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SEVEN NEW KECK PLANETS ORBITING G AND K DWARFS[1]

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ABSTRACT

Planetary mass companions orbiting seven nearby G and K dwarfs have been found from the Keck Precision Doppler Survey. A "51 Peg–like" planet orbiting HD 49674 has the smallest mass yet found, $M \sin i = 0.12\ M_J$. This system does not transit. A double-planet system orbits HD 37124, with periods of 153 days and 6 yr and minimum masses of 0.91 and 1.70 M_J. Single companions with moderate eccentricity have been found orbiting HD 108874, HD 72659, HD 114729, and HD 145675 with orbital periods ranging from 1.09 to 5.98 yr, yielding minimum masses ranging from 0.90 to 4.87 M_J. Periodic Doppler velocity variations, consistent with a mildly eccentric planet in a 1 AU orbit, are reported for the chromospherically active K0 dwarf HD 128311. It remains plausible that these velocity variations are due to stellar photospheric "jitter."

Subject headings: planetary systems — stars: individual (HD 37124, HD 49674, HD 72659, HD 108874, HD 114729, HD 128311, HD 145675)

1. INTRODUCTION

The discovery of extrasolar planets, especially those with large semimajor axes and low masses, improves our understanding of the overall properties of planets (see Marcy & Butler 2000; Jorrisen, Mayor, & Udry 2001). A current list of planets that have been published in refereed journals is given by Butler et al. (2002c). The observed distribution of semimajor axes constrains models of the formation and migration of giant planets (Butler et al. 2002a, Bodenheimer, Hubickyj, & Lissauer 2000; Kley, D'Angelo, & Henning 2001; Armitage et al. 2002). Moreover, the apparent correlation between metallicity and occurrence of planets may depend on the orbital distance of the planet and selection effects of the host stars (Fischer et al. 2002a; Murray & Chaboyer 2002).

To find extrasolar planets having low masses or large orbits requires high Doppler precision, which in turn requires high-quality spectra. The Keck Precision Doppler Survey began operation in 1996 July and has maintained a precision of 3 m s^{-1}. The Keck survey includes ~650 main-sequence and subgiant stars of spectral type F–M, with distances mostly within 50 pc. An additional 200 stars have one or more Keck observations but have been subsequently dropped from the program because of high chromospheric activity, a previously unknown spectroscopic companion, or a pre–*Hipparcos* Catalog mistake in spectral class. The Keck program has discovered or co-discovered about 25 extrasolar planets to date (Butler et al. 2002c). Highlights include the discovery of the only known transit planet (Henry et al. 2000b; Charbonneau et al. 2000), the first two sub-Saturn planets (Marcy, Butler, & Vogt 2000a), and several multiple-planet systems (Marcy et al. 2001a, 2001b; Fischer et al. 2002b).

In this paper we present evidence for seven planets, including single planets with moderate orbital eccentricity around HD 108874, HD 114729, HD 145675, and HD 72659, a large-amplitude planet orbiting the chromospherically active star HD 128311, a "51 Peg–like" planet orbiting HD 49674 with the smallest $M \sin i$ mass yet found, and a second planet orbiting HD 37124. Section 2 of this paper will describe the Keck Doppler measurements and the resulting Keplerian fits for these seven stars. This will be followed by a discussion in § 3.

2. DOPPLER VELOCITIES AND PERIODICITIES

Precise Doppler measurements are made with the High Resolution Echelle Spectrometer (HIRES; Vogt et al. 1994) on the 10 m Keck I telescope, operated at a resolution of $R \sim 80,000$. Wavelength calibration is carried out by means of an iodine absorption cell (Marcy & Butler 1992), which superimposes a reference iodine spectrum directly on the stellar spectra (Butler et al. 1996). This system currently achieves photon-limited measurement precision of 3 m s^{-1}. Detailed information including demonstration of stable stars can be found in Vogt et al. (2000).

The seven main-sequence stars examined here range in spectral type from G0 through K0. Relative to the Sun, three of the stars are metal-poor, while three are super–metal-rich with [Fe/H] > 0.3. Stellar properties of these seven stars are listed in Table 1. The first two columns provide the HD and the *Hipparcos* Catalog numbers, respectively. Spectral types are from a calibration of *Hipparcos*-derived $B-V$ and absolute magnitudes. The stel-

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

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TABLE 1
STELLAR PROPERTIES

Star (HD)	Star (Hipp)	Spectral Type	$M_{\rm Star}$ ($M_\odot$)	V (mag)	$B-V$	$\log R'_{\rm HK}$	[Fe/H]	d (pc)
37124	26381	G4 V	0.91	7.68	0.667	−4.88	−0.42	33.2
49674	32916	G5 V	1.00	8.10	0.729	−4.80	0.25	40.7
72659	42030	G0 V	0.95	7.46	0.612	−5.00	−0.14	51.4
108874	61028	G5 V	1.00	8.76	0.738	−5.07	0.14	68.5
114729	64459	G0 V	0.93	6.68	0.616	−5.02	−0.22	35.0
128311	71395	K0 V	0.80	7.48	0.973	−4.39	0.08	16.6
145675	79248	K0 V	1.00	6.64	0.877	−5.07	0.35	18.1

lar masses are estimated by interpolation of evolutionary tracks (Fuhrmann 1998; Fuhrmann, Pfeiffer, & Bernkopf 1997). The [Fe/H] values are from LTE spectral synthesis of our Keck HIRES spectra. Table 2 lists the best-fit Keplerian orbital parameters for the seven new systems.

Figure 1 shows the Ca II H line of the five G stars and the Sun for comparison. Figure 2 shows Ca II for the two K stars; $\log R'_{\rm HK}$ values for the G stars range from −4.80 to −5.07, consistent with chromospherically quiescent, slowly rotating stars, with ages ranging from 2 to 7 Gyr. The Doppler "jitter" associated with this level of stellar surface activity is 2.5–4 m $\rm s^{-1}$ (Saar, Butler, & Marcy 1998; Saar & Fischer 2000; Santos et al. 2000).

The Ca II H line for the two K dwarfs are shown in Figure 2. The level of chromospheric activity of the two K dwarfs is dramatically different. HD 145675 is chromospherically quiet with $\log R'_{\rm HK} = -5.07$, while HD 128311 is extremely

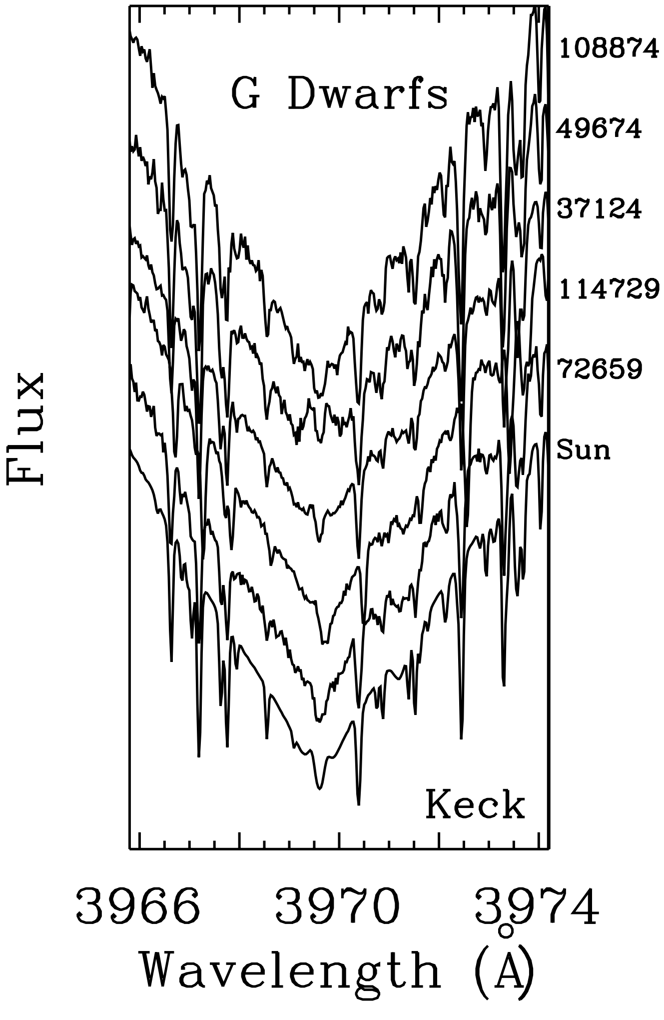

FIG. 1.—Ca II H line cores for five G dwarfs in ascending order of $B-V$. The HD catalog number of each star is shown along the right-hand edge. The Sun is shown for comparison. The $R'_{\rm HK}$ values derived from the H and K lines are similar to the Sun, indicating rotation periods of 20 days or longer and photospheric Doppler jitter of 4 m $\rm s^{-1}$ or less.

