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PLANETARY COMPANIONS TO THE METAL-RICH STARS BD $-10°3166$ AND HD 52265[1]

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ABSTRACT

Precise Doppler measurements from the Keck/HIRES spectrometer reveal periodic Keplerian velocity variations in the stars BD $-10°3166$ and HD 52265. BD $-10°3166$ (K0 V) has a period of 3.487 days and a semiamplitude of 61 m s^{-1}. An orbital fit yields a companion mass $M \sin i = 0.48\ M_{\rm JUP}$, a semimajor axis of $a = 0.046$ AU, and an eccentricity of $e = 0.05$ (consistent with zero). HD 52265 (G0 V) has a period of 119.0 days, a semiamplitude of 45 m s^{-1}, an eccentricity of 0.29, a semimajor axis of $a = 0.49$ AU, and companion mass $M \sin i = 1.13\ M_{\rm JUP}$. Both of these stars are metal-rich and chromospherically inactive. The mean metallicity of the 33 stars that have detected planets is significantly greater than that of typical stars in the solar neighborhood. We present a catalog of the 35 extrasolar planets known to date, with updated orbits and $M \sin i$ values.

Photometry of BD $-10°3166$ was obtained with an automated telescope to search for transits. No transits were found, indicating that the inclination of the orbit i is less than 84°.3 and $\sin i$ is less than 0.995. The photometry also reveals no photometric variability larger than 0.0008 ± 0.0009 mag at the orbital period of the planet. This confirms that neither starspots nor pulsations are the cause of the radial velocity variations in BD $-10°3166$.

Subject headings: planetary systems — stars: individual (BD $-10°3166$, HD 52265)

1. INTRODUCTION

About 35 extrasolar planets have been discovered over the last 5 years. Discoveries made during the last year include the first system of multiple planets (Butler et al. 1999), the first planet observed to transit its host star (Henry et al. 2000a; Charbonneau et al. 2000), and the first Saturn-mass candidates (Butler, & Vogt 2000a). These have all been found from precision Doppler surveys. With more than 2000 stars now under survey (Mayor et al. 1998; Marcy & Butler 1998; Noyes et al. 1997; Cochran et al. 1997), it is expected that more than 100 extrasolar planets will be uncovered within the next few years.

Already a number of patterns are beginning to emerge. All planets found orbiting beyond 0.2 AU have significant orbital eccentricities, $e > 0.1$, much larger than the giant planets in the solar system (Marcy & Butler 2000). The maximum ($M \sin i$) companion mass found from precision Doppler surveys is just 8 $M_{\rm JUP}$, despite the ease with which companions having masses of 10–80 $M_{\rm JUP}$ would have been detected. The mass function rises steeply toward lower masses all the way down to the detection limit near 1 $M_{\rm JUP}$ (Vogt et al. 2000). Most of the extrasolar planets discovered to date have heavy-element abundances similar to, or greater than, the Sun (Marcy & Butler 1998; Gonzalez 2000). Relative to nearby field stars, the Sun is itself a metal-rich star.

Here we report the detection of Keplerian Doppler velocity variations in the nearby metal-rich stars BD $-10°3166$ and HD 52265. Stellar characteristics and observations are discussed in the second section. Orbital solutions are presented in the third section, followed by photometry and a discussion of results, including a catalog of all known extrasolar planets.

2. OBSERVATIONAL TECHNIQUES AND STELLAR CHARACTERISTICS

2.1. *Velocity and Photometric Observations*

The Keck precision Doppler program began in 1996 and is currently surveying ~ 600 stars. High-resolution spectra, $R \sim 80{,}000$, are taken with the HIRES echelle spectrometer (Vogt et al. 1994) on Keck I. These spectra span the wavelength range from 3900 to 6200 Å. An iodine absorption cell (Marcy & Butler 1992) provides wavelength calibration from 5000 to 6000 Å. The H and K lines near 3950 Å provide a simultaneous chromospheric diagnostic (Saar et al. 1998).

Wavelength calibration and measurement of the spectrometer point-spread function (PSF) is determined for each exposure and for each 2 Å chunk of spectrum by using the iodine absorption lines superimposed on the stellar spectrum (Butler et al. 1996; Valenti et al. 1995). This system currently provides single-exposure Doppler precision of 3 m s^{-1} for typical observations having a signal-to-noise ratio of 200 or greater (Vogt et al. 2000).

In addition to the radial velocity observations, differential photoelectric photometry of BD $-10°3166$ in the Johnson B and V bandpasses was acquired with the T3 0.40 m automatic photoelectric telescope (APT) at Fairborn Observatory in southern Arizona. The comparison star used was HD 94206 ($V = 7.55$, $B-V = 0.34$, F0). The nominal precision of this telescope is 0.003–0.004 mag for a single observation, but the faintness of BD $-10°3166$ com-

[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.

