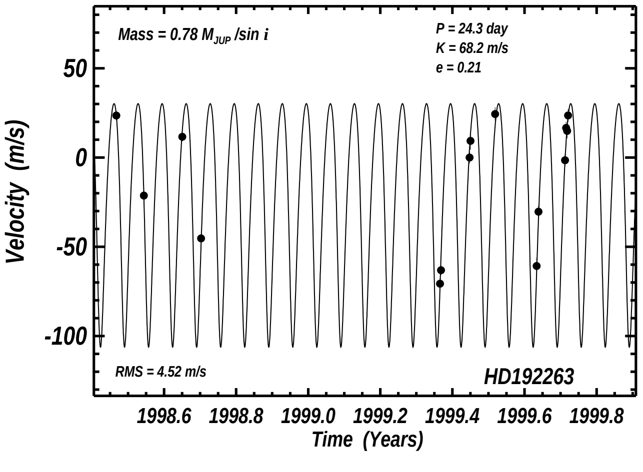

FIG. 9.—Velocities for HD 192263 (K0 V). The solid line is a Keplerian orbital fit with a $P = 24.36$ days, $K = 68$ m s^{-1}, and $e = 0.22$, yielding a minimum $M \sin i = 0.78\ M_{\rm JUP}$. The rms of the residuals is 4.5 m s^{-1}.

TABLE 6

VELOCITIES FOR HD 177830

JD (−2,450,000)	RV (m s^{-1})	Error (m s^{-1})
276.0345	0.0	2.5
605.0434	13.4	2.3
666.8855	0.0	2.3
982.9395	18.7	2.1
1009.9321	5.3	2.7
1068.8172	−15.0	2.0
1069.8500	−14.1	1.9
1070.8953	−10.5	2.2
1071.8312	−13.4	2.0
1072.8201	−9.7	2.1
1073.8180	−11.7	1.9
1074.8078	−17.8	2.0
1075.8981	−22.4	2.6
1311.1097	51.3	2.2
1312.1075	46.0	2.6
1313.1058	36.9	2.2
1314.1286	45.2	2.2
1341.9544	50.7	2.0
1367.9145	31.6	2.6
1368.9065	31.6	2.6
1369.9181	24.9	2.4
1409.8468	−3.5	2.4
1410.8018	−6.1	2.4
1411.7991	2.7	2.3
1438.7419	−2.1	2.0
1439.7602	−6.2	2.2
1440.8698	−3.4	2.3
1441.7234	−3.5	2.2
1488.7226	−3.0	2.7

TABLE 7

VELOCITIES FOR HD 192263

JD (−2,450,000)	RV (m s^{-1})	Error (m s^{-1})
984.0580	23.5	2.8
1011.9079	−21.3	2.6
1050.8738	11.6	2.6
1069.8856	−45.3	2.4
1312.0841	−70.7	3.1
1313.1102	−63.1	2.7
1342.0531	0.0	3.4
1342.9791	9.3	5.0
1367.9100	24.4	3.8
1409.9277	−60.8	4.6
1411.8736	−30.3	3.3
1438.7651	−1.5	3.4
1439.8239	16.6	3.4
1440.8836	14.9	4.2
1441.8293	23.6	3.6

our 15 Keck observations, $e = 0.22 \pm 0.14$, which indicates that the eccentricity is small but requires further observations to establish firmly. We find that $M \sin i = 0.78$ $M_{\rm JUP}$, $a = 0.15$ AU, implying an expected $T_{\rm eff} = 486$ K (Saumon et al. 1996).

HD 192263 is a rapidly rotating, chromospherically active, K0 dwarf with $R'_{\rm HK} = -4.37$ (Santos et al. 1999).

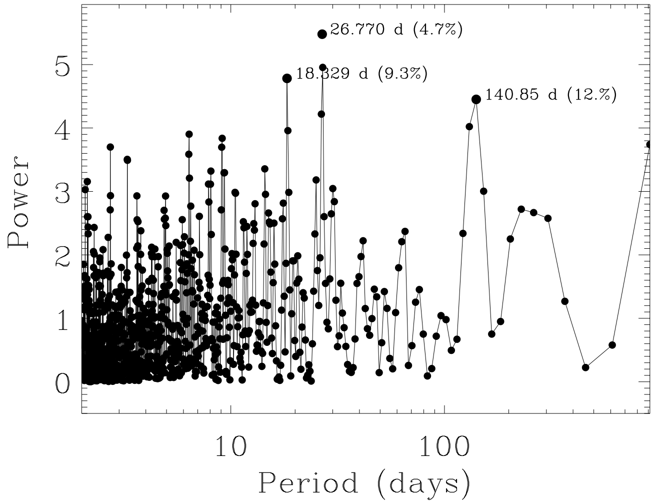

FIG. 10.—Periodogram of the chromospheric "*S*" measurements for HD 192263. The primary peak of 26.7 days is similar to the period, $P = 24$ days, exhibited in the velocities, leaving an ambiguous interpretation of the velocities. The orbital interpretation is favored (see text).