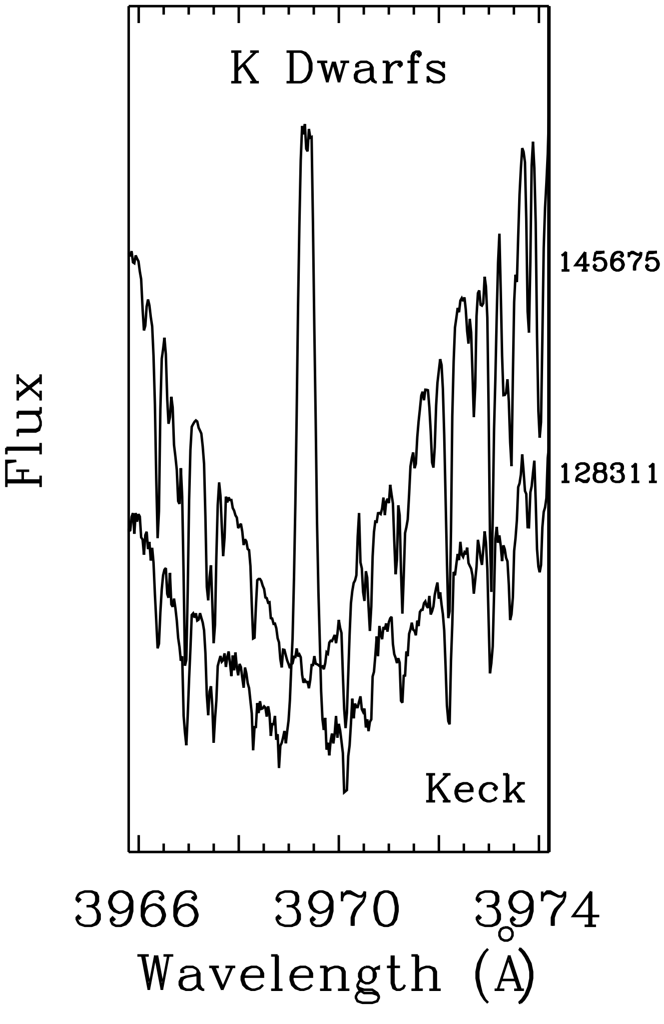

FIG. 2.—Ca II H line cores for two K dwarfs. The HD catalog number of each star is shown along the right-hand edge. Even slowly rotating K dwarfs show mild line core reversal. Dramatic line core reversal is seen in the rapidly rotating, chromospherically active, K0 V star HD 128311.

TABLE 2

Orbital Parameters

Star	Period (days)	K (m s^{-1})	e	ω (deg)	T_0 (JD−2,450,000)	$M \sin i$ (M_J)	a (AU)	N_{obs}	rms (m s^{-1})
145675	1724 (50)	89 (3)	0.37 (0.04)	15 (15)	1353 (30)	4.89	2.82	35	3.71
108874[a]	397.5 (4)	48 (4)	0.17 (0.06)	256 (30)	1310.6 (5)	1.71	1.06	18	7.82
72659	2185 (3000)	42 (20)	0.18 (0.2)	350 (100)	2140 (500)	2.55	3.24	12	6.98
114729	1135 (9)	18 (3)	0.32 (0.18)	73 (30)	451 (300)	0.84	2.08	38	5.34
128311[b]	422 (10)	85 (7)	0.31 (0.1)	228 (40)	28 (30)	2.57	1.02	30	29.5
49674[c]	4.948 (0.003)	14 (2)	0	0	1883.7 (0.1)	0.12	0.0568	24	5.55
37124 b	153.0 (1)	35 (4)	0.10 (0.06)	97 (40)	1227 (300)	0.86	0.54	30	4.42
37124 c	1942 (400)	19 (4)	0.40 (0.2)	265 (120)	1828 (400)	1.01	2.95	30	4.42

[a] Linear slope 7(3) m s^{-1} yr^{-1}.

[b] Linear slope 30(3) m s^{-1} yr^{-1}.

[c] Forced circular orbit.

active with $\log R'_{\rm HK} = -4.39$. Only planets that induce large-amplitude reflex velocities can be found around active stars since the associated Doppler jitter of 10–50 m s^{-1} can overwhelm the Keplerian signature of an orbiting planet.

2.1. *HD 145675*

The planet around HD 145675 (=14 Her) was originally announced in 1998 July based on ELODIE data.[7] This planet has not been described previously in any refereed journal, nor have Doppler velocity measurements been made public. Thus, we report here our velocities, errors, and Keplerian fits for this star.

The spectral type of HD 145675 is K0V, consistent with its $B-V$ of 0.88 (Perryman et al. 1997). Nonetheless, we estimate the mass to be 1.0 ± 0.05 $M_\odot$ from evolutionary models because the star is metal-rich (Taylor 1996). We derive $[\mathrm{Fe/H}] = 0.35$ from our Keck spectra, consistent with Taylor (1996), but ∼0.1 dex lower than the analysis of Feltzing & Gonzalez (2001). The star is chromospherically quiet, with $\log R'_{\rm HK} = -5.07$, based on the average of the 35 measurements of the Ca ii H and K lines obtained simultaneously with each Doppler measurement.

The Geneva team has described velocities of HD 145675 in two conference proceedings (Marcy, Cochran, & Mayor 2000b; Udry et al. 2002) with the orbital period, Doppler amplitude, and minimum mass all increasing by ∼10% between the first and second meetings. Their quoted orbital period and $M \sin i$ values were 4.44 yr, 3.3 M_J and 4.90 yr, 4.2 M_J, respectively, from the two conferences. The latter paper quotes an eccentricity $e = 0.34$.

We have obtained 35 Doppler measurements of HD 145675 between 1997 June and 2002 July. The velocities are listed in Table 3 and plotted in Figure 3. The solid line is the best-fit Keplerian. The period is 4.72 ± 0.1 yr, the semiamplitude is $K = 89$ m s^{-1}, and the eccentricity is $e = 0.37 \pm 0.02$. Uncertainties in the orbital parameters are derived from Monte Carlo simulations of synthetic velocity sets constructed by adding random velocity noise, consistent with measurement uncertainty, to the measured velocities listed in Table 3.

The minimum mass of the planet is 4.89 M_J. This is significantly higher than that found by the Geneva Team, with the difference stemming from our use of a stellar mass of 1.0 $M_\odot$, which takes into proper account the high metallicity of the star. The semimajor axis is 2.82 AU. The rms to the Keplerian fit to the Keck data is 3.71 m s^{-1}, while the rms to the Keplerian fit of the ELODIE data is 12.7 m s^{-1} (Udry et al. 2002).

TABLE 3

Velocities for HD 145675

JD (−2,450,000)	RV (m s^{-1})	Error (m s^{-1})
605.9115.....................	−83.2	2.1
862.1412.....................	−43.1	2.2
956.0369.....................	−29.2	2.3
1009.8790..................	−7.3	2.5
1069.7490..................	10.3	2.1
1073.8392..................	14.2	2.8
1173.1752..................	48.7	2.3
1200.1776..................	56.6	2.1
1227.1375..................	65.1	2.0
1310.9956..................	91.8	2.3
1314.0771..................	91.7	2.4
1340.9326..................	92.1	1.0
1367.8354..................	83.6	2.3
1373.9145..................	83.7	2.4
1409.8196..................	71.6	2.4
1410.7740..................	65.8	2.2
1411.7784..................	68.8	2.0
1438.7136..................	52.9	2.4
1581.1600..................	−15.3	2.2
1586.1584..................	−19.6	2.4
1680.0536..................	−47.1	2.2
1702.9464..................	−57.0	2.2
1755.7947..................	−63.1	2.1
1983.1538..................	−85.1	2.5
2003.9924..................	−89.0	2.7
2009.0651..................	−77.5	2.6
2030.9380..................	−92.2	3.1
2061.9081..................	−84.7	2.9
2062.9240..................	−78.1	2.8
2096.8833..................	−80.7	3.0
2128.8263..................	−87.0	2.5
2161.7864..................	−84.8	2.7
2390.0598..................	−70.1	3.0
2446.8697..................	−68.1	2.7
2486.7329..................	−60.4	2.3

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[7] See http://obswww.unige.ch/~udry/planet/14her.html.

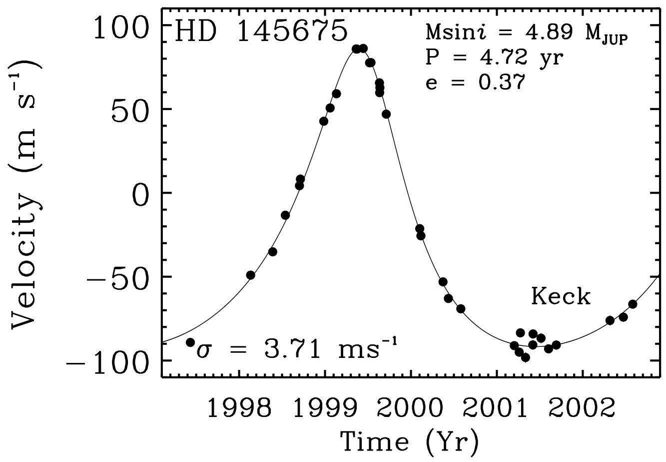

FIG. 3.—Doppler velocities for HD 145675. The solid line is the best-fit Keplerian orbit. The orbital parameters derived from the Keck Doppler velocities are similar to the those reported from the unpublished ELODIE Doppler data for this star, although the rms to the Keplerian fit to the Keck data is about a factor of 4 smaller.

