

## FIVE INTERMEDIATE-PERIOD PLANETS FROM THE N2K SAMPLE<sup>1,2</sup>

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### ABSTRACT

We report the detection of five Jovian-mass planets orbiting high-metallicity stars. Four of these stars were first observed as part of the N2K program, and exhibited low rms velocity scatter after three consecutive observations. However, follow-up observations over the last 3 years now reveal the presence of longer period planets with orbital periods ranging from 21 days to a few years. HD 11506 is a G0 V star with a planet of  $M \sin i = 4.74 M_{\text{Jup}}$  in a 3.85 yr orbit. HD 17156 is a G0 V star with a  $3.12 M_{\text{Jup}}$  planet in a 21.2 day orbit. The eccentricity of this orbit is 0.67, one of the highest known for a planet with a relatively short period. The orbital period for this planet places it in a region of parameter space where relatively few planets have been detected. HD 125612 is a G3 V star with a planet of  $M \sin i = 3.5 M_{\text{Jup}}$  in a 1.4 yr orbit. HD 170469 is a G5 IV star with a planet of  $M \sin i = 0.67 M_{\text{Jup}}$  in a 3.13 year orbit. HD 231701 is an F8 V star with planet of  $1.08 M_{\text{Jup}}$  in a 142 day orbit. All of these stars have supersolar metallicity. Three of the five stars were observed photometrically, but showed no evidence of brightness variability. A transit search conducted for HD 17156 was negative, but covered only 25% of the search space, and so is not conclusive.

*Subject headings:* planetary systems — stars: individual (HD 11506, HD 17156, HD 125612, HD 170469, HD 231701)

### 1. INTRODUCTION

Ongoing Doppler surveys of stars closer than 150 pc have detected more than 200 exoplanets (Butler et al. 2006; Wright et al. 2007). This ensemble of exoplanets exhibits a diverse range of statistical characteristics (Marcy et al. 2005). Notably, the mass distribution of exoplanets falls exponentially toward masses greater than 1 Jupiter mass. In addition, there is a statistical pile-up of planets in orbits of just a few days, a paucity of planets with periods between 10 and 100 days, and a rising number of gas giant planets found at separations greater than 1 AU. Orbital eccentricities span a surprising range from 0–0.93, although 92% of planet eccentricities are less than 0.6, and even for planets with periods longer than 5 days (i.e., not tidally circularized), the median exoplanet eccentricity is 0.26.

It has also been shown that planet formation is tied to the chemical composition of the host star. There is a few percent probability of finding a gas giant planet around a solar metallicity star, while

planet occurrence rises dramatically to  $\sim 25\%$  for stars with three times the heavy metal composition of the Sun (Santos et al. 2005; Fischer & Valenti 2005). Ida & Lin (2004) have accounted for this metallicity correlation within the context of core accretion.

The statistical characteristics of exoplanets serve as tracers of planet formation and migration histories. The planet-metallicity correlation indicates initial high metallicity in the protoplanetary disk, which in turn may be correlated with a higher surface density of solid particles in the midplane of the disk that enhances core accretion. Orbital eccentricities and the proximity of gas giant planets to their host stars are remnant signatures of gravitational interactions that drive orbital migration. The architecture of multiplanet systems, sometimes locked in resonances, adds to our understanding of the evolution of the protoplanetary disk.

The N2K program (Fischer et al. 2005) is a survey of metal-rich stars, designed to identify short-period planets. These planets are geometrically endowed with a higher transit probability; transit events provide a rare opportunity to derive information about the planet’s density, internal structure, and atmosphere (Burrows et al. 2007; Charbonneau et al. 2006; Sato et al. 2005). Because short-period planets can be flagged with just a few observations, the N2K program only requires three Doppler measurements to screen each star. However, an increased occurrence of planets is correlated with high host star metallicity at all detected separations. Therefore, additional observations were obtained for the highest metallicity stars to check for longer period planets. This extended program has detected six new intermediate-period planets: HD 5319 and HD 75898 (Robinson et al. 2007), and four of the five planets presented here: HD 11506, HD 17156, HD 125612, and HD 231701.

### 2. HD 11506

#### 2.1. Stellar Characteristics

HD 11506 is classified as a G0 star with  $V = 7.51$ . The *Hipparcos* catalog (ESA 1997) lists  $B - V = 0.607$  with a parallax of 18.58 mas, corresponding to a distance of 53.8 pc. The distance and apparent magnitude set the absolute visual magnitude

<sup>1</sup> Based on observations obtained at the W. M. Keck Observatory, which is operated by the University of California and the California Institute of Technology. Keck time has been granted by NOAO and NASA.

<sup>2</sup> Based on observations obtained at the Subaru Telescope, which is operated by the National Astronomical Observatory of Japan.

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TABLE 1  
STELLAR PARAMETERS

Parameter	HD 11506	HD 17156	HD 125612
$V$ .....	7.51	8.17	8.31
$M_V$ .....	3.85	3.70	4.69
$B - V$ .....	0.607	0.590	0.628
Spectral type.....	G0 V	G0 V	G3 V
Distance (pc).....	53.82	78.24	52.82
$L_{\text{bol}}/L_{\odot}$ .....	2.29	2.6	1.08
[Fe/H].....	0.31 (0.03)	0.24 (0.03)	0.24 (0.03)
$T_{\text{eff}}$ (K).....	6058 (51)	6079 (56)	5897 (40)
$v \sin i$ (km s $^{-1}$ ).....	5.0 (0.50)	2.6 (0.50)	2.1 (0.50)
$\log g$ .....	4.32 (0.08)	4.29 (0.06)	4.45 (0.05)
$M_{\text{star}} (M_{\odot})^a$ .....	(1.1) 1.19 (1.29)	(1.1) 1.2 (1.3)	(1.04) 1.1 (1.17)
$R_{\text{star}} (R_{\odot})^a$ .....	(1.25) 1.38 (1.53)	(1.3) 1.47 (1.6)	(0.99) 1.05 (1.13)
Age (Gyr) $^a$ .....	(3.9) 5.4 (7.0)	(3.8) 5.7 (7.0)	(0.16) 2.1 (5.6)
$S_{\text{HK}}$ .....	0.156	0.15	0.178
$\log R'_{\text{HK}}$ .....	-4.99	-5.04	-4.85
$P_{\text{rot}}$ (days).....	12.6	12.8	10.5
$\sigma_{\text{phot}}$ (mag).....	0.0023	0.0024	...