Figure 7 shows the line core reversal of the Ca II H line for HD 192263 (*dark solid line*). The slowly rotating chromospherically inactive K dwarf σ Dra is shown for comparison. Based on the measured $R'_{\rm HK}$ value of −4.37, we estimate that the intrinsic Doppler "jitter" for this star is 10–30 m s^{-1} (Saar et al. 1998). Figure 10 shows the periodogram of the chromospheric "*S*" value measurements from our 15 Keck spectra. The highest peak corresponds to a period of 26.7 days, uncomfortably close to the observed Doppler velocity period of 24 days. The false alarm probability for this periodogram peak is 4.7%, suggesting the peak may be coincidental. It remains possible that the velocity periodicity is not due to an orbiting body, but rather to surface effects. However, the stellar rotation period is expected to be ∼8 days from the chromospheric strength (Noyes et al. 1984). This short rotation period argues against rotational modulation of surface features as the cause of the velocity variations having $P = 24$ days.

Hipparcos found photometric variability for HD 192263 of ∼0.011 mag, which is low given its high chromospheric activity. This star should be subject to intensive photometric monitoring. If photometry or "*S*" value measure-

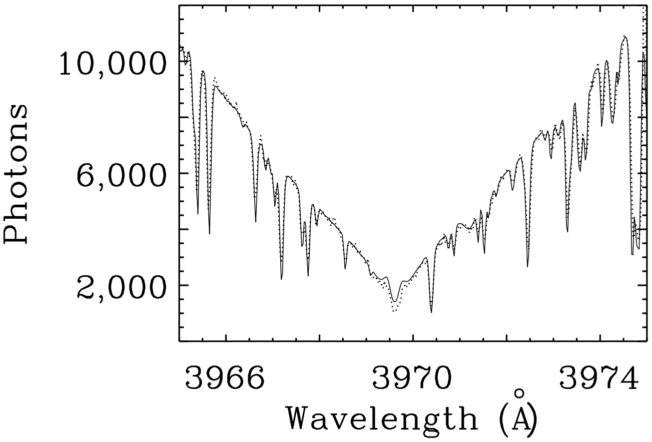

FIG. 11.—Comparison of Ca II H line core for HD 222582 (*dotted line*) with the Sun (*solid line*). The solar spectrum is remarkably similar to that of HD 222582 throughout the visible region.

ments continue to show periodicities similar to the observed Doppler velocity period, this would suggest that the source of the variations is intrinsic to the star rather than to an orbiting planet

The rotational Doppler broadening in the Keck/HIRES spectra implies $V \sin i < 3.0$ km s^{-1}, consistent with that found, $V \sin i = 1.8 \pm 1.2$ km s^{-1}, by Santos et al. (1999). Given the short rotation period of ~8 days, implied by the chromospheric activity, along with low $V \sin i$, the star must be viewed within 30° of pole-on. Such a pole-on vantage point is consistent with the nearly constant photometric brightness reported by *Hipparcos*. Apparently the chromospheric activity and spotted regions remain visible on the (polar) hemisphere during an entire rotation period. If the orbital plane of the companion is also nearly pole-on, its mass is considerably higher than $M \sin i$ of 0.78 $M_{\rm JUP}$. We also remain puzzled by the rms of 4.5 m s^{-1} of the velocity residuals to our Keplerian fit. This rms is just too low for such an active star, which should exhibit jitter of at least 10 m s^{-1}. Perhaps it is because the inclination angle is so low, and thus there is not much radial velocity jitter produced by the surface brightness inhomogeneities since they are not strongly rotationally modulated. We will continue to monitor the "S" value and Doppler velocities. For now, we are not yet completely convinced of a planet-companion interpretation for the velocity variations of HD 192263.

3.6. *HD 222582*

HD 222582 is a G5 dwarf. Figure 11 shows a comparison of the solar flux spectrum (Kurucz et al. 1984) and a spectrum of HD 222582, centered on the core of the Ca II H line with a resolution of $R \approx 80{,}000$. The many narrow absorption lines due to neutral metal atoms (mostly Fe I) have the same widths and depths in HD 222582 and the Sun, indicating that the two stars have similar temperature, abundances, and $V \sin i$. The core of the H line, formed in the chromosphere, is deeper in HD 222582, suggesting slightly weaker chromospheric and magnetic activity than that of the Sun.