2.2. *HD 108874*

At $V = 8.76$, HD 108874 is among the faintest G dwarfs monitored to date by precision Doppler velocities. This star was added to the Keck program in 1999 based on its identification as a metal-rich star (Laughlin 2000).

A total of 20 observations, obtained between 1999 June and 2002 June, are shown in Figure 4 and listed in Table 4. The solid line in Figure 4 shows the best-fit Keplerian. The orbital period is 398 ± 4 days, the semiamplitude (K) is 48 m s^{-1}, and the eccentricity is 0.17 ± 0.06. The rms to the Keplerian is 7.82 m s^{-1}, yielding a reduced $(\chi_\nu^2)^{1/2}$ of 1.70, indicating velocity discrepancies that are slightly greater than the expected photon-limited precision of 5 m s^{-1}.

With $M \sin i$ of 1.71 M_J and a semimajor axis of 1.06 AU, this is typical of the dominant class of planets, the eccentric giants. At a distance of 68.5 pc, this is not a primary candidate for imaging or astrometry.

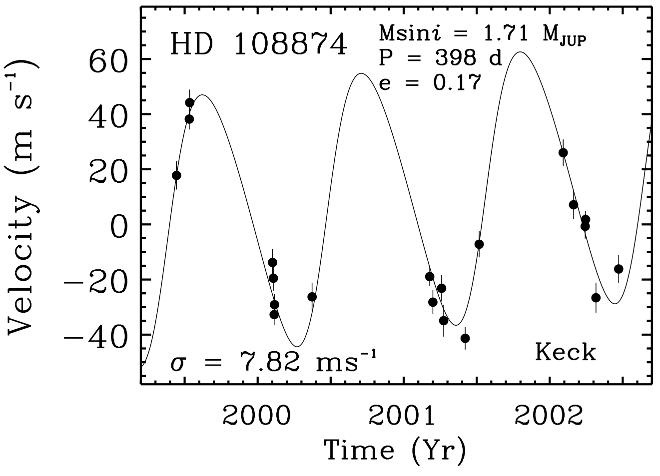

FIG. 4.—Keck Doppler velocities for the G5 dwarf HD 108874. The solid line is the best-fit Keplerian orbit, including linear trend.

TABLE 4

VELOCITIES FOR HD 108874

JD (−2,450,000)	RV ($\mathrm{m\,s^{-1}}$)	Error ($\mathrm{m\,s^{-1}}$)
340.8062	23.8	5.1
372.7472	44.2	3.8
373.7507	50.2	4.7
581.0702	−7.8	4.9
583.0358	−13.5	4.6
585.1059	−26.7	3.8
585.9948	−23.1	3.9
679.9143	−20.3	5.1
974.1172	−12.9	3.4
982.0464	−22.2	4.4
1003.8750	−17.2	4.8
1009.0390	−28.9	5.8
1062.8012	−35.3	4.1
1097.8145	−1.2	4.7
1307.9910	32.0	4.8
1333.9908	13.1	5.1
1363.0076	5.3	4.5
1364.0303	7.8	3.2
1389.9786	−20.6	5.5
1446.8056	−10.2	5.1

2.3. *HD 72659*

While the spectral type of HD 72659 is G0, we estimate the mass to be 0.95 $M_\odot$, slightly less than 1 $M_\odot$ because the star is somewhat metal-poor relative to the Sun. The star is chromospherically quiet, with $\log R'_\mathrm{HK} = -5.00$.

A total of 12 Doppler velocity observations, obtained between 1998 January and 2002 March, are shown in Figure 5 and listed in Table 5. The solid line is the best-fit Keplerian. The period is 5.98 yr, the semiamplitude is $K = 42\ \mathrm{m\,s^{-1}}$, and the eccentricity is 0.18. Because less than one full period has been observed, the period remains quite uncertain and the orbital solution is preliminary. Nonetheless, the precision of the measurements is sufficiently high that the approximate orbital solution is possible with large errors, as reported in Table 2. The minimum mass of the planet is 2.55 M_J, and the semimajor axis is 3.24 AU.

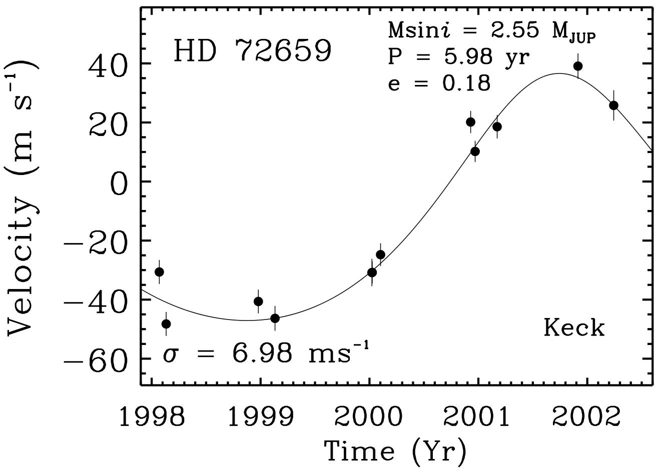

FIG. 5.—Keck Doppler velocities for HD 72659. The solid line is the best-fit Keplerian orbit. Since less than a full orbit has been observed, the orbital period remains uncertain.

TABLE 5

Velocities for HD 72659

JD (−2450000)	RV (m s^{-1})	Error (m s^{-1})
838.8934	−24.6	4.1
861.9147	−42.2	4.1
1171.0263	−34.6	4.0
1226.9380	−40.3	4.2
1551.9891	−24.8	4.6
1553.0072	−24.8	3.7
1580.9318	−18.8	3.9
1883.1159	26.1	3.8
1898.1275	16.2	3.6
1971.9956	24.6	4.0
2243.1162	45.1	4.3
2362.9627	31.8	5.1

2.4. *HD 114729*

HD 114729 is listed as spectral type G3 V by SIMBAD but G0 V by *Hipparcos*. We assign a spectral type of G0 V to this star, consistent with $B-V = 0.62$ and $T_{\rm eff} = 5915$ K derived from our LTE spectral synthesis of the Keck spectra. While metal-poor relative to the Sun, with [Fe/H] $= -0.22$, HD 114729 has typical metallicity for field stars. Based on the metallicity, we estimate the mass of the star to be 0.93 $M_\odot$, slightly less than solar. The star is chromospherically quiet, with $\log R'_{\rm HK} = -5.02$ as measured from our Keck spectra, consistent with the results of Henry et al. (1996). The expected jitter due to this level of activity is $\sim$4 m s^{-1}, and the jitter is unlikely to be greater than 6 m s^{-1}. With an absolute magnitude of 3.95, this star has presumably evolved about a half-magnitude above the zero-age main sequence, consistent with the chromospherically estimated age of 6 Gyr.

TABLE 6

Velocities for HD 114729

JD (−2,450,000)	RV (m s^{-1})	Error (m s^{-1})
463.1474	−2.1	3.4
546.9722	−11.6	3.1
838.1203	−9.2	3.3
954.8943	−22.8	3.8
981.7827	−13.2	3.4
982.7994	−10.5	3.5
1227.0437	10.1	3.2
1312.8518	6.6	3.6
1370.7856	12.9	4.0
1581.1159	−0.1	3.1
1582.0389	6.8	3.4
1582.1410	2.2	2.2
1583.0928	5.4	2.6
1584.1016	9.5	3.7
1585.0836	7.0	2.8
1586.0007	3.6	4.1
1679.8785	−6.1	3.8
1702.8864	−16.6	3.5
1703.7990	−16.4	3.5
1704.8170	−17.6	3.9
1705.8413	−25.2	3.5
1706.8599	−15.2	3.3
1972.0790	−12.3	3.3
1973.0866	−4.4	4.0
1974.0539	−12.9	3.7
1981.9815	−18.6	3.6
2002.9627	−20.6	4.1
2003.8865	−9.4	4.3
2008.9501	−15.4	4.4
2062.7707	−23.1	3.8
2094.7553	−4.8	4.1
2100.7605	−6.5	4.1
2128.7361	−7.1	4.1
2334.0902	6.5	4.1
2364.0079	5.9	2.7
2390.9444	5.0	3.6
2445.7820	12.6	3.5
2487.7399	8.6	4.2

A total of 38 Doppler velocity observations, obtained between 1997 January and 2002 June, are shown in Figure 6 and listed in Table 6. The solid line is the best-fit Keplerian. The period is 3.10 yr, the semiamplitude is $K = 18$ m s^{-1}, and the eccentricity is 0.32. The minimum mass of the planet is 0.84 $M_{\rm J}$, and the semimajor axis is 2.08 AU. The rms to the Keplerian fit to the Keck data is 5.34 m s^{-1}, consistent with our Doppler errors of 3 m s^{-1} combined with expected velocity jitter of 4 m s^{-1} for this star.