<sup>a</sup> Stellar masses, radii, and ages are derived from evolutionary tracks.

as  $M_V = 3.85$  and the stellar bolometric luminosity as  $2.29 L_{\odot}$ , including a bolometric correction of  $-0.033$  (VandenBerg & Clem 2003), based on effective temperature, surface gravity, and metallicity of the star. A high-resolution spectroscopic analysis described in Valenti & Fischer (2005) yields  $T_{\text{eff}} = 6058 \pm 51$  K,  $\log g = 4.32 \pm 0.08$ ,  $v \sin i = 5.0 \pm 0.5$  km s $^{-1}$ , and  $[\text{Fe}/\text{H}] = 0.31 \pm 0.03$  dex. HD 11506 is about 0.65 mag above the main sequence. We expect the star to be located about 0.3 mag above the main sequence because of high stellar metallicity, so this star appears to be slightly evolved by a few tenths of a magnitude, and is likely just beginning to transition onto the subgiant branch.

The stellar radius is calculated to be  $1.3 R_{\odot}$  using  $L = 4\pi R^2 \sigma T^4$ . We have also run a fine grid of evolutionary tracks (described in Takeda et al. 2007), tuned to the uniform spectroscopic analysis of Valenti & Fischer (2005), and based on the Yale Stellar Evolution Code. This analysis provides posterior probability distributions for stellar mass, radius, gravity, and ages. Based on these evolutionary tracks, we derive a stellar mass of  $1.19 M_{\odot}$ , a radius of  $1.38 R_{\odot}$ , and an age of 5.4 Gyr. As a measure of the formal uncertainties, the lower and upper 95% credibility intervals from a Bayesian posterior probability distribution are provided in parentheses in Table 1 for these values.

The Ca II H & K lines (Fig. 1) show that HD 11506 is chromospherically inactive. We measure  $S_{\text{HK}}$ , the core emission in the Ca II H & K lines relative to the continuum, for all of our stars. Based on 19 Keck observations, we measure an average  $S_{\text{HK}} = 0.156$  for HD 11506. The ratio of flux from  $S_{\text{HK}}$  to the bolometric stellar flux is designated as  $\log R'_{\text{HK}}$ , and gives the best diagnostic of chromospheric activity. The average  $\log R'_{\text{HK}} = -4.99$  for this star; we derive an activity-based rotational period (Noyes et al. 1984)  $P_{\text{rot}} = 12.6$  days, and an activity-based age of 5.4 Gyr, in excellent agreement with the age from evolutionary tracks. The activity, spectral type, and evolutionary stage of the star allow us to estimate an additional source of astrophysical noise, or stellar jitter, for the velocities of each of the stars on our Doppler survey (Wright 2005).

We monitored the brightness of HD 11506 with the T10 0.8 m automatic photometric telescope (APT) at Fairborn Observatory (Henry 1999; Eaton et al. 2003). The T10 APT measures the brightness of program stars relative to nearby constant comparison stars with a typical precision of 0.0015–0.0020 mag for a single mea-

surement. For HD 11506, we obtained 102  $b$  and  $y$  measurements spanning 451 days between 2004 October and 2006 January. The standard deviation of a single observation from the mean was 0.0023 mag, our upper limit to possible photometric variability in HD 11506. A periodogram analysis found no significant periodicity between 1 and 225 days, so our photometry confirms the star's low chromospheric activity. The stellar parameters are summarized in Table 1.

## 2.2. Doppler Observations and Keplerian Fit

Doppler observations were made at the Keck telescope using HIRES (Vogt et al. 1994) with an iodine cell to model the instrumental profile and to provide the wavelength scale (Butler et al. 1996). An exposure meter maintains a constant signal-to-noise ratio (S/N) of about 200 in our spectra, yielding a mean radial velocity precision of  $2.75$  m s $^{-1}$  for HD 11506. We obtained a total of 26 Doppler measurements. The observation dates, radial velocities, and measurement uncertainties for the radial velocities are listed in Table 2 and plotted in Figure 2.

In addition to velocity errors arising from our measurement uncertainties (including photon shot noise), the star itself can have pulsations, cool spots, or granular convective flows that contribute nondynamical velocity noise. These astrophysical sources of noise are termed jitter, and we empirically estimate stellar jitter based on the spectral type and chromospheric activity of the star, following Wright (2005). For purposes of fitting a Keplerian model, the stellar jitter is added in quadrature to the formal instrumental errors; however, the estimated jitter is never included in the measurement uncertainties for the tabulated radial velocity sets.

The periodogram of the radial velocities shows a strong, broad peak in the power spectrum at about 1270 days, with an associated false-alarm probability (FAP)  $< 0.0001$ . The FAP associated with the periodogram tests whether scrambled velocities yield power that exceeds the observed, unscrambled velocities. A high FAP suggests that the signal is not significant, or could have been caused by a window function in the data. Using a Monte Carlo simulation, 1000 data sets of noise were generated by randomly drawing (with replacement) sets of actual stellar velocities. The fraction of trials with maximum periodogram power that exceeds the observed value from the initial unscrambled data set defines the FAP (Cumming 2004).

For each of the radial velocity data sets in this paper, a Levenberg-Marquardt fitting algorithm was used to model the radial velocities with a theoretical Keplerian orbital curve. There are six orbital parameters derived in the fit: orbital period ( $P$ ), time of periastron passage ( $T_p$ ), eccentricity ( $e$ ), the orientation of the orbit (or line of apsides) ( $\omega$ ), the semivelocity amplitude ( $K$ ) and the residual center-of-mass radial velocity (after subtracting a median radial velocity).