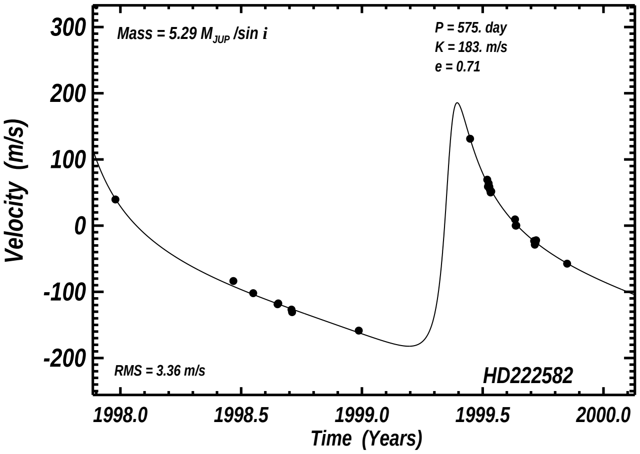

FIG. 12.—Velocities for HD 222582 (G5 V). The solid line is a Keplerian orbital fit with $P = 575.9$ days, $K = 184$ m s^{-1}, and $e = 0.71$, yielding $M \sin i = 5.29$ $M_{\rm JUP}$. The rms of the residuals is 3.36 m s^{-1}, consistent with measurement errors.

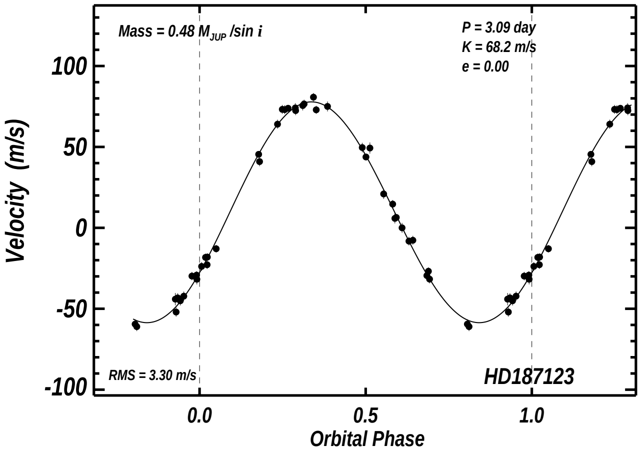

FIG. 13.—Phased velocities for HD 187123 (G3 V). The solid line is a Keplerian orbital fit with $P = 3.096$ days, a semiamplitude of 68 m s^{-1}, and an eccentricity of 0.01, yielding $M \sin i = 0.48$ $M_{\rm JUP}$. The rms of the residuals to the Keplerian fit is 3.29 m s^{-1}. A linear trend of -7 ± 2 m s^{-1} yr^{-1} has been removed here. This linear trend suggests presence of a second companion with an orbital period much longer than 2 yr.

We have made 24 Doppler observations spanning 1.7 yr, as shown in Figure 12 and listed in Table 8. The Keplerian shown in Figure 12 has $P = 575.9$ days, a velocity semi-amplitude, $K = 184$ m s^{-1}, and an eccentricity, $e = 0.71$, yielding a minimum mass, $M \sin i = 5.29$ $M_{\rm JUP}$. The rms to the Keplerian orbital fit is 3.4 m s^{-1}.

The semimajor axis of the orbit is $a = 1.35$ AU, yielding a maximum angular separation between planet and star of 55 mas. The amplitude of the astrometric wobble is 165/sin i μas. The effective temperature of the planet is expected to be 234 K (Saumon et al. 1996).

TABLE 8

VELOCITIES FOR HD 222582

JD (−2,450,000)	RV (m s^{-1})	Error (m s^{-1})
805.7232	40.0	3.3
984.1216	−83.5	3.9
1014.1166......	−101.7	3.2
1050.9569......	−118.6	3.1
1051.9943......	−117.5	3.1
1071.9679......	−126.7	3.2
1072.8569......	−130.5	2.9
1173.7117......	−158.4	5.0
1342.0968......	131.4	3.8
1368.0064......	69.5	3.6
1369.0076......	59.4	5.0
1370.0873......	63.8	3.1
1371.0903......	59.0	3.1
1372.0672......	54.5	3.8
1373.0733......	50.0	4.1
1374.0611......	52.1	3.3
1410.0295......	9.8	3.2
1411.0017......	0.0	3.2
1411.9651......	0.4	3.1
1438.8624......	−22.9	3.5
1439.9007......	−28.4	3.0
1440.8981......	−25.4	2.8
1441.9259......	−21.6	3.4
1488.7946......	−60.1	3.4

4. UPDATE OF PREVIOUSLY ANNOUNCED PLANETS

Orbital parameters for several previously announced extrasolar planet candidates are updated in this section based on recent Keck observations. The stellar properties of these stars are listed in Table 9, which has the same format as Table 1. The updated orbital parameters are listed in Table 10, while the individual Keck Doppler velocity measurements are listed in Tables 11–14 for HD 187123, HD 195019, HD 210277, and HD 217107, respectively.