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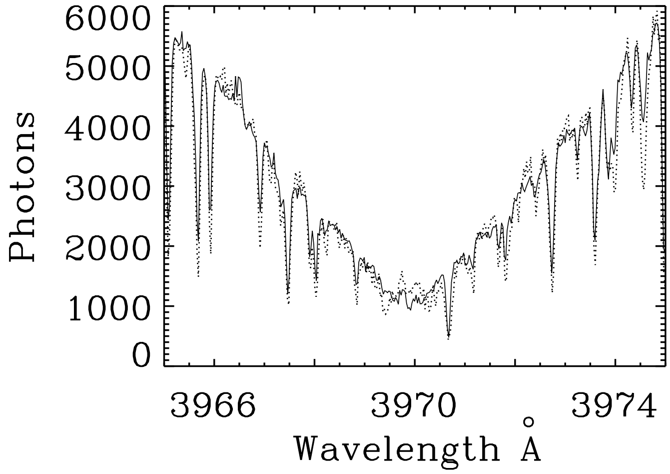

FIG. 1.—Comparison of the Ca II H line for BD −10°3166 (*dotted line*) and the chromospherically inactive K0 V star HD 143291 (*solid line*). The lack of core reversal in the H line for BD −10°3166 indicates the star is chromospherically inactive. The similarity in the H line and the other metal lines supports the assignment of K0 V spectral type to BD −10°3166, although BD −10°3166 appears metal-rich relative to HD 143291.

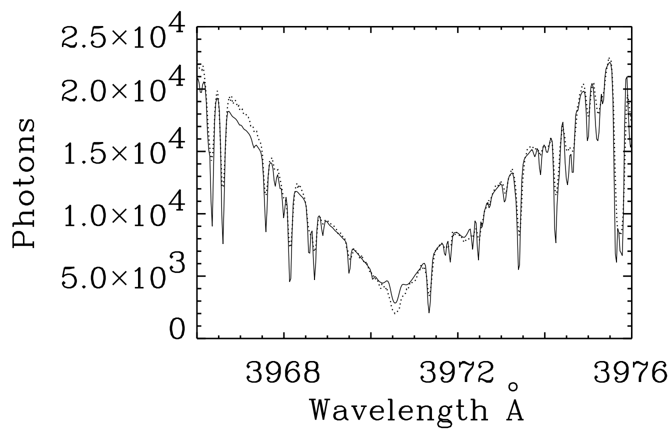

FIG. 2.—Comparison of the Ca II H line for HD 52265 (*dotted line*) and the Sun (*solid line*). The lack of core reversal in the H line indicates that HD 52265 is chromospherically inactive.

TABLE 1

VELOCITIES FOR BD −10°3166

JD (+2,450,000)	Radial Velocity ($m\ s^{-1}$)	Error ($m\ s^{-1}$)
1172.0800	33.6	5.1
1227.0089	56.8	4.6
1312.7961	−48.5	5.0
1340.7694	−56.6	5.4
1341.8510	51.7	8.0
1342.8045	48.3	5.6
1551.0474	27.2	6.3
1553.0449	−50.6	5.2
1581.0110	−50.1	3.9
1582.0041	−22.4	4.8
1582.1435	−10.8	4.8
1582.9633	53.6	4.7
1583.9370	0.0	4.5
1584.1337	−28.5	4.1
1585.1506	−25.1	7.8
1585.9415	31.0	5.1
1586.1319	55.1	4.9

pared to most program stars resulted in a precision of around 0.006 mag due to increased photon noise. Details on the telescope and photometer, observing sequences, and reduction of the data can be found in Henry (1995a, 1995b) and Henry, Fekel, & Hall (1995).

2.2. *Characteristics of BD −10°3166*

Because of its relative faintness, $V = 10.0$, BD −10°3166 has not been extensively studied, and no parallax is known to us. The star was added to our Keck telescope target list at the suggestion of Gonzalez et al. (1999), based on the study by Castro et al. (1997), who carried out spectral synthesis of high-resolution spectra. Castro et al. (1997) find $T_{\rm eff} = 5400$ K, $\log g = 4.4$, and $[{\rm Fe/H}] = +0.50$. The surface gravity implies main-sequence status, and is supported by narrowband photometry which yields $\log g = 4.5$ (Castro et al. 1997). Thus, BD −10°3166 appears to be a super–metal-rich dwarf, with a likely spectral type of K0 V.

Dwarf status for BD −10°3166 is also consistent with its kinematics. SIMBAD lists the proper motion of BD −10°3166 as 0".183 yr^{-1}. If BD −10°3166 were significantly evolved (i.e., $M_v \lesssim 3.5$, rendering it a subgiant) then the star would have to be at a distance greater than 200 pc to explain its $V_{\rm mag} = 10.0$. Such a hypothetical distance implies a transverse velocity greater than 180 km s^{-1}, a velocity so large as to imply membership in the Galactic halo. But with high metallicity, $[{\rm Fe/H}] = +0.50$, halo membership seems unlikely. Thus the distance to BD −10°3166 is probably considerably less than 200 pc, making the star a metal-rich disk dwarf, consistent with the surface gravity. Based on our Keck/HIRES spectra, we estimate the heliocentric radial velocity of BD −10°3166 to be 26.4 ± 2 km s^{-1}. Because of the enhanced metallicity of BD −10°3166 and its $T_{\rm eff} = 5400$, we estimate the mass of the star to be $M = 1.1 \pm 0.1\ M_{\odot}$, similar to the masses of metal-rich stars, HR 3522 and 14 Her.