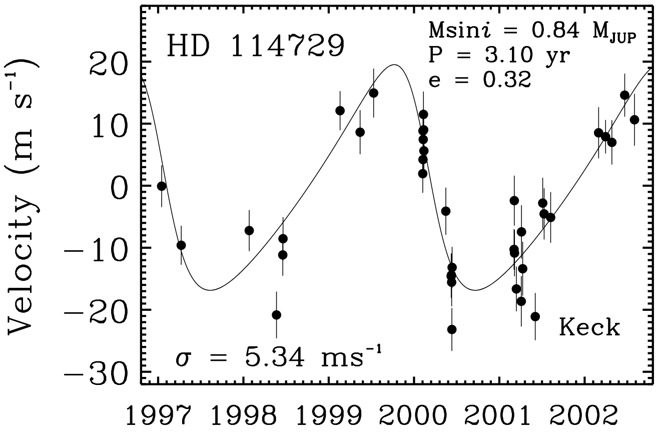

Fig. 6.—Keck Doppler velocities for the G0 dwarf HD 114729. The solid line is the best-fit Keplerian orbit that has $K = 19$ m s^{-1} and period $P = 3.1$ yr.

2.5. *HD 128311*

HD 128311 is listed as spectral type K0 V by SIMBAD and *Hipparcos*, although the $B-V$ color is consistent with K3 V. The metallicity is roughly solar, [Fe/H] $= 0.08$ (Haywood 2001). With $\log R'_{\rm HK} = -4.39$, this star is similar to the well-known active K2 dwarf ϵ Eridani. The expected velocity jitter associated with this level of activity is 30 m s^{-1} (Saar et al. 1998; Saar & Fischer 2000; Santos et al. 2000).

A total of 30 Doppler velocity observations, obtained between 1998 June and 2002 August, are shown in Figure 7 and listed in Table 7. The solid line represents the best-fit Keplerian model including an ad hoc linear trend. The period is 422 days, the semiamplitude is $K = 85$ m s^{-1}, and the eccentricity is 0.31. The minimum mass of the planet is 2.57 $M_{\rm J}$, and the semimajor axis is 1.02 AU. The best-fit linear trend is 30 m s^{-1} yr^{-1}. The rms to the Keplerian plus

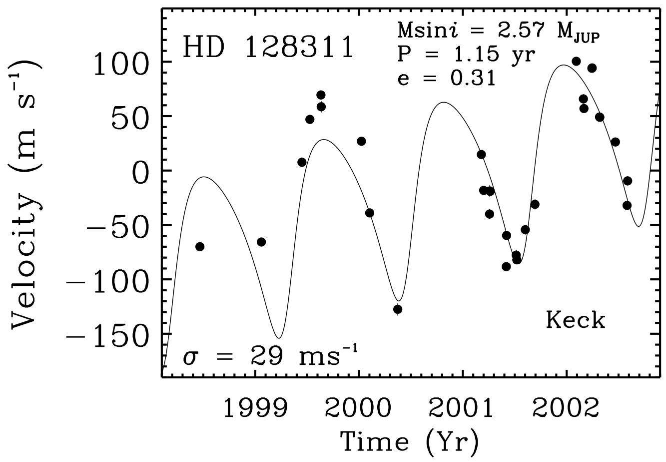

FIG. 7.—Keck Doppler velocities for the K0 dwarf HD 128311. This star is extremely active, as shown in Fig. 2. Based on the chromspheric diagnostic, we estimate the Doppler jitter associated with this level of activity to be 30 m s^{-1}. The solid line is the best-fit Keplerian plus linear trend to the Keck Doppler velocities. The period is 422 days, the semiamplitude is $K = 85$ m s^{-1}, and the eccentricity is $e = 0.31$, yielding $M \sin i = 2.57\ M_J$. The linear trend is 30 m s^{-1} yr^{-1}. The rms to the Keplerian plus linear trend is 29 m s^{-1}. It remains possible that the observed Doppler variation is due entirely to photospheric jitter.

linear trend is 29 m s^{-1}, consistent with the expected jitter. The reduced $(\chi^2_\nu)^{1/2}$ of the orbital fit taking only measurement uncertainty into account is 7.80. If expected jitter is also taken into account, the $(\chi^2_\nu)^{1/2}$ drops to 0.95.

TABLE 7

VELOCITIES FOR HD 128311

JD (−2,450,000)	RV (m s^{-1})	Error (m s^{-1})
983.8269	−70.0	3.2
1200.1379	−65.7	3.8
1342.8584	7.6	4.4
1370.8290	47.0	4.2
1409.7466	69.4	4.2
1410.7491	58.6	5.3
1552.1646	26.9	4.1
1581.1701	−38.9	3.3
1680.0254	−127.5	5.8
1974.1614	14.7	4.0
1982.1528	−18.2	3.3
2003.0227	−40.0	4.8
2003.9016	−18.8	5.7
2005.1301	−19.1	3.5
2061.8783	−88.3	3.3
2062.8675	−59.7	3.7
2096.7758	−77.7	4.7
2098.8480	−82.1	3.8
2128.7664	−54.4	4.4
2162.7239	−31.1	4.7
2308.1725	100.4	3.5
2333.1597	65.8	4.2
2335.1175	57.0	3.5
2362.9940	94.0	3.4
2364.0802	94.3	3.3
2389.9906	49.2	3.5
2390.9569	48.9	3.6
2445.8265	26.2	3.1
2486.8272	−32.0	3.2
2488.7709	−9.5	4.3

The relationship between chromospheric activity and Doppler jitter has not been well explored for K dwarfs of all ages because late F and G dwarfs make up the bulk of the precision Doppler target stars. Few K dwarfs are as young and active as HD 128311 apparently is. Some K0V dwarfs with large chromospheric emission, such as HD 128311, show great velocity jitter, but a few do not, as seen among stars in our Doppler survey.

Velocity jitter in extremely active stars can yield pseudo-Keplerian velocity variations, as in the cases of HD 166435 (Queloz et al. 2001) and HD 192263 (Henry, Donahue, & Baliunas 2002). The Doppler velocities for these stars have periodicities of 3.8 and 24 days and semiamplitudes (K) of 83 and 52 m s^{-1}, respectively. Precision photometry has subsequently ruled out Keplerian motion for both these stars since the photometric periodicities match those of the Doppler velocities. The chromospherically estimated rotation periods (Noyes et al. 1984) for these two stars are 1.6 and 20 days, respectively, consistent with the observed velocity and photometric periods. This suggests that the observed Doppler velocity variations are caused by rotational modulation of surface features, such as spots.

Hipparcos lists the photometric variability type of HD 128311 as "blank," indicating that the star could not be determined to be variable or constant. Strassmeier et al. (2000) found the star to be variable with a period of 11.54 days and an amplitude of 0.035 mag. Their data set lasted only 119 days, but that time span is contained within the observations presented here. From that level of photometric variability, the radial velocity jitter could be as high as 100 m s^{-1}, similar to HD 166435 (Queloz et al. 2001). This star differs from HD 166435 in that the photometric period is not consistent with the Doppler velocity period.

The chromospherically estimated rotation period of HD 128311 is 11.9 days, similar to the observed photometric period. While the Doppler velocity periodicity of HD 128311 is much longer than inferred rotation period of ~11.5 days, we cannot rule out non-Keplerian explanations for the observed velocity variations. The active K2 V star ϵ Eri represents a similar case. Both ϵ Eri and HD 128311 show variations in the Ca II H and K S-value index. In the case of ϵ Eri, Hatzes et al. (2000) have argued for a Keplerian interpretation of the observed velocity variations because the periodogram of the Ca II H and K S-value does not show significant power at the observed Keplerian periodicity, although it does show evidence for pseudoperiodicities that change from season to season.

Figure 8 shows a periodogram of the Mount Wilson–calibrated S-value of HD 128311 from our Keck spectra. The only peaks that (barely) rise above the 1% false alarm probability are at 31 and 25 days. Peaks at 547 and 1103 days do not rise to the level of significance. The lack of a strong S-value periodicity at the observed Keplerian period, similar to the case of ϵ Eri, is not interpreted as strong evidence that the observed Doppler velocity variations are due to Keplerian motion. If the Doppler velocity variations are not Keplerian in nature, continued monitoring should reveal excursions from the predicted Keplerian orbit.

2.6. *HD 49674*

This star was added to the Keck program in 2000 December based on its identification as a metal-rich star (Laughlin 2000). Laughlin's photometric estimate, [Fe/H] = 0.23, is

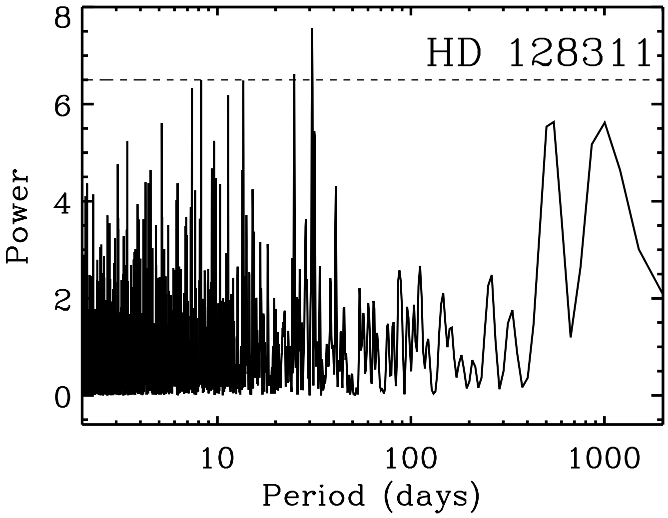

FIG. 8.—Periodogram of Ca II H and K S-value for HD 128311. Only peaks at 31 and 25 days rise (barely) above the 1% false alarm level, indicated by the dashed line.

supported by our LTE spectral synthesis of our Keck HIRES spectra, yielding $[Fe/H] = 0.26$ and $T_{\rm eff} = 5598$ K.