Uncertainties in the orbital parameters are determined with a bootstrap Monte Carlo analysis. First, a best-fit Keplerian model is obtained. Then, for each of 100 trials, the theoretical best fit is subtracted from the observed radial velocities. The residual velocities are then scrambled (with replacement) and added back to the theoretical best-fit velocities, and a new trial Keplerian fit is then obtained. The standard deviation of each orbital parameter for the 100 Monte Carlo trials is adopted as the parameter uncertainty.

The best-fit Keplerian model gives an orbital period of  $1405 \pm 45$  days, a semivelocity amplitude of  $80 \pm 3$  m s $^{-1}$ , and an orbital eccentricity of  $0.3 \pm 0.1$ . The rms to this fit is  $10.8$  m s $^{-1}$ . Based on the chromospheric activity of this star, we estimated a jitter of  $2$  m s $^{-1}$  (Wright 2005). When this jitter is added in quadrature with the error bars listed in Table 2,  $(\chi_{\nu}^2)^{1/2} = 3.2$ . While the large-amplitude Doppler variation is clear, the  $(\chi_{\nu}^2)^{1/2}$  fit is worse

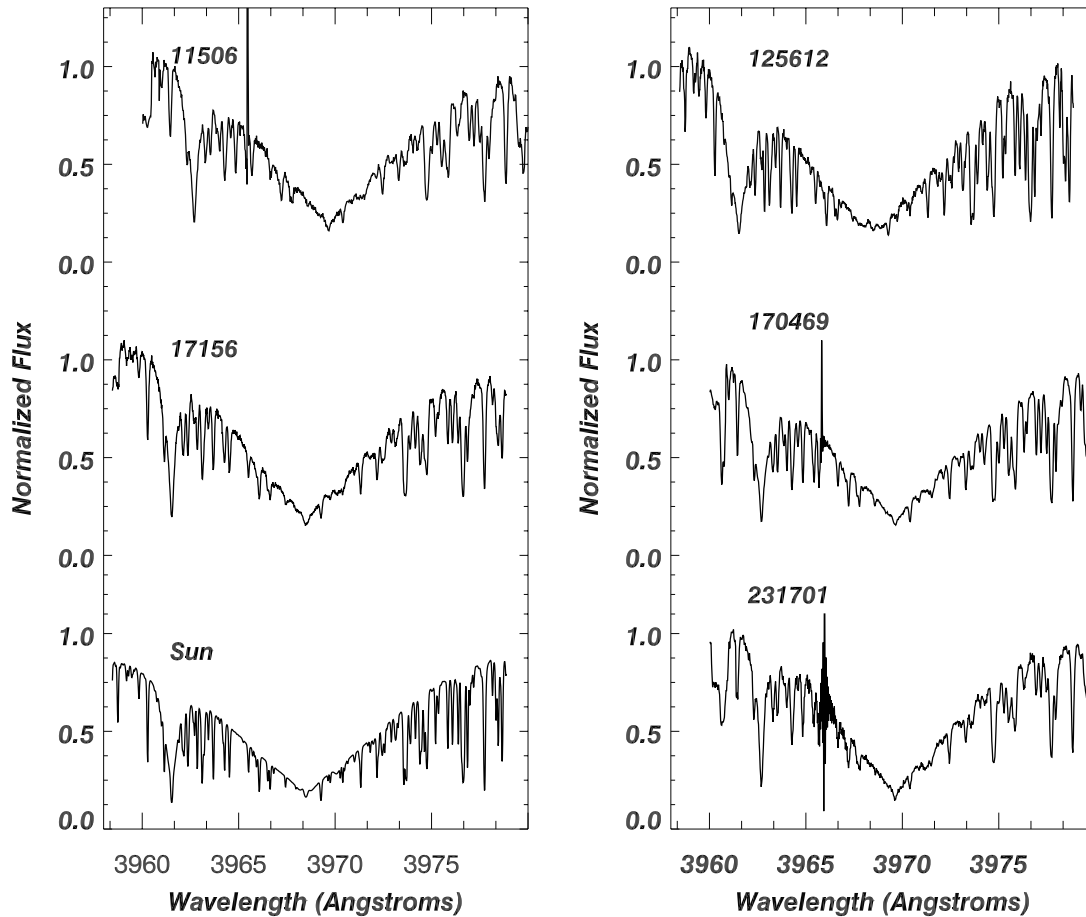


FIG. 1.—*Left*: Ca H line for HD 11506 and HD 17156, with the same wavelength segment of the Sun shown for comparison. *Right*: HD 125612, HD 170469, and HD 231701. All of these stars have low chromospheric activity based on our measurement of line core emission relative to the continuum.

than usual, suggesting that our velocity errors may be underestimated, or that additional low-amplitude dynamical velocities are present. A periodogram of the residual velocities to the single Keplerian fit shows several peaks with similar power. For example, we can fit a second planet with a period of 170 days with a significant reduction in the residual velocity rms and an improvement in  $(\chi^2_\nu)^{1/2}$ . However, this is not yet a unique double-planet fit; additional data are required to better evaluate the possible second signal.

Using the stellar mass of  $1.19 M_\odot$  derived from evolutionary tracks, we find  $M \sin i = 4.74 M_{\text{Jup}}$  and a semimajor axis of 2.48 AU. At the distance of this star, this physical separation corresponds to an angular separation of  $\alpha = 0.04''$ . The Keplerian orbital solution is listed in Table 3, and the best-fit Keplerian model is plotted in Figure 2.

### 3. HD 17156

#### 3.1. Stellar Characteristics

HD 17156 is listed as a G5 star in the SIMBAD database and the *Hipparcos* catalog. However, this spectral type seems at odds with other data for the star. The visual magnitude is  $V = 8.17$ ,  $B - V = 0.59$ , and the *Hipparcos* parallax (ESA 1997) is 12.78 mas, corresponding to a distance of 78.24 pc. The bolometric correction  $-0.039$  (VandenBerg & Clem 2003) and absolute visual magnitude  $M_V = 3.70$  imply a bolometric stellar luminosity of  $2.6 L_\odot$ . Spectroscopic analysis yields  $T_{\text{eff}} = 6079 \pm 56$  K,  $\log g = 4.29 \pm 0.06$ ,  $v \sin i = 2.6 \pm 0.5$  km s $^{-1}$ , and  $[\text{Fe}/\text{H}] = 0.24 \pm 0.03$ . The  $B - V$  color and the effective

temperature are independent measurements that are consistent with each other. Together with the absolute magnitude and position on the H-R diagram, the spectral type for this star is more likely to be G0, with the star just beginning to evolve off the main sequence.