APT differential photometry of BD −10°3166 (TYC 5503 946 1), combined with the V magnitude and $B-V$ color of the comparison star from *Hipparcos*, results in $V = 10.02$ and $B-V = 0.85$. The rms of the APT V measurements is 0.006 mag. This photometry is consistent with 66 photometric measurements by the Tycho star mapper on the *Hipparcos* mission, which found $V = 10.090$ (Hog et al. 2000).

Figure 1 shows a comparison of the Ca II H line of BD −10°3166 (*dotted line*) and the chromospherically inactive K0 V star HD 143291 (*solid line*), which was previously shown to have Doppler velocity variations of less than 4 m s^{-1} (Vogt et al. 2000). The similarity of the two spectra supports the assignment of a K0 V spectral type to BD −10°3166. The chromospheric emission measure, log R'(H K), for BD −10°3166 and HD 143291 are −4.92 and −4.93, respectively, consistent with slowly rotating, chromospherically inactive stars (Noyes et al. 1984). The deeper absorption lines in BD −10°3166 indicate higher metallicity for BD −10°3166 relative to HD 143291.

2.3. *Characteristics of HD 52265*

Hipparcos (Perryman et al. 1997) made 83 observations of HD 52265 (HR 2622, HIP 33719), deriving a distance of 28.0 pc, and an absolute V magnitude of, $M_V = 4.06$. Based on the absolute magnitude and the $B-V$ value of 0.572, we assign an expected spectral type of G0 V, in contrast to the Bright Star Catalogue (Hoffleit & Jaschek 1982) classi-

TABLE 2
VELOCITIES FOR HD 52265

JD (+2,450,000)	Radial Velocity (m s^{-1})	Error (m s^{-1})
838.8806	−6.8	3.5
1071.1178	−18.8	3.6
1171.9233	−40.6	3.4
1226.8652	39.3	2.8
1227.8595	42.4	2.8
1228.9463	42.1	3.4
1310.7606	−13.6	3.3
1312.7412	−10.9	3.3
1544.0501	−29.1	3.9
1550.9736	−14.3	3.6
1551.9842	−5.5	4.0
1552.9597	0.0	3.7
1580.8680	38.3	3.5
1581.8907	37.3	3.7
1582.7971	38.8	4.0
1583.9146	41.8	3.3
1585.9235	37.4	3.8

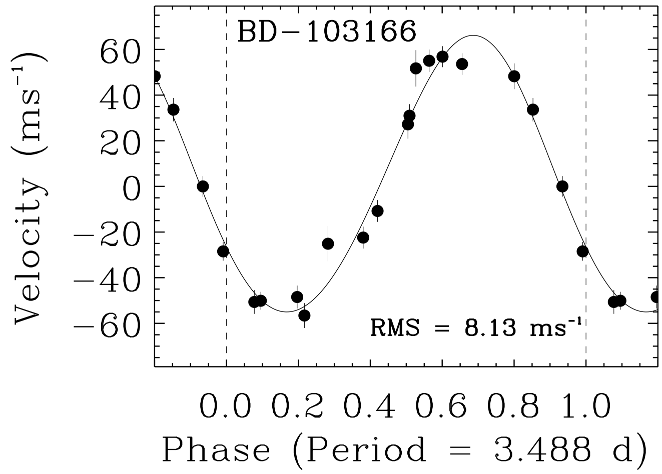

FIG. 4.—Phased Doppler velocities for BD −10°3166. The same best-fit sinusoid is shown in Figs. 3 and 4. The rms to the sinusoidal fit is 8.1 m s^{-1}, slightly worse than the best-fit Keplerian. The period is 3.487 days, and the semiamplitude is 60.6 m s^{-1}. Assuming the mass of BD −10°3166 is 1.1 $M_{\odot}$, the minimum ($M \sin i$) mass of the companion is 0.48 $M_{\rm JUP}$, and the semimajor axis is 0.046 AU.

fication of G0 III–IV. The star is photometrically stable within *Hipparcos* measurement error, ∼0.004 mag.

We estimate the metallicity of HD 52265 to be [Fe/H] = +0.11, based on *uvby* photometry (Hauck & Mermilliod 1998) which we have calibrated for [Fe/H] by using spectroscopic fine analysis (Favata et al. 1997; Gonzalez et al. 1999; Gonzalez & Vanture 1998; Gonzalez 1998, 2000). Using this metallicity, we compute estimates of stellar mass.