HD 49674 is listed by both *Hipparcos* and SIMBAD as spectral type G0, inconsistent with the measured $B-V$ of 0.73 and effective temperature of 5600 K. We therefore suspect that the actual spectral type is G5V not G0V. In addition, the absolute magnitude of this star, $M_V = 5.05$, is consistent with a G5 main-sequence star. This absolute magnitude is more than half a magnitude fainter than a typical G0 V star, thus casting further doubt on that spectral type. The $T_{\rm eff}$, M_V, and (high) metallicity of HD 49675, along with evolutionary tracks, imply a mass of 1.0 ± 0.1 $M_\odot$.

A total of 24 spectra, taken over 1.2 yr, are listed in Table 8. The median measurement uncertainty of this data set is 3.5 m s^{-1}. Based on the chromospheric diagnostic Ca II H and K, the intrinsic Doppler jitter of HD 49674 is estimated to be ~4 m s^{-1} (Saar et al. 1998; Saar & Fischer 2000; Santos et al. 2000). The velocity uncertainty due to the combined effects of Doppler jitter and measurement uncertainty is 5.2 m s^{-1}. In contrast, the rms of the measured velocities (prior to any Keplerian fit) is 11.0 m s^{-1}, indicating that the velocity of this star is varying.

A periodogram of the velocities is shown in Figure 9*a*. A single strong periodicity is detected at 4.948 days. No other peaks rise above the 1% false alarm level (as determined by Monte Carlo simulation). The velocities are shown phased with this period in Figure 10. The solid line represents the best-fit Keplerian model, with a semiamplitude of 14 m s^{-1}. The minimum mass of the planet is 0.12 ± 0.02 $M_{\rm J}$. The rms to the Keplerian fit is 5.55 m s^{-1}, consistent with the combined effects of intrinsic Doppler jitter and measurement uncertainty.

Figure 9*b* shows the periodogram of the velocity residuals after subtracting off the best-fit Keplerian. No strong periods remain. This planet yields a velocity wobble amplitude among the lowest ever detected (Marcy et al. 2000a, 2000b; Fischer et al. 2002a). At this low velocity level, it is crucial to rule out non-Keplerian explanations for the observed Doppler velocity variations. We have searched for periodicities in our chromospheric diagnostic and precision photometric observations. Figure 9*c* shows the periodogram of the S-value measured directly from the Ca II H and K lines in our Keck spectra. No strong periodicities are revealed, especially near the observed 5 day periodicity in the Keck Doppler velocities.

TABLE 8

VELOCITIES FOR HD 49674

JD (−2,450,000)	RV (m s^{-1})	Error (m s^{-1})
883.0580	−7.8	3.2
884.1371	−2.9	3.7
898.0243	6.4	2.9
899.0322	5.7	2.7
900.0578	−9.8	3.0
901.0620	−20.2	2.9
971.9825	3.3	3.2
972.9615	0.8	3.5
973.7681	−10.2	3.0
974.8130	−24.4	2.9
1003.7551	−4.3	4.0
1062.7438	−0.9	3.6
1064.7511	−17.1	3.7
1218.9872	−17.2	3.9
1220.1081	4.9	3.9
1235.9637	−1.0	3.5
1236.0478	−4.9	3.4
1236.9183	−26.5	3.3
1237.9074	−19.5	3.6
1238.9109	−3.6	3.4
1243.0150	−18.7	3.5
1307.8526	−3.1	3.3
1334.0010	3.5	3.9
1334.8197	8.0	4.4

Precision photometric observations are critical in establishing the credibility of small-amplitude 51 Peg–like planets. Photometric variations in the young rapidly rotating stars HD 166435 (Queloz et al. 2001) and HD 19632 (Butler et al. 2002b) argue against Keplerian motion as the cause of the 51 Peg–like velocity variations. These stars exhibit photometric variability at the level of 10–50 mmag in phase with the Doppler velocity variations, presumably due to rotating spots. Moreover, the quietest GK dwarfs exhibit photometric stability ~1 mmag or less and yet show typical jitter of 2–3 m s^{-1}, often termed the "astrophysical floor" of stellar Doppler measurements. Based on this limited set of two stars, along with stable stars, we estimate that each millimag (rms) of photometric variation leads to an increase in the observed Doppler velocity variations (rms) of 3–4 m s^{-1}.

Differential Strömgren b and y photometric observations of HD 49674 were obtained from 2001 March through 2002 April with the T12 0.80 m Automatic Photoelectric Telescope (APT) at Fairborn Observatory in southern Arizona. The instrumentation and techniques used to acquire and reduce these observations are described in Henry (1999) and Henry et al. (2000a). The precision of a typical individual observation is 0.0012 mag.

The top panel of Figure 11 shows the differential magnitudes of HD 49674 in the $\delta(b+y)/2$ bandpass with respect to the comparison star HD 47882 ($V = 7.04$, $B-V = 0.36$, F2) and phased with the Keplerian orbital period from Figure 10. The semiamplitude of a sine curve

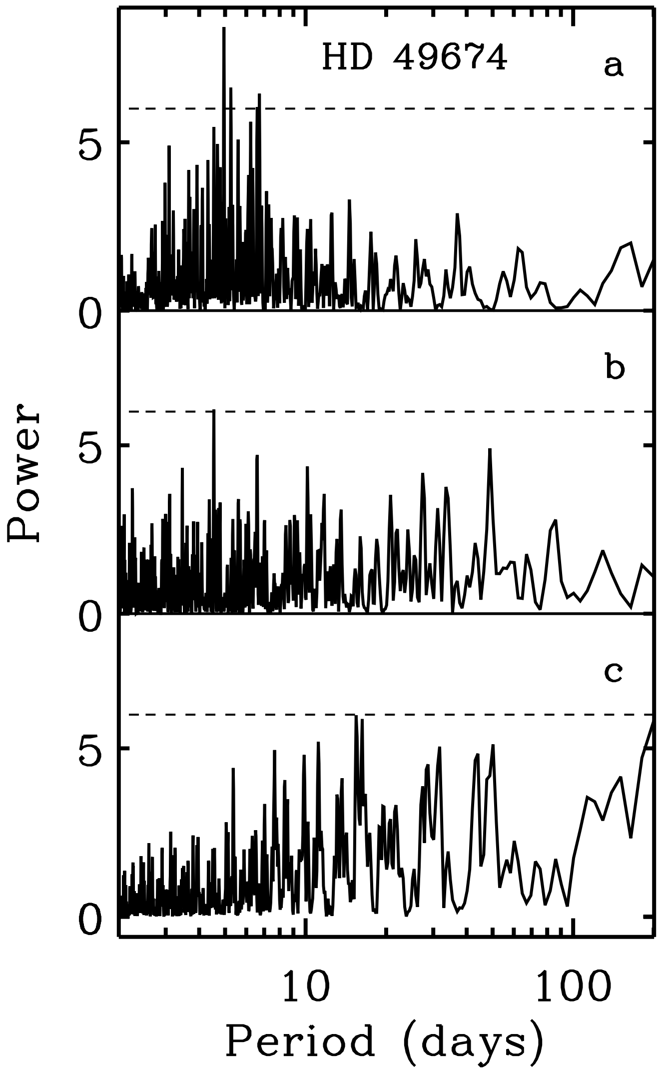

FIG. 9.—Periodogram of HD 49674 Keck velocities. (*a*) Periodogram of measured velocities. The 4.94 day periodicity is indicated by the highest periodogram peak. The 1% false alarm level is indicated with the dotted line. (*b*) Periodogram of residual velocities, after subtracting off the best-fit Keplerian. No significant periodicities remain after subtracting off the best-fit single-Keplerian. (*c*) Periodogram of Ca II *S*-value. There are no significant periodicities, especially near 5 days.