The stellar mass, from evolutionary models described by Takeda et al. (2007), is  $1.2 M_\odot$ , and the age is 5.7 Gyr. The stellar radius from evolutionary models is  $1.47 R_\odot$ , and agrees with the value we derive using the observed luminosity and the Stefan-Boltzmann relation.

The absence of Ca II H and K emission (Fig. 1) demonstrates low chromospheric activity. Taking the average of 25 observations, we measure  $S_{\text{HK}} = 0.15$  and  $\log R'_{\text{HK}} = -5.04$ , and derive a rotational period  $P_{\text{rot}} = 12.8$  days, with an estimated stellar age of  $6.4 \pm 2$  Gyr, which compares favorably with the age derived above from stellar evolution tracks.

We obtained 241 photometric measurements with the T12 APT, spanning 179 days between 2006 September and 2007 March. The standard deviation of the observations from their mean was 0.0024 mag, the upper limit to photometric variability in the star. Periodogram analysis revealed no significant periodicity between 1 and 100 days. In particular, a least-squares sine fit of the observations on the 21.22 day radial velocity period resulted in a photometric amplitude of only  $0.00039 \pm 0.00023$  mag, providing further evidence that the radial velocity variations in HD 17156 are not due to chromospheric activity. The stellar characteristics, including our assessment of photometric variability, are summarized in Table 1.

TABLE 2  
RADIAL VELOCITIES FOR HD 11506

JD-2440000.	Radial Velocity (m s <sup>-1</sup> )	Uncertainties (m s <sup>-1</sup> )
13014.73505.....	-6.67	2.94
13015.73893.....	-6.58	2.89
13016.74089.....	-18.73	2.98
13191.12201.....	-43.89	3.56
13207.10116.....	-71.30	3.17
13208.08401.....	-56.92	3.41
13368.83778.....	-80.87	2.26
13369.75897.....	-80.35	2.18
13370.73242.....	-81.24	2.17
13397.73009.....	-75.66	2.36
13750.73807.....	59.16	2.67
13775.72853.....	71.94	2.77
13776.70435.....	74.90	2.57
13777.72528.....	76.27	2.93
13778.71858.....	78.70	2.73
13779.74737.....	71.93	2.77
13926.12744.....	73.68	2.66
13933.09065.....	75.37	2.62
13959.13935.....	80.47	2.46
13961.12421.....	81.24	2.73
13981.98256.....	74.91	3.12
14023.97438.....	44.32	3.07
14083.84327.....	26.82	2.44
14085.92115.....	38.66	2.54
14129.74332.....	56.29	2.48
14286.11838.....	28.66	3.01

### 3.2. Doppler Observations and Keplerian Fit

We initially obtained eight Doppler observations of HD 17156 using the High Dispersion Spectrometer (Noguchi et al. 2002) at the Subaru Telescope in 2004 and 2005. For the first observing runs, the iodine absorption cell was located behind the entrance slit of the spectrometer (Kambe et al. 2002; Sato et al. 2002, 2005). The box holding the I<sub>2</sub> cell included a window with a lens to maintain constant focal length inside the spectrometer. This eliminated the need to adjust the collimator position when moving the I<sub>2</sub> cell in and out of the light path (i.e., when taking program and template observations). However, the lens introduced a different wavelength dispersion for program observations rela-

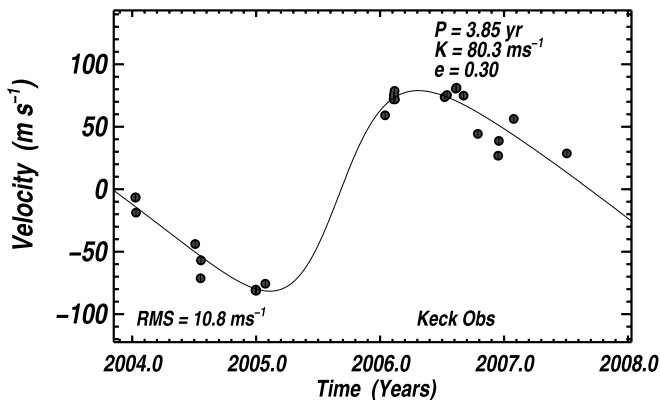


FIG. 2.—Radial velocities for HD 11506. The velocity error bars have been augmented by adding 2 m s<sup>-1</sup> in quadrature to the single measurement precision listed in Table 2. This gives  $(\chi^2_\nu)^{1/2} = 3.2$  for the Keplerian fit. With a stellar mass of 1.19  $M_\odot$ , we derive a planet mass of  $M \sin i = 4.74 M_{\text{Jup}}$  and semimajor axis  $a_{\text{rel}} = 2.48$  AU.

TABLE 3  
ORBITAL PARAMETERS

Parameter	HD 11506	HD 17156	HD 125612
$P$ (days).....	1405 (45)	21.2 (0.3)	510 (14)
$T_p$ (JD).....	13603 (102)	13738.529 (0.5)	13228.3 (12)
$\omega$ (deg).....	262 (19)	121 (11)	21 (9)
Eccentricity.....	0.3 (0.1)	0.67 (0.08)	0.38 (0.05)
$K_1$ (m s <sup>-1</sup> ).....	80 (3)	275 (15)	90.7 (8)
$dv/dt$ (m s <sup>-1</sup> days <sup>-1</sup> ).....	...	...	0.037
$a_{\text{rel}}$ (AU).....	2.48	0.15	1.2
$a_1 \sin i$ (AU).....	0.0099	0.00039	0.0039
$f_1(m)$ ( $M_\odot$ ).....	6.53e-08	1.83e-08	3.09e-08
$M \sin i$ ( $M_{\text{Jup}}$ ).....	4.74	3.12	3.5
$N_{\text{obs}}$ .....	26	33	19
rms (m s <sup>-1</sup> ).....	10.8	3.97	10.7
Jitter (m s <sup>-1</sup> ).....	2	3	2
Reduced $(\chi^2_\nu)^{1/2}$ .....	3.2	1.17	3.56
FAP (periodogram).....	<0.0001	<0.0001	0.0003

tive to the template observation. Modeling of those early data is still ongoing; however, standard stars, known to have constant radial velocities, show rms scatter greater than 15 m s<sup>-1</sup>, with larger run-to-run velocity offsets for Doppler observations obtained with that setup.