We cannot at this time update the orbits for two stars, HD 168443 (Marcy et al. 1999) and Gliese 876 (Marcy et al. 1998; Delfosse et al. 1998), for which planetary companions were found previously in the Keck Doppler survey. As noted in those discovery papers, both stars continue to show small secular departures from simple Keplerian motion, making the fit to a single orbit imprecise. In the case of HD 168443, the velocity residuals to the Keplerian fit now exhibit a long-term trend with significant curvature (as of 1999 October), strongly indicative of a second companion with long period. However, more data are required to test the Keplerian nature of the velocity residuals for both stars and to place constraints on plausible orbits.

4.1. *HD 187123*

The Keck velocities for HD 187123 are listed in Table 11, and the phased velocities are shown in Figure 13 with a linear trend removed. The updated orbital elements shown in Table 10 are consistent with the discovery data (Butler et al. 1998), though the rms to the Keplerian fit has improved by about a factor of 2.

Two years of additional monitoring reveal a linear trend in the velocities with a slope of -7 ± 2 m s^{-1} yr^{-1}. This suggests the existence of a second companion with a period much longer than 3 yr. Another few years of monitoring will be required to determine if this slope is real. HD 187123 does not have any known companions.

4.2. *HD 195019*

The discovery of the planet around HD 195019 was initially announced from data collected with both the Lick 3 m and the Keck telescopes (Fischer et al. 1999). The newly derived orbit given here is in good agreement with the originally published orbit, but again with smaller velocity residuals owing to the improvements in our Doppler technique. The measured velocities are listed in Table 12, and the phased velocities are shown on Figure 14.

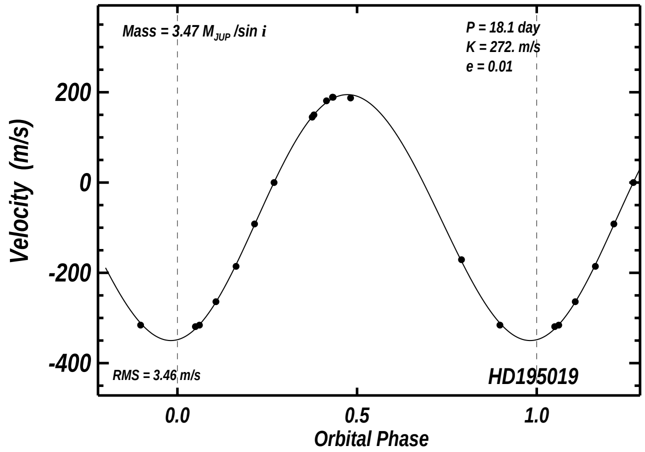

FIG. 14.—Phased velocities for HD 195109 (G3 V). The solid line is a Keplerian orbital fit with $P = 18.20$ days, $K = 272$ m s^{-1}, and $e = 0.02$, yielding $M \sin i = 3.47$ $M_{\rm JUP}$. The rms of the residuals to the Keplerian fit is 3.46 m s^{-1}.

With an orbital period of 18.2 days and a semimajor axis of 0.13 AU, this is the most distant planet yet found in a circular orbit, $e = 0.02 \pm 0.02$.

4.3. *HD 210277*

We have made 45 velocity measurements of HD 210277, listed in Table 13 and shown in Figure 15. The newly derived orbit confirms the orbit from the discovery paper (Marcy et al. 1999), but the rms (3.3 m s^{-1}) of the residuals to the orbital fit is again smaller by a factor of ~2 owing to our improved Doppler precision.

TABLE 9

STELLAR PROPERTIES OF PREVIOUSLY ANNOUNCED PLANETS

Star (HD)	Star (Hipp)	Spectral Type	$M_{\rm Star}$ ($M_\odot$)	V (mag)	$R'_{\rm HK}$	[Fe/H]	d (pc)
187123......	97336	G3 V	1.00	7.83	−5.00	+0.16	47.9
195019......	100970	G3 V	0.98	6.87	−5.02	+0.00	37.4
210277......	109378	G7 V	0.92	6.54	−5.03	+0.24	21.3
217107......	113421	G7 V	0.96	6.17	−5.06	+0.29	19.7