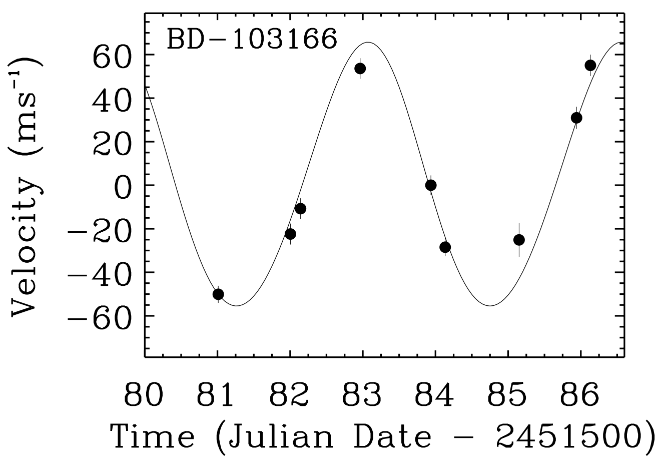

FIG. 3.—Doppler velocity observations of BD −10°3166 from the 2000 February observing run. A 3.5 day periodicity is evident for this 6 night observing string. Measurement uncertainties are ∼5.0 m s^{-1}.

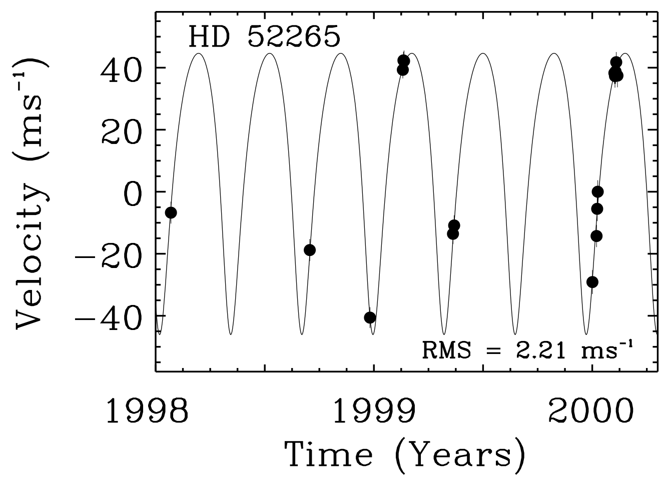

FIG. 5.—Doppler velocities for HD 52265. The rms to the best-fit Keplerian (*solid line*) is 2.2 m s^{-1}, slightly better than the measurement error of 3.5 m s^{-1}. The period is 118.96 days, and the semiamplitude is 45 m s^{-1}. Assuming the mass of HD 52265 is 1.13 $M_{\odot}$, the minimum ($M \sin i$) mass of the companion is 1.13 M_J, and the semimajor axis is 0.49 AU.

TABLE 3
ORBITAL PARAMETERS

Parameter	BD −10°3166	HD 52265
Orbital period P (days)	3.487 (0.001)	118.96 (0.1)
Velocity amplitude = K (m s^{-1})......	60.6 (1.0)	45.4 (1.0)
Eccentricity e	0.05 (0.05)	0.29 (0.04)
ω (deg)................................	35 (20)	166.0 (10)
Periastron time (JD)	2,451,342.7 (0.06)	2,451,293.4 (0.5)
M sin i ($M_{\rm JUP}$)	0.48 (0.03)	1.13 (0.03)
a (AU)	0.046	0.49

The position of the star in the color-magnitude diagram of $B-V$ versus M_{bol}, along with its age, permit determination of a first-order estimate of the stellar mass, assuming solar metallicity. This mass is then adjusted for metallicity by employing a fit to stars with published masses and [Fe/H] values. This metallicity-based adjustment of stellar mass is typically 0.05 $M_{\odot}$, for stars in our metallicity range of [Fe/H] = -0.5 to $+0.5$. The mass of HD 52265 is found to be 1.13 $M_{\odot}$, based on its $B-V$, M_V, and [Fe/H].

From the Ca II H and K lines in our Keck spectra, we find a chromospheric emission measure for HD 52265 of log $R'(\mathrm{HK}) = -4.99$, similar to the Sun, and typical for chromospherically (and magnetically) quiet stars (Noyes et al. 1984). Figure 2 shows a detailed comparison of the Ca II H line for the Sun (*solid line*) and HD 52265 (*dotted line*). The photospheric Doppler "jitter" of chromospherically quiet stars such as these is less than 3 m s^{-1} (Saar et al. 1998).

HD 52265 was added to the Keck precision Doppler survey in early 1998 as part of the expansion of this program. Table 2 lists the 17 observations that have been obtained between 1998 January and 2000 February.

3. ORBITAL SOLUTIONS

Table 1 lists the Doppler velocities of the 17 observations of BD $-10°3166$ we obtained at the Keck I telescope between 1998 December and 2000 February. Figure 3 shows observations of BD $-10°3166$ for the 6 night observing run in 2000 February. A 3.5 day periodicity is immediately apparent. All 17 observations are shown phased in Figure 4. The same best-fit sinusoid is included in both figures. The best-fit Keplerian yields an orbital period of 3.487 days, a velocity amplitude of 60.6 m s^{-1}, and an eccentricity of 0.050 (consistent with zero). The minimum (M sin i) mass of the planet is 0.48 M_{JUP}, and the semimajor axis is 0.046 AU. The best-fit Keplerian has a reduced χ^2 of 1.57 for 17 data points and 11 degrees of freedom, while the best-fit sinusoid has a reduced χ^2 of 1.52 for 13 degrees of freedom. This relatively poor fit is probably not due to stellar jitter as the BD $-10°3166$ is chromospherically quiet. This star is among the fainter stars on the program, accounting for the relatively large measurement error of ~ 5.0 m s^{-1}.