The Subaru N2K program was awarded 10 nights of intensive time in summer 2006 and 2006 December. Before the intensive time allocation, the iodine cell was moved in front of the slit, eliminating the change in wavelength dispersion between template and program observations. With this new setup, the rms scatter decreased, ranging from 4–12 m s<sup>-1</sup> in a set of four RV standard stars.

HD 17156 had exhibited large radial velocity variations in 2004–2005 at Subaru. Follow-up observations at Keck confirmed velocity variations, so the star was observed on nine consecutive nights at Subaru from 2006 December 8 to 16. Setup StdI2b was used to cover the wavelength region of 3500–6100 Å with a mosaic of two CCDs. The slit width of 0.6'' was used to give a reciprocal resolution ( $\lambda/\Delta\lambda$ ) of 60,000. We obtained a typical S/N of  $\sim 150$  pixel<sup>-1</sup> at 5500 Å with exposure times of about 120 s. Because of the larger systematic errors for observations taken before summer 2006 (when the iodine cell was behind the slit), only the nine radial velocities from 2006 December are listed in Table 4. To account for the intrinsic rms velocity scatter in standard stars, 5 m s<sup>-1</sup> was added in quadrature to the nine Subaru observations in Table 4.

After HD 17156 was flagged as an N2K candidate at Subaru, it was added to the N2K planet search program at Keck. We obtained 24 radial velocity measurements at the Keck Observatory with an average internal velocity precision of 1.6 m s<sup>-1</sup>. Observation dates, radial velocities, and uncertainties for 33 observations are listed in Table 4. The last column designates the source of the observations as “K” (Keck Observatory) or “S” (Subaru Observatory). The periodogram of the radial velocity data shows a strong narrow peak at 21.1 days, with a FAP less than 0.0001 (for 10,000 Monte Carlo trials).

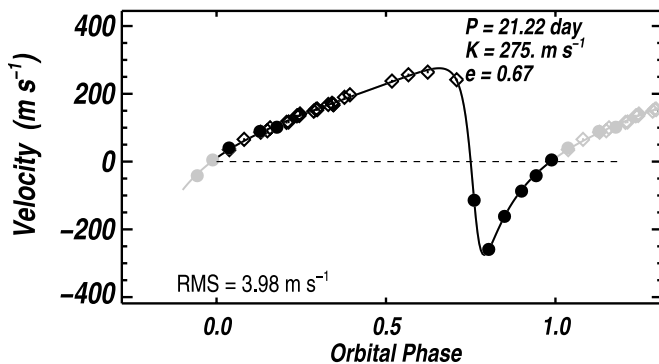
When combining the Subaru and Keck velocities, we first determined a velocity difference of about 130 m s<sup>-1</sup> between two observations taken at Subaru and Keck on the same night (JD 2,454,083.9). With that initial guess, we included a velocity offset as a free parameter, and found that an offset of 116.0 m s<sup>-1</sup> produced a minimum  $(\chi^2_\nu)^{1/2}$ . That offset was added to the Subaru velocities listed in Table 4. The best-fit Keplerian model for the combined Subaru and Keck data sets yields an orbital period of

TABLE 4  
RADIAL VELOCITIES FOR HD 17156

JD–2440000.	RV (m s <sup>−1</sup> )	Uncertainties (m s <sup>−1</sup> )	Observatory Keck/Subaru
13746.75596.....	88.49	1.70	K
13748.79814.....	138.15	1.73	K
13749.79476.....	151.35	1.67	K
13750.80160.....	169.65	1.76	K
13775.77821.....	235.17	1.83	K
13776.80791.....	253.80	1.81	K
13779.82897.....	239.14	1.64	K
13959.13219.....	97.33	1.55	K
13962.07028.....	152.64	1.51	K
13963.10604.....	165.48	1.68	K
13964.13118.....	194.69	1.70	K
13982.03231.....	132.55	1.20	K
13983.08575.....	146.35	1.70	K
13983.99480.....	166.11	1.32	K
13985.00847.....	187.22	1.57	K
14023.95206.....	114.39	1.77	K
14047.95773.....	166.01	1.74	K
14078.01162.....	−116.60	5.14	S
14078.92501.....	−261.56	5.18	S
14079.91371.....	−164.10	5.23	S
14080.98093.....	−89.57	5.13	S
14081.89406.....	−44.08	5.15	S
14082.86071.....	2.39	5.14	S
14083.88445.....	37.62	5.16	S
14083.90314.....	32.76	1.33	K
14084.82860.....	63.22	1.63	K
14085.82560.....	86.67	5.20	S
14085.86537.....	84.28	1.56	K
14086.87960.....	99.01	5.20	S
14129.92513.....	113.30	1.43	K
14130.73019.....	133.66	1.32	K
14131.85485.....	151.11	1.77	K
14138.76720.....	261.56	1.37	K

$21.2 \pm 0.3$  days, a semivelocity amplitude  $K = 275 \pm 15$  m s<sup>−1</sup>, and an orbital eccentricity  $e = 0.67 \pm 0.08$ . The rms to the fit is 3.97 m s<sup>−1</sup>. Adding jitter of 3 m s<sup>−1</sup> (expected for this star) in quadrature with the actual single-measurement errors gives  $(\chi_\nu^2)^{1/2} = 1.04$  for this Keplerian fit.

Adopting a stellar mass of  $1.2 M_\odot$ , we derive  $M \sin i = 3.12 M_{\text{Jup}}$  and a semimajor axis of 0.15 AU. The Keplerian orbital solution is summarized in Table 3. The phase-folded plot of the Doppler measurements for Keck and Subaru observations are



shown in Figure 3 (*left*), and include 3 m s<sup>−1</sup> jitter. Keck observations are represented by diamonds, and Subaru observations are shown as filled circles.