TABLE 10

ORBITAL PARAMETERS OF PREVIOUSLY ANNOUNCED PLANETS

Star (HD)	Period (days)	K (m s^{-1})	e	ω (deg)	T_0 (JD −2,450,000)	$M \sin i$ ($M_{\rm JUP}$)	N	rms (m s^{-1})
187123[a]......	3.0966 (0.0002)	68 (2)	0.01 (0.03)	324 (45)	1013.8 (0.31)	0.48	41	3.29
195019.......	18.200 (0.006)	272 (4)	0.02 (0.02)	227 (33)	1306.5 (2)	3.47	14	3.46
210277.......	436.6 (4)	39 (2)	0.45 (0.03)	118 (6)	1428 (4)	1.23	45	3.24
217107[b]......	7.1260 (0.0007)	140 (3)	0.14 (0.02)	31 (7)	1331.4 (0.2)	1.27	21	4.20

[a] Additional slope is -7 ± 2 m s^{-1} yr^{-1}.

[b] Additional slope is 40 ± 3 m s^{-1} yr^{-1}.

TABLE 11

VELOCITIES FOR HD 187123

JD (−2,450,000)	RV ($m\ s^{-1}$)	Error ($m\ s^{-1}$)
805.7017	−9.1	2.3
983.0277	76.9	2.6
1009.9419......	−23.9	2.7
1011.1156......	74.9	3.1
1011.8744......	−8.4	2.7
1012.0665......	−31.8	2.6
1012.8400......	−45.2	2.9
1012.9485......	−30.0	2.6
1013.0751......	−18.4	2.4
1013.7906......	73.0	2.8
1013.9150......	72.3	2.8
1014.0811......	80.6	2.6
1043.0075......	−30.2	1.8
1043.9607......	−32.5	3.2
1044.0560......	−23.6	2.6
1050.7296......	44.5	1.7
1051.0040......	73.0	1.9
1051.7296......	42.9	1.6
1052.0122......	5.5	2.1
1068.8311......	−19.3	2.3
1069.8458......	71.7	2.5
1070.8914......	−28.1	2.5
1071.8273......	−30.5	2.4
1072.8169......	74.3	3.0
1073.8431......	−9.0	2.7
1074.8048......	−43.6	2.9
1312.1143......	0.0	3.1
1341.0340......	−50.5	3.8
1341.9865......	57.6	2.8
1342.9757......	14.5	3.1
1367.9201......	−6.9	3.1
1368.9109......	−58.9	2.9
1370.0220......	67.2	3.0
1370.9293......	7.7	2.5
1372.0223......	−50.3	2.9
1373.0195......	66.1	2.7
1373.8137......	42.3	3.5
1409.9445......	33.2	2.9
1410.9016......	41.9	2.9
1411.8813......	−67.2	3.0
1439.7663......	−69.3	2.7

TABLE 12

VELOCITIES FOR HD 195019

JD (−2,450,000)	RV ($m\ s^{-1}$)	Error ($m\ s^{-1}$)
1068.8520......	−319.2	2.9
1069.8930......	−264.0	2.9
1070.9127......	−185.7	2.6
1071.8489......	−91.8	2.8
1072.8369......	0.0	3.0
1074.8568......	149.9	2.7
1075.7970......	189.1	4.2
1312.0909......	181.0	3.1
1342.0562......	−315.9	3.2
1367.9120......	187.3	3.4
1409.9302......	−170.9	3.1
1411.8760......	−315.8	2.9
1438.7673......	144.9	2.8
1439.8259......	188.9	3.1

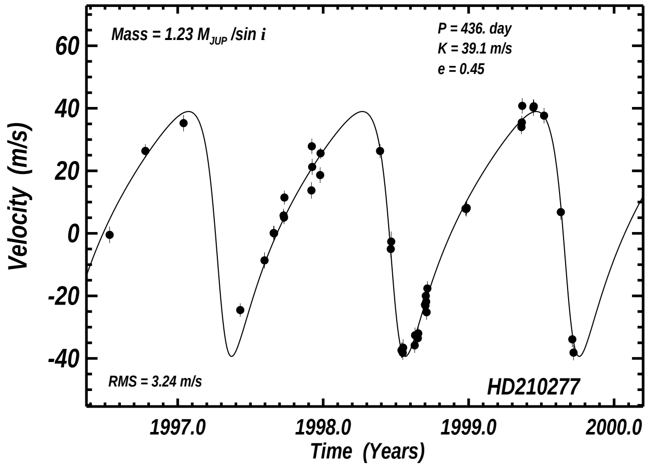

FIG. 15.—Doppler velocities for HD 210277 (G7 V). The implied orbital parameters are $P = 436.6$ days, $K = 39\ m\ s^{-1}$, and $e = 0.45$, giving $M \sin i = 1.23\ M_{JUP}$. The rms of the residuals is 3.24 m s^{-1}.