The 17 observations of HD 52265 are listed in Table 2 and shown in Figure 5. The reduced χ^2 to the best-fit Keplerian (*solid line*) is 0.74 for 11 degrees of freedom. This is slightly better than anticipated given an expected measurement error of 3.5 m s^{-1}. The period is 118.96 days, the semiamplitude is 45.4 m s^{-1}, and the eccentricity is 0.29. The minimum mass of the companion is M sin $i = 1.13$ M_{JUP}, and the semimajor axis is $a = 0.49$ AU. Our final orbital parameters for both stars are listed in Table 3.

4. PHOTOMETRY AND TRANSIT SEARCH FOR BD $-10°3166$

For random orbital inclinations and an assumed radius of 0.9 $R_{\odot}$ for BD $-10°3166$, there is a 10% chance that the companion will transit the host star. The probability of transit increases with increasing stellar radius. It will not be possible to estimate the radius of BD $-10°3166$ accurately until the stellar parallax is measured. The observation of a transit in BD $-10°3166$ would allow the direct measurement of the radius and mean density of a second extrasolar planet, to compare with HD 209458b (Henry et al. 2000a; Charbonneau et al. 2000).

To search for transits, we plot the 101 Johnson ΔV magnitudes[7] obtained with the APT between 2000 March 1 and April 5 in Figure 6. Phases in both panels have been computed with the ephemeris

$$\mathrm{JD} = 2{,}451{,}601.347 + 3.487E\ , \qquad (1)$$

where the epoch is a time of inferior conjunction of the planet (a time of mid-transit for favorable orbital inclinations) derived from our orbital elements and the period is the planetary orbital period. The top panel plots the complete data set, while the bottom panel plots only the observations near the time of conjunction with an expanded scale on the abscissa. The predicted transit depth (0.027 mag) and duration (2.6 hr) are shown schematically, estimated from an assumed planetary radius of 1.4 R_J (the measured radius of HD 209458b from Henry et al. 2000a; Charbonneau et al. 2000) and the estimated stellar radius of 0.9 $R_{\odot}$. The error bar immediately below the transit window in the lower panel gives the computed uncertainty in the predicted time of mid-transit. The error bar in the lower right of the panel gives the precision of a single observation.

Transits of the expected depth clearly do not occur. The mean of the 27 observations within the transit window

[7] The APT observations are available on the web at http://schwab.tsuniv.edu/t3/bd-103166/bd-103166.html.

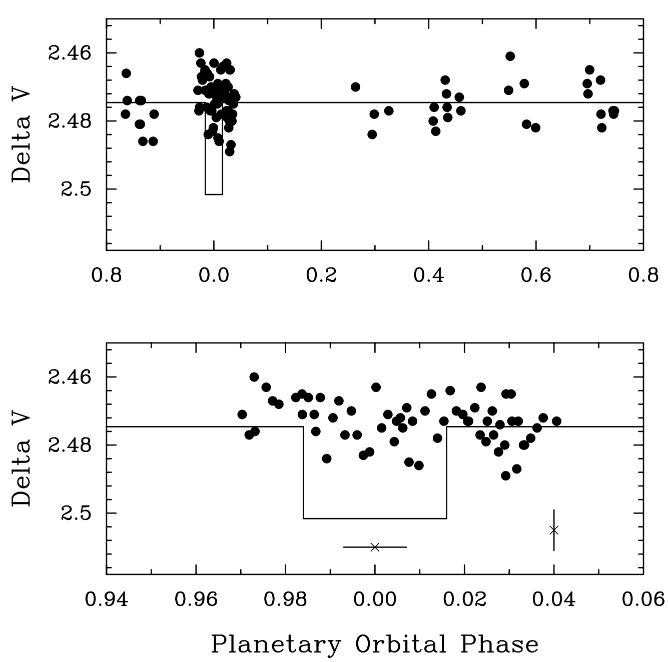

FIG. 6.—*Top*: The complete set of Johnson ΔV differential magnitudes for BD $-10°3166$ plotted against orbital phase of the companion. The predicted depth and duration of a planetary transit are shown schematically. The star has no light variability on the planetary period larger than about 0.0008 mag. *Bottom*: The observations around the phase of predicted transit are replotted with an expanded scale on the abscissa. The error bars are described in the text. Transits deeper than about 0.0002 mag or so are ruled out by these observations.