Because the high eccentricity is unusual, we examined the Keplerian fit for the Keck data alone, shown in Figure 3 (*right*). The Keck data have poor phase coverage near periastron, and yield a Keplerian fit with lower amplitude and lower eccentricity. The Subaru observations map periastron passage, and help to model the eccentricity of the orbit.

### 3.3. Transit Search

The 21.22 day period of the companion to HD 17156 is by far the shortest planetary orbital period in this paper. The orbital semimajor axis of 0.15 AU and the stellar radius of  $1.47 R_\odot$  lead to an a priori transit probability of 7% (Seagroves et al. 2003). Therefore, we used our 241 brightness measurements to conduct a preliminary transit search. The orbital parameters in Table 3 constrain the predicted times of transit to about  $\pm 0.3$  days, which is slightly greater than the 0.25 day duration of a central transit. We performed our transit search, using a technique similar to the one described by Laughlin (2000), over all orbital phases for periods between 20 and 23 days. The search was negative, but was only able to effectively cover 25% of the period-phase search space, corresponding to the uncertainties in the orbital parameters. Thus, our photometric data do not preclude the possibility of transits in HD 17156.

## 4. HD 125612

### 4.1. Stellar Characteristics

HD 125612 is a G3 V main sequence star with  $V = 8.31$ ,  $B - V = 0.628$ , and *Hipparcos* parallax (ESA 1997) of 18.93, corresponding to a distance of 52.82 pc and absolute visual magnitude  $M_V = 4.69$ . Spectroscopic analysis yields  $T_{\text{eff}} = 5897 \pm 40$  K,  $\log g = 4.45 \pm 0.05$ ,  $v \sin i = 2.1 \pm 0.5$  km s<sup>−1</sup>, and  $[\text{Fe}/\text{H}] = 0.24 \pm 0.03$  dex. The bolometric correction is  $-0.061$ , giving a stellar luminosity of  $1.08 L_\odot$ . The luminosity and  $T_{\text{eff}}$  imply a stellar radius of  $1.0 R_\odot$ . Within uncertainties, this agrees well with the value of  $1.05 R_\odot$  determined from stellar evolutionary tracks. We also derive a stellar mass of  $1.1 M_\odot$  from stellar evolution models, and an age of 2.1 Gyr.

Figure 1 shows the Ca H line for HD 125612; the lack of emission indicates low chromospheric activity for this star. Taking the mean of 18 observations, we measure  $S_{\text{HK}} = 0.178$  and  $\log R'_{\text{HK}} = -4.85$ , and derive  $P_{\text{rot}} = 10.5$  days, with a stellar age of  $3.3 \pm 2$  Gyr (which compares well with the age of 2.1 Gyr from

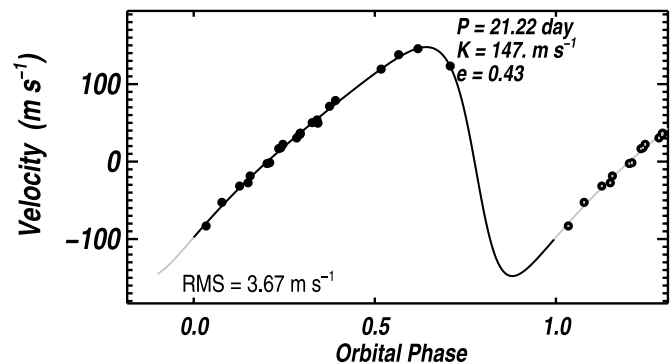


FIG. 3.—*Left*: Radial velocities for HD 17156 from Keck Observatory (diamonds) and Subaru Observatory (filled circles) have 3 m s<sup>−1</sup> added in quadrature to the uncertainties listed in Table 4 to account for expected photospheric jitter. Adopting a stellar mass of  $1.2 M_\odot$ , we derive a planet mass  $M \sin i = 3.12 M_{\text{Jup}}$  and semimajor axis for the orbit  $a_{\text{rel}} = 0.15$  AU. *Right*: Keck velocities only. Although the phase coverage misses periastron, the Keck velocities alone confirm high eccentricity in HD 17156b.

TABLE 5  
RADIAL VELOCITIES FOR HD 125612

JD -2440000.	Radial Velocity (m s <sup>-1</sup> )	Uncertainties (m s <sup>-1</sup> )
13190.83262.....	52.80	2.85
13197.83363.....	61.40	2.66
13198.85557.....	60.49	2.59
13199.83792.....	44.35	2.70
13604.75480.....	-60.07	2.04
13754.12824.....	45.68	1.83
13776.15380.....	17.80	2.03
13777.11940.....	21.71	2.16
13838.01492.....	-77.76	2.35
13841.94894.....	-86.49	2.52
13927.79007.....	-90.28	2.01
13961.75080.....	-79.07	2.01
13962.74127.....	-80.81	1.83
13981.72862.....	-83.16	1.90
13983.74037.....	-81.92	2.11
13984.72815.....	-80.88	2.03
14130.13392.....	-22.62	2.18
14139.12383.....	1.31	1.94
14251.82778.....	90.28	2.39

stellar evolution tracks). Stellar parameters are summarized in Table 1.

#### 4.2. Doppler Observations and Keplerian Fit

We obtained 19 Keck velocity measurements for HD 125612 with a typical uncertainty of 2.2 m s<sup>-1</sup>. Observation dates, radial velocities, and instrumental uncertainties in the radial velocities are listed in Table 5. A periodogram of the velocities shows a strong broad peak at about 500 days.

The best-fit Keplerian model is plotted in Figure 4, and yields a period of  $510 \pm 14$  days, with a semiveloc amplitude of  $90.7 \pm 8$  m s<sup>-1</sup>, an orbital eccentricity of  $0.38 \pm 0.05$ , and a linear trend of  $0.037$  m day<sup>-1</sup>. Adopting a stellar mass of  $1.1 M_{\odot}$ , we derive  $M \sin i = 3.5 M_{\text{Jup}}$  and a semimajor axis of 1.2 AU (angular separation  $\alpha = 0.023''$ ). The Keplerian orbital solution is listed in Table 3, and the RV data are plotted with the best-fit Keplerian model in Figure 4 (*solid line*).