The new orbit implies $a = 1.10$ AU and $e = 0.45 \pm 0.03$. The maximum separation between the companion and the primary is 75 mas, and the amplitude of the astrometric variation is 65/sin i μas. The expected equilibrium temperature of the companion is 243 K.

4.4. *HD 217107*

We have made 21 Keck velocity measurements of HD 217107, listed in Table 14 and shown in Figure 16 with a linear trend of 40 m s^{-1} yr^{-1} removed from this plot. The updated orbit agrees with the orbit from the discovery paper (Fischer et al. 1999), which was based on data from both the Lick and Keck Observatories.

The current Lick observations (51 measurements) reveal a linear trend in the velocity residuals to the orbital fit, strongly indicative of a second companion. A simultaneous

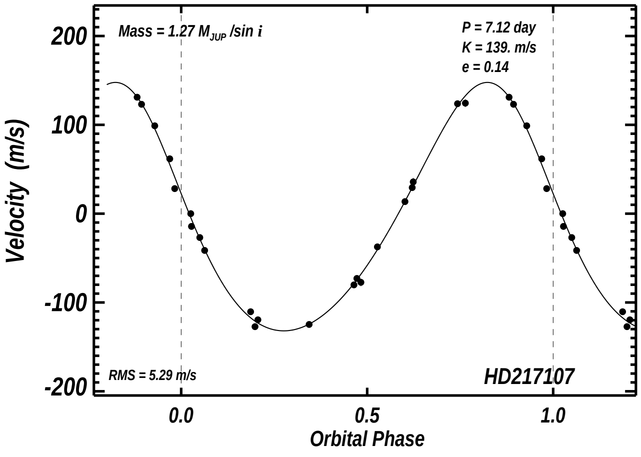

FIG. 16.—Phased velocities for HD 217107 (G7 V). The solid line is a Keplerian orbital fit giving $P = 7.126$ days, $K = 140\ m\ s^{-1}$, and $e = 0.14$, yielding $M \sin i = 1.27\ M_{JUP}$. An apparent linear trend of 40 m s^{-1} yr^{-1} has been removed from the measured velocities prior to performing the fit. This linear trend suggests a second companion with an orbital period much longer than 2 yr and mass $> 4\ M_{JUP}$. The rms of the residuals to the Keplerian fit is 4.20 m s^{-1}.

TABLE 13

VELOCITIES FOR HD 210277

JD (−2,450,000)	RV (m s^{-1})	Error (m s^{-1})
277.0413	−2.2	2.6
366.7926	24.6	2.2
462.7062	33.5	2.6
605.0940	−26.3	2.2
665.9876	−10.4	2.6
688.9457	−1.7	2.4
689.9833	−1.8	2.3
713.8792	3.9	2.2
714.9728	3.3	2.1
715.9286	9.7	2.2
783.7124	12.0	2.6
784.7205	26.1	2.5
785.6995	19.5	2.6
805.7146	16.9	2.5
806.7032	23.8	1.8
956.0877	24.6	2.2
983.0511	−6.8	2.7
984.0878	−4.4	3.2
1010.0261......	−39.2	2.5
1011.1015......	−39.4	2.2
1011.9692......	−38.9	2.2
1013.0816......	−40.0	2.2
1014.0859......	−38.3	2.7
1043.0057......	−37.6	2.4
1043.9942......	−34.4	2.5
1050.9169......	−35.3	1.6
1051.9839......	−33.8	2.0
1068.8670......	−24.6	2.1
1069.9748......	−24.9	2.2
1070.9566......	−21.8	2.3
1071.8706......	−23.6	2.3
1072.9307......	−27.0	2.4
1074.8716......	−19.4	2.3
1170.6885......	6.1	2.2
1172.6894......	6.1	2.5
1173.6868......	6.4	2.1
1311.1031......	32.2	2.3
1312.0938......	33.7	2.1
1313.1131......	39.0	2.5
1341.1060......	38.5	2.7
1342.0662......	38.9	2.0
1367.9567......	35.9	2.5
1410.0179......	5.0	2.4
1438.8105......	−35.7	2.5
1441.9290......	−39.9	2.4