TABLE 4

METALLICITIES OF PLANET-BEARING STARS

Star	Star (HD)	Star (Hipparcos)	Spectral Types	V (mag)	[Fe/H]	[Fe/H] Reference
GJ 3021	1237	1292	G6 V	6.59	+0.2	1
υ And	9826	7513	F8 V	4.09	+0.12	2
109 Pis	10697	8159	G6 IV	6.27	+0.15	3
	12661	9683	K0 V	7.44	+0.32	4
GJ 86	13445	10138	K1 V	6.17	−0.24	5
79 Cet	16141	12048	G5 IV	6.78	+0.02	6
ι Hor	17051	12653	G0 V	5.40	+0.11	2
	37124	26381	G4 V	7.68	−0.32	3
	46375	31246	K1 IV-V	7.94	+0.34	7
	52265	33719	G0 V	6.30	+0.11	This paper
	75289	43177	G0 V	6.36	+0.28	2
55 Cnc	75732	43587	G8 V	5.95	+0.45	2
	89744	50786	F7 V	5.74	+0.18	8
BD −10°3166	...	...	K0 V	10.0	+0.50	9
47 UMa	95128	53721	G1 V	5.10	+0.01	2
70 Vir	117176	65721	G4 V	5.00	−0.03	2
τ Boo	120136	67275	F7 V	4.50	+0.32	2
	130322	72339	K0 V	8.05	−0.02	10
23 Lib	134987	74500	G5 V	6.47	+0.23	3
ρ CrB	143761	78459	G0 V	5.40	−0.29	2
14 Her	145675	79248	K0 V	6.67	+0.50	2
	168443	89844	G5 V	6.92	−0.14	11
	177830	93746	K2 IV	7.18	...	
16 Cyg B	186427	96901	G3 V	6.20	+0.06	2
	187123	97336	G3 V	7.83	+0.16	2
	192263	99711	K2 V	7.79	+0.00	2
	195019	100970	G3 V	6.87	+0.00	12
	209458	108859	G0 V	7.65	+0.00	2
	210277	109378	G7 V	6.54	+0.24	2
GJ 876	...	113020	M4 V	10.2	...	
51 Peg	217014	113357	G2 V	5.49	+0.21	2
	217107	113421	G7 V	6.17	+0.30	13
	222582	116906	G3 V	7.68	+0.00	3

REFERENCES.—(1) Naef et al. 2000; (2) Gonzalez 2000; (3) Vogt et al. 2000; (4) Fischer et al. 2000; (5) Flynn & Morell 1997; (6) Fuhrmann 1998; (7) Marcy et al. 2000a; (8) Edvardsson et al. 1993; (9) Castro et al. 1997; (10) Udry et al. 2000; (11) Marcy et al. 1999; (12) Fischer et al. 1999; (13) Randich et al. 1999.

agrees with the mean of the 74 observations outside the window to 0.0002 mag. Furthermore, the mean of the 10 observations within the central 40 minutes of the transit window agree with the mean of the observations outside the window to 0.0008 mag. Therefore, full (nongrazing) transits of gas giant and rocky planets with normal densities are excluded by the photometry (see Henry et al. 2000b, § 5.3). The inclination, i, of the orbit must be less than 84°.3, and sin i is less than 0.995.

The semiamplitude of a sine-curve fit to the complete V photometric data set with the period fixed to the planetary orbital period is 0.0008 ± 0.0009 mag. This low limit of possible variability in BD −10°3166 confirms that neither star spots nor pulsations are the cause of the radial velocity variations (see Henry et al. 2000b) and, thus, strongly supports the existence of the planet even in the absence of transits.

5. DISCUSSION

5.1. *Catalog of Extrasolar Planets*

A complete catalog of the extrasolar planets known to date is provided in Tables 4 and 5. Table 4 provides the identifications, spectral types, and [Fe/H] values for all 33 stars which harbor companions having $M \sin i < 10\ M_{\rm JUP}$. About half of these [Fe/H] estimates come from Gonzalez (2000). Two of the stars have no [Fe/H] estimate.

Table 5 provides a catalog of orbital parameters and $M \sin i$ values for the 35 companions having $M \sin i < 10\ M_{\rm JUP}$. The orbits and $M \sin i$ values in Table 5 have been updated from the discovery papers based on the current velocity measurements at Lick and Keck observatories. These revised orbital parameters supersede those previously published, as more velocity measurements are included and the velocity precision has improved.

Table 5 also contains updated values of $M \sin i$ that stem from modern determination of stellar masses. The new stellar masses are based on *Hipparcos* distances and our calibration of *uvby* photometry, and include the estimates of [Fe/H] from Table 4. The photometry and [Fe/H] values permit placement of each star on theoretical evolutionary tracks to establish its metallicity-dependent stellar mass. The new stellar masses differ from the original estimates by 5% typically, and sometimes more for stars of extreme metallicity. For example, 70 Vir (G4 V) was originally thought to have a mass $M = 0.92\ M_\odot$ (Marcy & Butler 1996), but our modern estimate is, $M = 1.10\ M_\odot$, forcing the companion $M \sin i$ to increase from 6.6 $M_{\rm JUP}$ to 7.4