The rms to the Keplerian fit shown in Figure 4 is  $10.7$  m s<sup>-1</sup>. The velocity jitter for this star is expected to be about  $2$  m s<sup>-1</sup>. Therefore, the residual rms is several times the typical error bar, consistent with the poor  $(\chi^2_{\nu})^{1/2}$  statistic of 3.56. A periodogram of the residuals to a 510 day planet fit shows power near 3.5 days. However, there are several other peaks of nearly comparable height, showing that other orbital solutions may give similar improvements. Thus, while we could fit the residuals with a second Keplerian, the FAP of the peak does not yet meet our standards of statistical significance, and more data are required for follow up.

### 5. HD 170469

#### 5.1. Stellar Characteristics

HD 170469 is a G5 subgiant star with visual magnitude  $V = 8.21$ ,  $B - V = 0.677$ , and a *Hipparcos* parallax (ESA 1997) of 15.39 mas, corresponding to a distance of 64.97 pc. The absolute visual magnitude of the star is  $M_V = 4.14$ . The bolometric correction is  $-0.072$ , providing a bolometric stellar luminosity of  $1.6 L_{\odot}$  and (with  $T_{\text{eff}}$ ) a stellar radius of  $1.2 R_{\odot}$ , calculated from

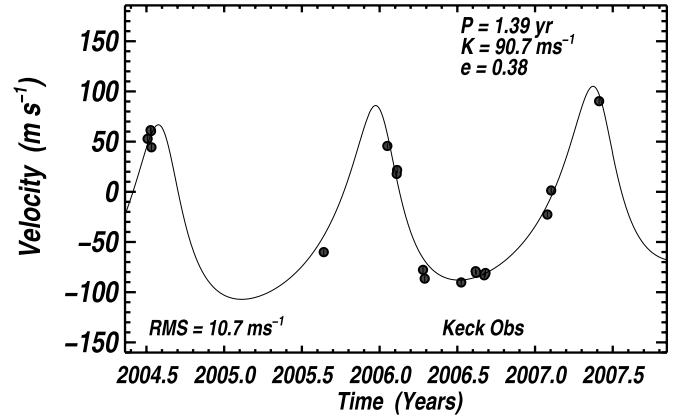


FIG. 4.—Radial velocities for HD 125612. The velocity measurements have  $2$  m s<sup>-1</sup> added to their error bars, listed in Table 5, to account for the level of astrophysical noise (jitter) we expect from the star. With an assumed stellar mass of  $1.1 M_{\odot}$ , we derive a planet mass of  $M \sin i = 3.5 M_{\text{Jup}}$ , and a semimajor axis of 1.2 AU. This Keplerian model still has a high rms and  $(\chi^2_{\nu})^{1/2}$  of 3.56, suggesting the possible presence of an additional planet.

the luminosity. Evolutionary tracks provide a stellar mass estimate of  $1.14 M_{\odot}$ , a stellar radius of  $1.22 R_{\odot}$ , and an age of 6.7 Gyr. Our spectroscopic analysis gives  $T_{\text{eff}} = 5810 \pm 44$  K,  $\log g = 4.32 \pm 0.06$ ,  $v \sin i = 1.7 \pm 0.5$  km s<sup>-1</sup>, and  $[\text{Fe}/\text{H}] = 0.30 \pm 0.03$  dex.

The Ca H & K lines (Fig. 1) indicate low chromospheric activity. Taking the mean of 13 observations, we measure  $S_{\text{HK}} = 0.145$  and  $\log R'_{\text{HK}} = -5.06$ , and derive a rotational period  $P_{\text{rot}} = 13.0$  days and an activity-calibrated age (Noyes et al. 1984) of  $7 \pm 2$  Gyr.

We obtained 215 brightness measurements with the T10 APT spanning 630 days between 2005 March and 2006 November. The standard deviation of the observations was 0.0018 mag, the upper limit to photometric variability in HD 170469. A periodogram analysis found no significant periodicity between 1 and 315 days, confirming the star's low chromospheric activity. The stellar characteristics are summarized in Table 6.

#### 5.2. Doppler Observations and Keplerian Fit

We obtained 35 Keck velocities for HD 170469 with a mean velocity precision of  $1.6$  m s<sup>-1</sup>. Observation dates, radial velocities, and instrumental uncertainties in the radial velocities are listed in Table 7. A periodogram of the velocities yields very strong power at about 1100 days, with a FAP less than 0.0001.

The best-fit Keplerian model gives an orbital period of  $1145 \pm 18$  days, a semiveloc amplitude of  $12.0 \pm 1.9$  m s<sup>-1</sup>, and an orbital eccentricity of  $0.11 \pm 0.08$ . The rms to the fit is  $4.18$  m s<sup>-1</sup>, with  $(\chi^2_{\nu})^{1/2} = 1.59$ , including an estimated astrophysical jitter of  $2.0$  m s<sup>-1</sup>. Adopting a stellar mass of  $1.14 M_{\odot}$ , we derive  $M \sin i = 0.67 M_{\text{Jup}}$  and a semimajor axis of 2 AU ( $\alpha = 0.03''$ ). The Keplerian orbital parameters are listed in Table 8, and the RV data are plotted with the best-fit Keplerian model in Figure 5 (*solid line*).

### 6. HD 231701

#### 6.1. Stellar Characteristics

HD 231701 is an F8 V star with  $V = 8.97$ ,  $B - V = 0.539$ , and *Hipparcos* parallax (ESA 1997) of 9.22 mas, corresponding to a distance of 108.4 pc. The absolute visual magnitude is  $M_V = 3.79$ , so this star is beginning to evolve onto the subgiant branch. Spectroscopic analysis yields  $T_{\text{eff}} = 6208 \pm 44$  K,  $\log g = 4.33 \pm 0.06$ ,  $v \sin i = 4.0 \pm 0.5$  km s<sup>-1</sup>, and  $[\text{Fe}/\text{H}] = 0.07 \pm 0.03$  dex.