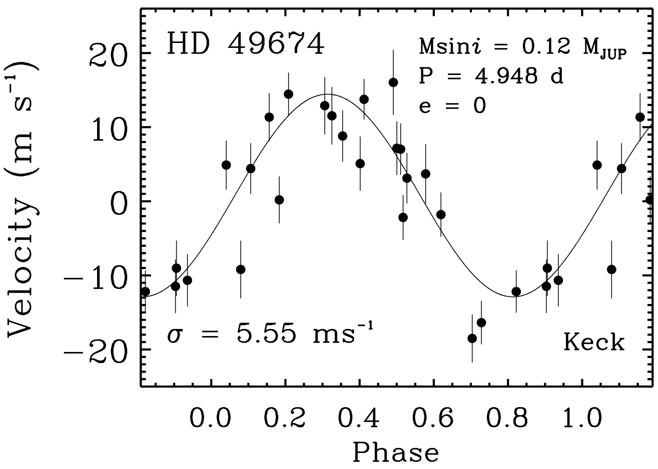

FIG. 10.—Phased Doppler velocities for HD 49674 (G5 V). The solid line is the best-fit Keplerian. The period is 4.948 days, and the semiamplitude is 14 m s^{-1}, yielding $M \sin i = 0.12\ M_{\rm J}$. The rms to the Keplerian fit is consistent with the combined effects of measurement uncertainty (3.5 m s^{-1}) and intrinsic Doppler jitter (3.8 m s^{-1}).

fit to these data is 0.00012 ± 0.00021 mag. This very low limit of possible photometric variability at the radial velocity period strongly supports the planetary interpretation of the radial velocity variations. The rms of the photometric observations is 0.0014 mag, consistent with the typical measurement precision, and further suggests that the star's radial velocity should be stable at the 3–4 m s^{-1} level. The bottom panel of Figure 11 shows the phased data near the time of transit predicted from the radial velocities. The box function approximates the expected signal of a 1.35 $R_{\rm J}$ companion, similar to HD 209458 (Henry et al. 2000b; Charbonneau et al. 2000). The horizontal error bar below the transit box gives the uncertainty in the predicted transit time. The vertical error bar gives the precision of a single observation. The seven observations inside the transit box have a mean of 1.1675 ± 0.0005 mag; the 93 points outside transit have a mean of 1.1668 ± 0.0002 mag. Since the two levels agree to within their uncertainties, we do not detect a transit. A 3 σ transit depth of 0.0015 mag (perhaps the shallowest transit we could detect in the present data set) corresponds to a planet with a radius of 0.36 $R_{\rm J}$ (four Earth radii). Therefore, the lack of observed transits implies a very small planetary radius or an orbital inclination less than ∼85°.

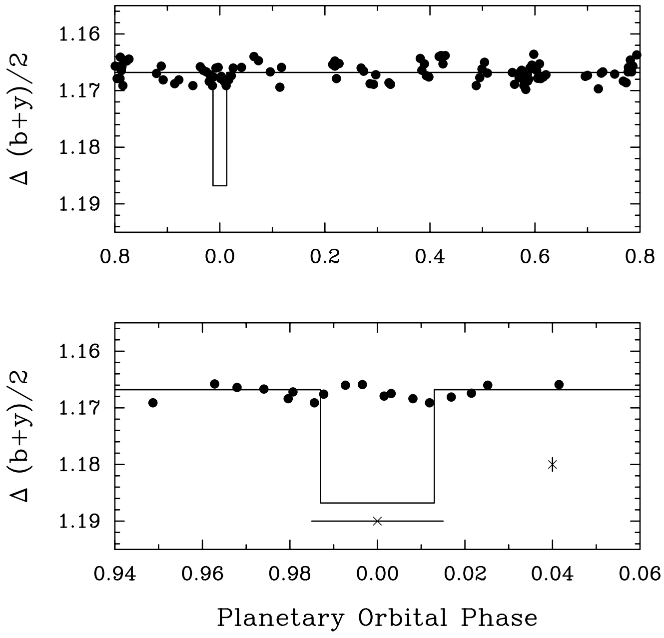

FIG. 11.—Photometric observations of HD 49674 phased with the Keplerian period from Figure 10. The width of the box function indicates the predicted time of transit, while the depth indicates the dimming of the star for a 1.35 $R_{\rm J}$ planet similar to HD 209458. *Top*: The full data set. The semiamplitude of a sine curve fit to these data is 0.00012 ± 0.00021 mag, and the rms of the individual measurements is 0.0014 mag. This level of photometric stability is consistent with a Doppler velocity jitter of ∼3–4 m s^{-1}. *Bottom*: The data set near the predicted time of transit. The uncertainty in the predicted transit time is indicated by the error bar. The photometric means in and out of transit agree to within their uncertainties and so rule out transits by planets larger than about four Earth radii.

2.7. *HD 37124*

HD 37124 is a slowly rotating, metal-poor, G4 dwarf with a previously discovered planet in a ∼155 day orbit (Vogt et al. 2000). With $\log R'_{\rm HK} = -4.90$, we estimate the stellar jitter of HD 37124 to be ∼3.5 m $\rm s^{-1}$. We have obtained 30 Doppler observations from 1996 December through 2002 March, listed in Table 9. Figure 12 shows the best-fit single-Keplerian model to these data. The rms of the velocity residuals is 13.3 m $\rm s^{-1}$, and the reduced $(\chi^2_\nu)^{1/2}$ is 3.73. In contrast, the estimated velocity discrepancies due to the combined effects of stellar jitter and measurement error are expected to be 4.8 m $\rm s^{-1}$. Obviously the single-planet model offers a poor fit.

As Figure 12 shows, observations of HD 37124 taken in early 2000 fall systematically below the single-Keplerian fit, while observations from 2001 onward lie systematically above the Keplerian, suggesting a second planet with a period longer than 2 yr. Periodogram analysis of the residuals to the single-Keplerian fit show significant power near 2000 days. Figure 13 shows a plausible double-Keplerian model (*solid line*) overplotted on the HD 37124 velocities. The resulting rms to this double-Keplerian model is 5.3 m $\rm s^{-1}$, only slightly larger than the expected measurement discrepancies due to errors and jitter (added in quadrature) of 4.8 m $\rm s^{-1}$. The reduced $(\chi^2_\nu)^{1/2}$ to the Keplerian fit is 1.55, a significant improvement over the single-Keplerian model that gave $(\chi^2_\nu)^{1/2} = 3.73$.

TABLE 9

Velocities for HD 37124

JD (−2,450,000)	*RV* (m $\rm s^{-1}$)	Error (m $\rm s^{-1}$)
420.0466	60.7	3.4
546.7365	38.4	2.6
837.7662	13.6	3.1
838.9487	12.7	3.0
861.8046	30.8	2.9
1069.0362	12.6	3.0
1070.1319	9.2	3.0
1071.1149	12.9	3.3
1072.1295	5.3	3.1
1073.0296	0.4	3.2
1172.8957	44.0	3.3
1226.7806	7.7	3.2
1227.7817	4.4	3.1
1228.7429	−2.1	2.9
1412.1416	−25.7	4.3
1543.9828	−26.6	3.1
1550.9426	−38.5	3.5
1551.9401	−36.9	3.6
1552.8916	−41.0	3.4
1580.7612	−31.2	4.1
1581.8356	−31.6	3.1
1582.7885	−33.5	3.4
1583.7239	−28.1	3.8
1884.0444	−11.0	3.7
1900.0352	11.3	3.3
1974.8002	53.6	3.6
2007.7452	9.3	3.5
2242.9906	57.2	3.9
2333.9455	−10.5	4.3
2334.7856	−1.1	4.0

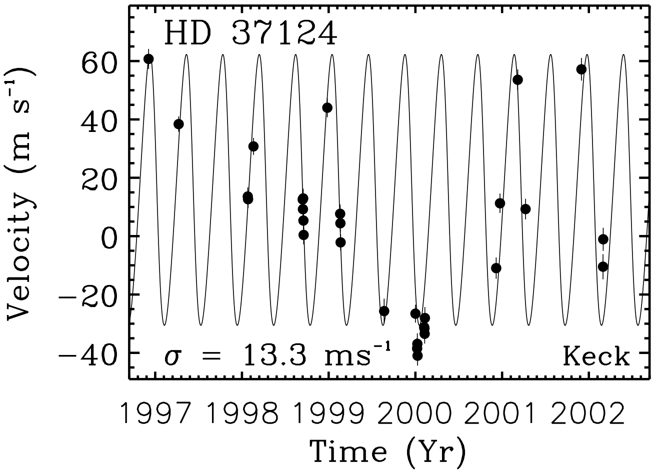

Fig. 12.—Keck Doppler velocities for the G4 dwarf HD 37124. The solid line is the best-fit single Keplerian. Vogt et al. (2000) reported that this star has a planet with a ∼155 day orbit, consistent with the 153 day period found here. The rms to the single-Keplerian fit, 13.3 m $\rm s^{-1}$, is much larger than the expected velocity uncertainty of 4.8 m $\rm s^{-1}$. Observations taken in early 2000 are systematically low relative to the Keplerian fit, while observations taken from 2001 onward are systematically high, suggesting a possible second Keplerian with a period greater than 2 yr.

The orbital parameters for this two-planet model, represented in Figure 13, are listed in Table 2. The parameters include periods of 153 and 1942 days, eccentricities of 0.10 and 0.40, and Doppler semiamplitudes of 35 and 19 m $\rm s^{-1}$, yielding minimum masses of 0.86 and 1.01 $M_{\rm J}$ and orbital distances of 0.54 and 2.95 AU for the inner and outer planets, respectively.