TABLE 5

Updated Catalog of Extrasolar Planets

Star	M_{Star} ($M_\odot$)	P (days)	K (m s^{-1})	e	$M \sin i$ (M_J)	a (AU)
HD 46375	0.96	3.024	35.3	0.00	0.24	0.040
HD 187123	1.06	3.097	72.0	0.01	0.54	0.042
τ Boo	1.30	3.313	474.0	0.02	4.14	0.047
BD $-10°3166$......	1.10	3.487	60.6	0.05	0.48	0.046
HD 75289	1.22	3.508	54.0	0.00	0.46	0.048
HD 209458	1.05	3.524	82.0	0.02	0.63	0.046
51 Peg	1.06	4.231	55.2	0.01	0.46	0.052
υ And b	1.30	4.617	70.2	0.02	0.68	0.059
HD 217107	0.98	7.130	139.7	0.14	1.29	0.072
HD 130322	0.89	10.720	115.0	0.05	1.15	0.092
55 Cnc	1.03	14.656	75.8	0.03	0.93	0.118
GJ 86	0.86	15.800	379.0	0.04	4.23	0.117
HD 195019	1.02	18.200	271.0	0.01	3.55	0.136
HD 192263	0.79	24.35	68.2	0.22	0.81	0.152
ρ CrB	0.95	39.81	61.3	0.07	0.99	0.224
HD 168443	1.10	58.10	469.0	0.52	8.13	0.303
GJ 876	0.32	60.90	235.0	0.24	2.07	0.207
HD 16141	1.03	75.82	10.8	0.28	0.22	0.35
70 Vir	1.10	116.68	316.2	0.40	7.42	0.482
HD 52265	1.13	118.96	45.4	0.29	1.13	0.49
HD 1237............	0.96	133.80	164.0	0.51	3.45	0.505
HD 37124	0.91	154.80	48.0	0.31	1.13	0.547
υ And c	1.30	241.30	58.0	0.24	2.05	0.828
HD 134987	1.05	260.0	50.2	0.24	1.58	0.810
HD 12661	1.07	264.5	90.6	0.33	2.83	0.825
HD 89744	1.43	265.0	256.8	0.70	7.35	0.910
ι Hor	1.19	320.1	67.0	0.16	2.50	0.970
HD 177830	1.17	391.0	34.0	0.40	1.24	1.103
HD 210277	0.99	436.6	39.1	0.45	1.29	1.123
HD 222582	1.00	576.0	179.6	0.71	5.18	1.355
16 Cyg B	1.01	796.7	50.0	0.68	1.68	1.687
HD 10697	1.10	1074.0	114.0	0.11	6.08	2.119
47 UMa	1.03	1084.0	50.9	0.13	2.60	2.086
υ And d	1.30	1308.5	70.4	0.31	4.29	2.555
14 Her	1.06	1700.	95.9	0.37	5.44	2.842

M_{JUP}. When no metallicity is available, stellar masses in Table 5 come from Allcade Prieto & Lambert (1999).

The companions to BD $-10°3166$ and HD 52265 represent each of the two planetary archetypes that have emerged from precision velocity surveys. BD $-10°3166$ is similar to the other "51 Peg–like" planets that are characterized by periods of 3–5 days and circular orbits. The effective temperature of the planet around BD $-10°3166$ would be similar to the companions to 51 Peg and τ Boo, about 1400 K (Burrows et al. 1998). In contrast, HD 52265 resides in an eccentric orbit as do all planets found orbiting beyond 0.2 AU (Marcy & Butler 2000). The semimajor axis and equilibrium effective temperature (Guillot et al. 1996) of the planet orbiting HD 52265 are similar to those of the companion to 70 Vir, 0.49 AU and 360 K, respectively.

5.2. *The Metallicity-Planet Correlation*

As with the majority of the previously discovered planets, BD $-10°3166$ and HD 52265 are metal-rich relative both to nearby field stars and to the Sun (see Marcy, Cochran, & Mayor 2000b; Queloz et al. 2000). Figure 7 shows a histogram of the metallicities of the planet-bearing stars (*solid*

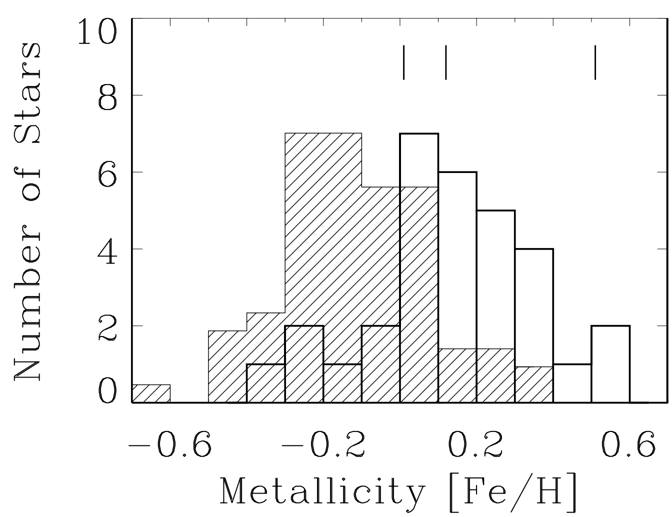

Fig. 7.—Histogram of metallicities of planet-bearing stars (*solid line*), compared to the nearest field stars (*dashed line*). The majority of the planet-bearing stars are metal-rich relative to the Sun, which is itself metal-rich relative to nearby field stars. The metallicities of the Sun, HD 52265, and BD $-10°3166$ are indicated from left to right by the tick marks at [Fe/H] = 0.00, 0.11, and 0.50, respectively.