TABLE 14

VELOCITIES FOR HD 217107

JD (−2,450,000)	RV (m s^{-1})	Error (m s^{-1})
1068.8595......	−20.9	2.7
1069.9728......	−114.4	2.9
1070.9542......	−119.6	2.0
1071.8687......	−68.2	2.4
1072.9288......	34.5	2.7
1074.8695......	128.6	2.5
1075.8261......	−8.1	3.6
1171.7040......	−58.4	4.6
1172.7064......	53.3	4.9
1173.7052......	142.3	4.8
1312.1031......	−78.6	3.1
1343.0337......	−2.9	2.9
1367.9608......	37.2	3.5
1371.0873......	−43.4	2.7
1372.0642......	50.7	2.8
1373.0712......	161.3	3.2
1374.0587......	169.1	3.2
1410.0248......	140.3	2.7
1410.9805......	0.0	3.0
1411.9452......	−85.9	2.8
1438.8143......	107.0	2.6

fit of the Lick velocities to a model composed of a Keplerian orbit plus a trend yields a best-fit trend of 43.3 ± 2.8 m s^{-1} yr^{-1} and a period of $P = 7.127 \pm 0.001$ days (D. A. Fischer 1999, private communication). We attempted the same type of model fit to the Keck velocities and found a best-fit trend of 39.4 ± 3.5 m s^{-1} yr^{-1} and $P = 7.126 \pm 0.001$ days. Thus the velocity trend in the Lick data are confirmed independently by those from Keck.

The Keck data yield an orbital eccentricity, $e = 0.14 \pm 0.02$, in agreement with that from Lick (Fischer et al. 1999). Thus the noncircular orbit for such a close companion ($a = 0.072$ AU) raises questions about the tidal circularization timescale. Perhaps the eccentricity is driven by another companion, indeed possibly that which causes the linear velocity trend. The velocities indicate that any second companion must have a period longer than 2 yr and a mass greater than 4 $M_{\rm JUP}$. Follow-up work with astrometry and high-resolution IR imaging is warranted to detect this possible second companion.

5. DISCUSSION

Our Keck program has gathered velocity measurements for 3 yr, making it sensitive to planets orbiting out to 2 AU. Including the six new planet candidates described in this paper, the Keck survey has resulted in the discovery or codiscovery of 12 extrasolar planet candidates. The current precision of the Keck survey, held over the 3 yr time base, is 3 m s^{-1}, sufficient to eventually make 3 σ detections of Jupiter-mass companions in 5 AU orbits, should they exist. However, another decade of data will be required before the Keck survey will begin probing planets in these 5 AU orbits. We are working to improve single-shot precision with the Keck system to 2 m s^{-1}.

Four of the six newly discovered planets have minimum masses ($M \sin i$) less than 2 $M_{\rm JUP}$. Figure 17 shows the latest mass distribution of the known extrasolar planets (Marcy et al. 2000). The high incidence of companions having $M \sin i < 2\ M_{\rm JUP}$ adds further support to a planetary mass distribution that begins a dramatic rise at about 5–6 $M_{\rm JUP}$ and increases toward the lowest detectable masses from 8 to 0.5 $M_{\rm JUP}$ (Butler & Marcy 1997). Below 0.5 $M_{\rm JUP}$, detectability drops markedly. The highest planetary masses are apparently $\sim 8\ M_{\rm JUP}$, and this may constitute a physical upper limit that should be explained by planet-formation theory, perhaps via tidal truncation of growth in the protoplanetary disk (Bryden et al. 1999; Nelson et al. 1999). Having said that, we are not implying that this represents some formal upper limit, above which planets then become brown dwarfs. The dividing line between planets and brown dwarfs is not likely to be so sharp in the $M \sin i$ plane.

It is important to keep in mind here that there is no bias against brown dwarf companions in the Lick, Keck, or Geneva surveys. Indeed, the CORAVEL survey found 11

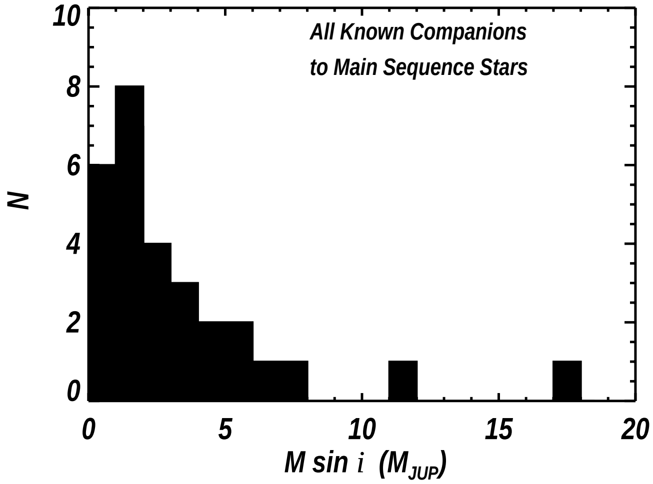

FIG. 17.—Mass histogram for all known planetary companions to main-sequence stars.

brown dwarf "candidates" orbiting within 5 AU (Duquennoy & Mayor 1991; Mayor et al. 1997). However, *Hipparcos* astrometry (Halbwachs et al. 1999) has subsequently revealed that most of these 11 brown dwarf candidates previously identified from the low-precision CORAVEL survey are, in fact, M dwarfs viewed at low inclination angles.