However, the double-Keplerian model in Figure 13 and Table 2 is not the best-fit double-planet model. We find a slightly lower value of χ^2_ν for an eccentricity of $e = 0.75$ and

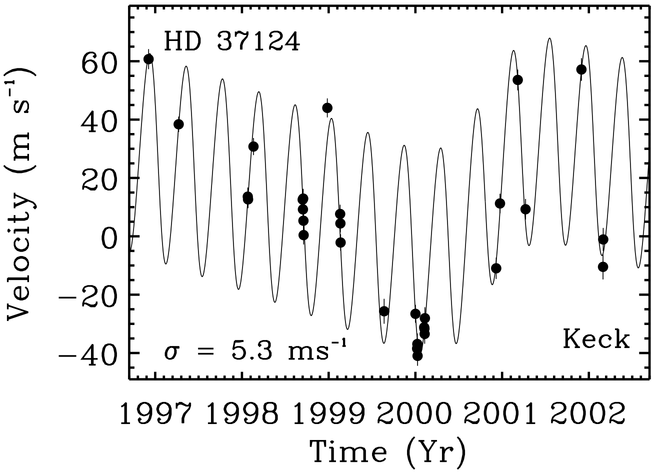

Fig. 13.—Plausible double-Keplerian model to the Keck Doppler velocities of HD 37124. The periods of the Keplerians are 153 and 1942 days, the semiamplitudes are 35 and 19 m $\rm s^{-1}$, and the eccentricities are 0.10 and 0.40, yielding minimum ($M \sin i$) masses of 0.86 and 1.01 $M_{\rm J}$ at orbital distances of 0.54 and 2.95 AU for the inner and outer planets, respectively. The rms of the velocity residuals is 5.3 m $\rm s^{-1}$, only slightly larger than the expected velocity discrepancies from errors and jitter. With only 30 observations during 5 yr, the eccentricity of the outer planet is poorly constrained. Any eccentricity from 0.3 to 0.8 for the outer planet fit the data to within velocity errors. Eccentricities larger than 0.6 can be ruled out on dynamic grounds.

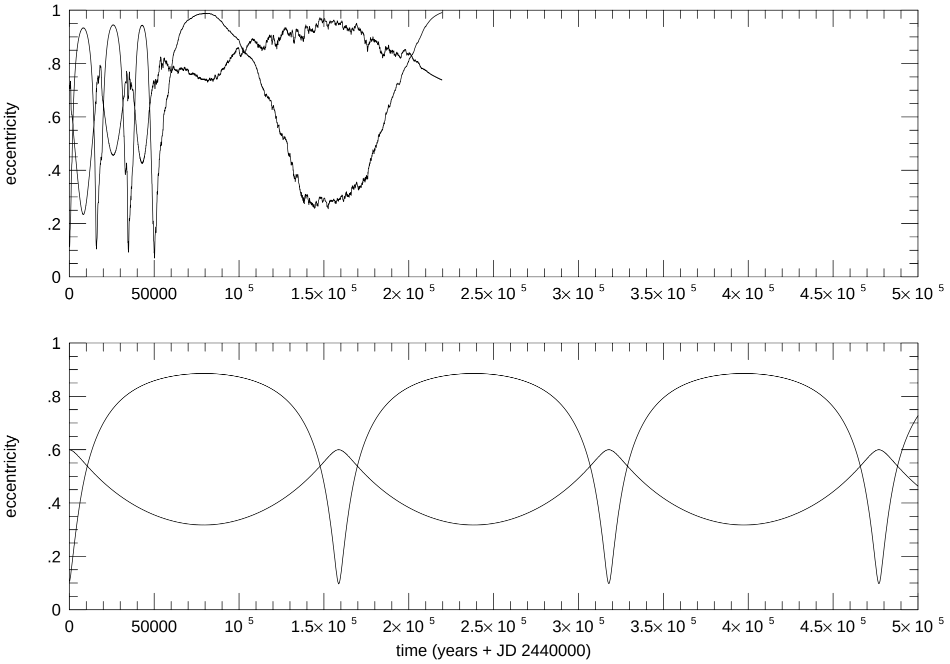

FIG. 14.—Dynamical simulations of model HD 37124 double-planet systems. *Bottom*: osculating eccentricities of the two planets during a simulation started at epoch JD = 2,440,000, with $P_b = 153.0$ days, $P_c = 2023.0$ days, $e_b = 0.103$, $e_c = 0.6$, $T_{\mathrm{peri}_b} =$ JD 2,451,985, $T_{\mathrm{peri}_c} =$ JD 2,451,844, $\varpi_b = 82^\circ.0$, $\varpi_c = 243^\circ.0$, $M_b = 0.89\ M_J$, and $M_c = 1.35\ M_J$. The mass of the central star is assumed to be 0.91 $M_\odot$. Over the plotted time frame of 5.0×10^5 yr, the planets experience a smooth periodic exchange of eccentricity. *Top*: osculating eccentricities of the two planets in a simulation with initial eccentricity $e_c = 0.72$ and all other initial conditions as above. In this case, the motion is chaotic, and the inner planet crashes into the star after 219,514 yr.

a period of 5.7 yr for the outer planet, with other parameters nearly the same as mentioned above.

This strict "best-fit" double-planet model yields an rms of 4.6 m s^{-1} and a reduced $(\chi^2_\nu)^{1/2}$ of 1.39, both slightly lower than the ad hoc model above ($e = 0.4$ for the outer planet) that gave rms = 5.3 m s^{-1} and $(\chi^2_\nu)^{1/2} = 1.55$. Clearly, with only 30 observations spanning 5.4 yr, the eccentricity of the outer planet remains poorly constrained. Eccentricities for the outer planet from 0.3 to 0.8 yield residuals to the double-planet fit that are consistent with the estimated velocity uncertainty of 4.8 m s^{-1}.

Eccentricities greater than $e_c \sim 0.7$ for the outer planet are likely ruled out by dynamical instability in the resulting orbital configurations. Three-body simulations of model systems with initial eccentricities $e_c = 0.7$ or larger lead to disruptive close encounters and star-planet collisions on timescales of the order of 10^5 yr, as shown in the top panel of Figure 14. (Note that the initial conditions for the planets—the osculating orbital elements—are assumed to map onto Jacobi coordinates.) For initial outer planet eccentricities of $e_c = 0.6$ or less, the two planets experience a stable secular cycle of eccentricity exchange, and as shown in the bottom panel of Figure 14, there is no immediate evidence of chaotic evolution. Evidently, for coplanar configurations with $\sin i = 1.0$, there is a threshold initial eccentricity for the outer planet, above which the system is destabilized. Numerical experimentation shows that this threshold occurs at $e_c \sim 0.65$. For orbital configurations that are not edge-on, the planet masses are larger, and the maximum initial eccentricity that preserves stability will decrease. Indeed, a more extensive dynamical analysis, in conjunction with more Doppler velocities, will eventually allow for much tighter constraints on the parameter space available to the planets.

3. DISCUSSION

Precision Doppler observations made with the HIRES on the 10 m Keck I telescope reveal seven previously unpublished planets, including an extremely low amplitude 51 Peg–like candidate with the smallest $M \sin i$ yet detected as well as an interesting second planet around HD 37124. The remaining five planets are typical of the majority of Doppler planets with mild eccentricities, ranging from 0.18 to 0.36, and masses ranging from roughly 1 to 5 M_J. Three of the seven planet-bearing stars in this paper are metal-poor relative to the Sun, including the double-planet system HD 37124.

With the exception of HD 128311, the host stars of the planet candidates presented in this paper are chromospherically quiescent, with R'_{HK} values similar or smaller than the Sun. For these quiescent stars, the expected astrophysical velocity jitter induced by the stars themselves is expected to be less than 4 m s^{-1} (Saar et al. 1998; Santos et al. 2000).

The extrasolar planet mass function abruptly begins rising near 8 M_J and continues to rise down to the detection limit near 1 M_J (Butler et al. 2002a). The 51 Peg–type planets offer a special window on the mass function below 1 M_J since only these planets can be reliably detected down to 1 M_{Sat}. Figure 15 shows the mass function of the 12 published extrasolar planets with orbital periods less than 5 days.[8] All of these planets are in circular orbits within

[8] These planets are HD 83443 (Butler et al. 2002c), HD 46375 (Marcy et al. 2000a), HD 179949 (Tinney et al. 2001), HD 187123 (Butler et al. 1998), τ Boo (Butler et al. 1997), BD− 103166 (Butler et al. 2000), HD 75289 (Udry et al. 2000; Butler et al. 2001), HD 209458 (Henry et al. 2000b; Charbonneau et al. 2000), HD 76700 (Tinney et al. 2002), 51 Peg (Mayor & Queloz 1995; Marcy et al. 1997), υ And b (Butler et al. 1997, 1999), and HD 49674 (this paper).