line), and a comparison set of field stars (*dashed lines*). The comparison field stars are the volume-limited sample of 77 single G dwarfs within 20 pc, as determined by *Hipparcos*. The metallicities of these stars were determined by *uvby* photometry (Hauck & Mermilliod 1998), as described in § 2.3.

As Figure 7 shows, the Sun ([Fe/H] = 0) is slightly metal-rich relative to the nearby field stars, but slightly metal-poor relative to the average planet-bearing star discovered to date. The host stars to the " 51 Peg–like " planets are particularly metal-rich, with BD $-10°3166$ as the extreme case. The [Fe/H] values of the Sun, HD 52265, and BD $-10°3166$ are indicated by the tick marks at the top of Figure 7.

The high metallicity of the planet-bearing stars relative to typical stars in the solar neighborhood represents a physical relationship between planets and host stars (Gonzalez 1997; Marcy & Butler 1998; Queloz et al. 2000; Gonzalez 2000). The metallicity-planet correlation is not caused by any known selection effect, as the target stars in the planet searches were not chosen on the basis of (or knowledge of) their metallicities, with the exception of BD $-10°3166$. The selection of target stars from the two largest planet surveys was based on two criteria, stellar mass (FGKM dwarf) and apparent brightness (roughly $V_{mag} < 8.5$) as described in Mayor et al. (1998) and Marcy et al. (2000a). Indeed, nearly all dwarfs brighter than $V = 8$ are included in current planet surveys, ensuring that metallicity plays little role in the target star selection.

Metallicity-related selection effects may, however, modify the rate of planet detections. Metal-rich stars have deeper absorption lines, thereby improving Doppler precision. However even subsolar metallicities as low as [Fe/H] = -0.5 yield adequate Doppler precision (± 5 m s^{-1} rather than ± 3 m s^{-1}) to detect nearly all planets known. Another selection effect occurs because metal-rich stars are brighter than average main-sequence stars at a given spectral type, leading to a Malmquist bias that could enrich our magnitude-limited stellar sample with high-metallicity stars. Nonetheless, these two selection effects are minor and are unlikely to explain the greatly enhanced [Fe/H] among planet-bearing stars seen in Figure 7.

Moreover, metal-poor stars appear deficient in planets. In our Keck sample of ~ 600 target stars, ~ 300 are metal-poor, out of which only two planets have been found, namely, HD 168443 and HD 37124 (see Table 4). In contrast, 10 planets have been found from the ~ 300 metal-rich stars in our Keck survey. Further, a photometric study with the *Hubble Space Telescope* of 30,000 stars in the globular cluster 47 Tucanae ([Fe/H] = -0.7) has revealed no planet transits (Gilliland et al. 2000; Brown et al. 2000), compared with 15 expected transits based on the occurrence of close-in jupiters among the solar neighborhood stars. Dynamical effects in a dense cluster may disturb protoplanetary disks, thus hindering or disrupting planet formation in 47 Tuc member stars. But an equally likely possibility is that planet formation is reduced in metal-poor environments, consistent with models of planet formation that require dust in the protoplanetary disks (Lissauer 1995; Papaloizou & Terquem 1999).

There are several competing hypotheses to explain the metal-rich nature of most planet-bearing stars found to date. Most prominently, planets may form more readily in metal-rich environments. It is important to consider selection effects in making such arguments. Precision Doppler surveys are most sensitive to massive planets in small orbits. Since Jupiter-mass planets presumably form beyond the ice boundary in a protoplanetary disk (Boss 1995; Lissauer 1995), the planets that have been found to date have presumably migrated from beyond 4 AU to less than 3 AU (Lin et al. 1996; Artymowicz 1998; Levison et al. 1998; Murray et al. 1998). It may be that migration occurs more readily in a metal-rich disk, and that Jupiter-mass planets around metal-poor stars will be found in more distant orbits. Another possibility is that metal-poor stars may preferentially form sub–Saturn-mass planets, making them harder to detect with current technology.

Choosing between these competing metallicity hypotheses will require the detection of Saturn-mass planets in the inner few AU and Jupiter-mass planets beyond 4 AU. With measurement errors of 3 m s^{-1}, the Keck planet search is sensitive to Jupiter-mass companions out to 5 AU, though another 10 years of data will be required to cover an entire orbital period. The first two Saturn-mass candidates (Marcy et al. 2000a) have just been reported from the Keck survey. Both of these planets, HD 46375b and HD 16141b, orbit metal-rich stars.

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