Nonetheless, companions of 10–80 $M_{\rm JUP}$ are much easier to detect than those of Jupiter-mass. But the most massive companion found to date from any precision velocity survey is 70 Vir b, with 7.4 $M_{\rm JUP}$ (Marcy & Butler 1996). Our Keck survey has *not* revealed any "brown dwarf candidates" (defined by $M \sin i = 10$–80 $M_{\rm JUP}$) out of the 530 stars being surveyed. Thus the occurrence of brown dwarf companions within 2 AU resides below 0.5%, in agreement with the few detections from previous surveys (Cumming, Marcy, & Butler 1999; Halbwachs et al. 1999).

More than 1000 stars have been surveyed for 2 yr or longer by the Geneva group and by our surveys, from which five "51 Peg–like" planets have emerged, with orbital periods less than 5 days. Precision Doppler programs are strongly biased toward detecting these planets. Thus we estimate that $\sim$0.5% of main-sequence stars have these "hot Jupiter" companions. Four planets have been found with orbital periods between 7 and 20 days, and the distribution of orbital radii is steadily filling in, suggesting a continuous and nearly flat distribution of semimajor axes above 0.04 AU.

The eccentricities of the six newly announced planet candidates range from 0.12 to 0.71. All of the extrasolar planets orbiting beyond 0.2 AU, now numbering 17, have eccentricities, $e \geq 0.1$. For comparison, the eccentricities of Jupiter and Earth are 0.05 and 0.017, respectively. HD 222582 has the largest eccentricity, 0.71, of any planet found to date. Unlike the other extreme eccentricity case, 16 Cyg B, HD 222582 has no known stellar companion. These eccentric extrasolar planet orbits may arise from gravitational interactions with other planets or stars or from resonant interaction with the protoplanetary disk. Whatever the ultimate cause of eccentric orbits, the growing ubiquity of high-eccentricity systems seems to suggest that "minimum entropy" planetary systems, like our own, with its suite of nested coplanar nearly circular orbits, may be rare.

Most of the stars with known planetary companions are metal-rich relative to the Sun (Gonzalez et al. 1999; Gonzalez & Vanture 1998; Gonzalez 1997, 1998). Two of the six new candidates described here are metal-rich, but two are metal- poor (Table 1), one has nearly solar abundances, and the metallicity of the remaining star is not yet known. Thus these six new planet-bearing stars do not add any additional support to the suspected metallicity correlation.

The Keck survey, after 3 yr, is now detecting planets out to 2.1 AU and is thus marching through and able to probe the interesting "habitable zone" (HZ) defined by Kasting, Whitmire, & Reynolds (1993) around main-sequence stars. Five of the six new planets lie either directly in, or near the edges of, the habitable zones for their stars. HD 10697 orbits at 1.87–2.39 AU, just at the outer edge of the HZ for a G5 V star but probably well within the HZ for its evolved G5 IV star. Its equilibrium insolation temperature is expected to be 274–284 K. HD 37124 orbits at 0.45–0.65 AU with an expected temperature of $T_{\rm eff} = 327$ K. It lies at the inner edge of the HZ for its G4 V star. HD 134987 orbits at 0.62–1.00 AU with a $T_{\rm eff} = 315$ K, solidly in the HZ for its G5 V star. HD 177830 orbits at 0.63–1.57 AU, with an expected $T_{\rm eff} = 362$ K. It would lie at the inner edge of the HZ for a K0 star but is probably slightly outside the inner edge since its star is an evolved subgiant. HD 222582 has an orbital semimajor axis of 1.35 AU, but the orbit is quite eccentric, and its orbital distance varies from 0.39 to 2.31 AU. It has an expected $T_{\rm eff} = 234$ K and also lies directly in the HZ of its G5 V star. Whether or not water could exist in liquid form, either in the atmospheres of these gas giants or possibly on accompanying moons, is beyond our ability to say at present and requires further detailed theoretical modeling of planetary atmospheres (Burrows & Sharp 1999).

Complementary extrasolar planet detection techniques include photometric transit surveys, interferometric astrometry, IR imaging of dust disks (Trilling et al. 1998; Trilling, Brown, & Rivkin 1999; Koerner et al. 1998; Schneider et al. 1999), and spectroscopic searches for reflected light (Cameron et al. 1999; Charbonneau et al. 1999). Several of the new planet candidates provide good targets for these new techniques. In particular, HD 10697 and HD 222582 will have minimum astrometric amplitudes of 373 and 165 μas, and astrometric detection will yield unambiguous masses.

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