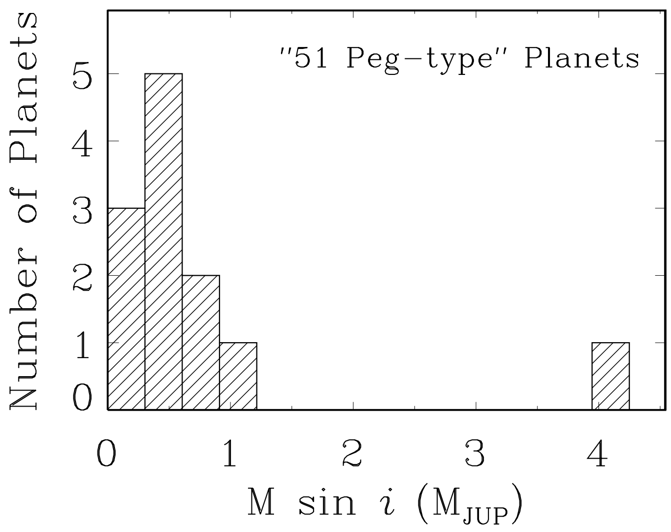

FIG. 15.—Mass function of 51 Peg–type planets. Mass bins are 1 $M_{\rm Sat}$. Only 51 Peg–like planets can be reliably detected down to 1 $M_{\rm Sat}$. The first mass bin, with three sub-Saturn candidates, suffers from extreme incompleteness. Nearly all 51 Peg–like planets have $M \sin i < 1\ M_{\rm J}$, with the mass function rising down to at least 1 $M_{\rm Sat}$.

measurement uncertainty, unlike the planet with the next smallest known orbital period (HD 68988; Vogt et al. 2002). The mass bins in Figure 15 are 1 $M_{\rm Sat}$. The first mass bin, with three sub-Saturn candidates, has the greatest observational incompleteness. The observed mass function is strongly peaked at less than 2 $M_{\rm Sat}$, suggesting that the real mass function continues rising down to at least 1 $M_{\rm Sat}$.

Of the ~3400 main-sequence dwarf stars within 50 pc brighter than $V = 9$, about one-third are younger than 2 Gyr and hence are active and rotating rapidly or they have a stellar companion within about 2″ making isolated spectra difficult. Our goal is to put all the remaining 2000 stars under precision Doppler scrutiny with measurement errors of 3 m s^{-1} or less. Our northern hemisphere surveys with the Keck 10 m and the Lick 3 m telescopes are currently monitoring ~1000 stars, while our Southern Hemisphere Anglo-Australian 3.9 m survey has 250 stars. These surveys have yielded 55 of the 70 extrasolar planets published or recently submitted to refereed journals (Butler et al. 2002c). We anticipate adding most of the remaining southern hemisphere stars to our Magellan 6.5 m survey, set to begin in 2002 November. We are working to improve our long-term single-shot precision of 3 m s^{-1} (Butler et al. 1996, 2001; Butler & Marcy 1997; Vogt et al. 2000) to 2 m s^{-1} and our seasonally averaged precision to 1 m s^{-1}, making these surveys sensitive to Saturn analogs at 10 AU and 51 Peg–like planets with masses down to 10 $M_{\odot}$.

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REFERENCES

Armitage, P. J., Livio, M., Lubow, S. H., & Pringle, J. E. 2002, MNRAS, 334, 248
Bodenheimer, P. Hubickyj, O., & Lissauer, J. J. 2000, Icarus, 143, 2
———. 1997, in ASP Conf. Ser. 134, Brown Dwarfs and Extrasolar Planets, ed. R. Rebolo, E. L. Martin, & M. R. Zapatero Osorio (San Francisco: ASP), 162
Butler, R. P., Marcy, G. W., Fischer, D. A., Brown, T. M., Contos, A. R., Korzennik, S. G., Nisenson, P., & Noyes, R. W. 1999, ApJ, 526, 916
Butler, R. P., Marcy, G. W., Fischer, D. A., Vogt, S. S., Tinney, C. G., Jones, H. R. A., Penny, A. J., & Apps, K. 2002a, in ASP Conf. Ser., Planetary Systems in the Universe: Observation, Formation and Evolution, ed. A. Penny, P. Artymowicz, A. M. Lagrange, & S. Russell (San Francisco: ASP), in press
Butler, R. P., Marcy, G. W., Henry, G. W., Tinney, C. G., Jones, H. R. A., McCarthy, C., Penny, A. J., & Carter, B. D. 2002b, ApJ, submitted
Butler, R. P., Marcy, G. W., Williams, E., Hauser, H., & Shirts, P. 1997, ApJ, 474, L115
Butler, R. P., Marcy, G. W., Williams, E., McCarthy, C., Dosanjh, P., & Vogt, S. S. 1996, PASP, 108, 500
Butler, R. P., Marcy, G. W., Vogt, S. S., & Apps, K. 1998, PASP, 110, 1389
Butler, R. P., Tinney, C. G., Marcy, G. W., Jones, H. R. A., Penny, A. J., & Apps, K. 2001, ApJ, 555, 410
Butler, R. P., Vogt, S. S., Marcy, G. W., Fischer, D. A., Henry, G. W., & Apps, K. 2000, ApJ, 545, 504
Butler, R. P., et al. 2002c, ApJ, 578, 565
Charbonneau, D., Brown, T. M., Latham, D. W., & Mayor, M. 2000, ApJ, 529, L45
Feltzing, S., & Gonzalez, G. 2001, A&A, 367, 253
Fischer, D. A., Marcy, G. W., Butler, R. P., Laughlin, G., & Vogt, S. S. 2002a, ApJ, 564, 1028
Fischer, D. A., Marcy, G. W., Butler, R. P., Vogt, S. S., Walp, B., & Apps, K. 2002b, PASP, 114, 529
Fuhrmann, K. 1998, A&A, 338, 161
Fuhrmann, K., Pfeiffer, M. J., & Bernkoph, J. 1997, A&A, 326, 1081
Hatzes, A. P., et al. 2000, ApJ, 544, L145
Haywood, M. 2001, MNRAS, 325, 1365
Henry, G. W. 1999, PASP, 111, 845
Henry, G. W., Baliunas, S. L., Donahue, R. A., Fekel, F. C., & Soon, W. 2000a, ApJ, 531, 415
Henry, G. W., Donahue, R. A., & Baliunas, S. L. 2002, ApJ, 577, L111
Henry, G. W., Marcy, G. W., Butler, R. P., & Vogt, S. S. 2000b, ApJ, 529, L41
Henry, T. J., Soderblom, D. R., Donahue, R. A., & Baliunas, S. L. 1996, AJ, 111, 439
Jorissen, A., Mayor, M., & Udry, S. 2001, A&A, 379, 992
Kley, W., D'Angelo, G., & Henning, T. 2001, ApJ, 547, 457
Laughlin, G. 2000, ApJ, 545, 1064
Marcy, G. W., & Butler, R. P. 1992, PASP, 104, 270
———. 2000, PASP, 112, 137
Marcy, G. W., Butler, R. P., Fischer, D. A., Vogt, S. S., Lissauer, J. J., & Rivera, E. J. 2001a, ApJ, 556, 296
Marcy, G. W., Butler, R. P., & Vogt, S. S. 2000a, ApJ, 536, L43
Marcy, G. W., Butler, R. P., Williams, E., Bildsten, L., Graham, J. R., Ghez, A. M., & Jernigan, J. G. 1997, ApJ, 481, 926
Marcy, G. W., Cochran, W. D., & Mayor, M. 2000b, in Protostars and Planets IV, ed. V. Mannings, A. P. Boss, & S. S. Russell (Tucson: Univ. Arizona Press), 1285
Marcy, G. W., et al. 2001b, ApJ, 555, 418
Mayor, M., & Queloz, D. 1995, Nature, 378, 355
Murray, N., & Chaboyer, B. 2002, ApJ, 566, 442
Noyes, R. W., Hartmann, L., Baliunas, S. L., Duncan, D. K., & Vaughan, A. H. 1984, ApJ, 279, 763
Perryman, M. A. C., et al. 1997, A&A, 323, L49
Queloz, D., et al. 2001, A&A, 379, 279
Saar, S. H., Butler, R. P., & Marcy, G. W. 1998, ApJ, 498, L153
Saar, S. H., & Fischer, D. A. 2000, ApJ, 534, L105
Santos, N. C., Mayor, M., Naef, D., Pepe, F., Queloz, D., Udry, S., & Blecha, A. 2000, A&A, 361, 265

Strassmeier, K., Washuettl, A., Granzer, T., Scheck, M., & Weber, M. 2000, A&AS, 142, 275
Taylor, B. J. 1996, ApJS, 102, 105
Tinney, C. G., Butler, R. P., Marcy, G. W., Jones, H. R. A., Penny, A. J., McCarthy, C., & Carter, B. D. 2002, ApJ, 571, 528
Tinney, C. G., Butler, R. P., Marcy, G. W., Jones, H. R. A., Penny, A. J., Vogt, S. S., & Henry, G. W. 2001, ApJ, 551, 507
Udry, S., Mayor, M., & Queloz, D. 2002, in ASP Conf. Ser., CORALIE-ELODIE New Planets and Planetary Systems: Looking for Fossil Traces of Formation and Evolution, ed. A. J. Penny, P. Artymowicz, A. M. LaGrange, & S. S. Russell (San Francisco: ASP), in press
Udry, S., et al. 2000, A&A, 356, 590
Vogt, S. S., Butler, R. P., Marcy, G. W., Fischer, D. A., Pourbaix, D., Apps, K., & Laughlin, G. 2002, ApJ, 568, 352
Vogt, S. S., Marcy, G. W., Butler, R. P., & Apps, K. 2000, ApJ, 536, 902
Vogt, S. S., et al. 1994, Proc. Soc. Photo-opt. Instrum. Eng., 2198, 362