TABLE 6  
STELLAR PARAMETERS

Parameter	HD 170469	HD 231701
$V$ .....	8.21	8.97
$M_V$ .....	4.14	3.79
$B - V$ .....	0.677	0.539
Spectral type.....	G5 IV	F8 V
Distance (pc).....	64.97	108.4
$L_{\text{bol}}/L_{\odot}$ .....	1.6	2.4
[Fe/H].....	0.30 (0.03)	0.07 (0.03)
$T_{\text{eff}}$ (K).....	5810 (44)	6208 (44)
$v \sin i$ (km s $^{-1}$ ).....	1.7 (0.5)	4 (0.50)
$\log g$ .....	4.32 (0.06)	4.33 (0.06)
$M_{\text{star}} (M_{\odot})^a$ .....	(1.05) 1.14 (1.16)	(1.08) 1.14 (1.22)
$R_{\text{star}} (R_{\odot})^a$ .....	(1.15) 1.22 (1.3)	(1.16) 1.35 (1.55)
Age (Gyr) $^a$ .....	(5.0) 6.7 (7.8)	(3.5) 4.9 (6.2)
$S_{\text{HK}}$ .....	0.145	0.159
$\log R'_{\text{HK}}$ .....	-5.06	-5.00
$P_{\text{rot}}$ (days).....	13.0	12.2
$\sigma_{\text{phot}}$ (mag).....	0.0018	...

<sup>a</sup> Stellar masses, radii, and ages are derived from evolutionary tracks.

TABLE 7  
RADIAL VELOCITIES FOR HD 170469

JD-2440000.	Radial Velocity (m s $^{-1}$ )	Uncertainties (m s $^{-1}$ )
11705.96808.....	6.04	1.51
11793.81330.....	-0.05	1.39
12008.04881.....	-10.21	1.50
12099.03294.....	-14.05	1.59
12162.76894.....	-15.48	1.42
12364.13287.....	-7.07	1.67
12390.12499.....	-2.46	1.63
12391.12567.....	2.80	1.76
12445.93867.....	-12.12	1.72
12515.82777.....	14.53	1.96
12535.75539.....	3.45	1.53
12536.74191.....	0.06	1.50
12537.82520.....	1.72	1.50
12538.74254.....	0.83	1.30
12539.75501.....	4.11	1.51
12572.69435.....	6.59	1.60
12573.69333.....	5.76	1.34
12574.70725.....	10.11	1.45
12575.69822.....	2.35	1.40
12778.04455.....	15.48	1.96
12804.05044.....	7.80	1.56
12848.92274.....	5.06	2.35
13180.90825.....	-14.03	1.55
13181.89752.....	-12.91	1.57
13548.99248.....	-2.83	1.54
13603.80234.....	4.11	1.50
13842.01212.....	9.79	1.59
13932.96654.....	14.41	1.49
13960.91798.....	10.12	1.42
13961.83115.....	11.29	1.54
13981.82421.....	7.85	1.27
13982.77494.....	5.33	1.26
13983.76067.....	5.96	1.33
13984.83377.....	7.38	1.22
14250.01196.....	-4.92	1.57

TABLE 8  
ORBITAL PARAMETERS

Parameter	HD 170469	HD 231701
$P$ (days).....	1145 (18)	141.6 (2.8)
$T_p$ (JD).....	11669.0 (21)	13180.0 (4.2)
$\omega$ (deg).....	34 (19)	46 (24)
Eccentricity.....	0.11 (0.08)	0.10 (0.08)
$K_1$ (m s $^{-1}$ ).....	12.0 (1.9)	64 (8)
$dv/dt$ (m s $^{-1}$ days $^{-1}$ ).....	...	...
$a_{\text{rel}}$ (AU).....	2.1	0.53
$a_1 \sin i$ (AU).....	0.00126	0.0005
$f_1(m)$ ( $M_{\odot}$ ).....	2.03e-10	8.6e-10
$M \sin i$ ( $M_{\text{Jup}}$ ).....	0.67	1.08
$N_{\text{obs}}$ .....	35	17
rms (m s $^{-1}$ ).....	4.18	5.90
Jitter (m s $^{-1}$ ).....	2.0	2.22
Reduced ( $\chi^2_{\nu}$ ) $^{1/2}$ .....	1.59	1.46
FAP (periodogram).....	<0.0001	0.006

The bolometric correction is  $-0.037$ , and bolometric luminosity is  $2.4 L_{\odot}$ . The luminosity and effective temperature yield a stellar radius of  $1.36 R_{\odot}$ . Modeling the stellar evolutionary tracks, we derive a stellar mass of  $1.14 M_{\odot}$ , a radius of  $1.35 R_{\odot}$ , and an age of 4.9 Gyr.

The Ca H & K lines (Fig. 1) show that the star has low chromospheric activity. We measure  $S_{\text{HK}} = 0.159$  and  $\log R'_{\text{HK}} = -5.0$ , and derive a rotational period,  $P_{\text{rot}} = 12.2$  days and a stellar age of  $5.6 \pm 2$  Gyr. Stellar parameters are listed in Table 6.

## 6.2. Doppler Observations and Keplerian Fit

We obtained 17 Keck observations of HD 231701, with mean internal errors of  $3.2 \text{ m s}^{-1}$ . Observation dates, radial velocities, and measurement uncertainties in the radial velocities are listed in Table 9. The periodogram of this data set has a FAP of 0.006 for a period near 140 days.

The best-fit Keplerian model has an orbital period of  $141.6 \pm 2.8$  days, with semivelocity amplitude  $39 \pm 3.5 \text{ m s}^{-1}$  and an orbital eccentricity of  $0.1 \pm 0.06$ . The rms to this fit is  $5.9 \text{ m s}^{-1}$ . The expected astrophysical jitter for this star is  $2.2 \text{ m s}^{-1}$ . Adding this jitter in quadrature with the error bars listed in Table 9 yields  $(\chi^2_{\nu})^{1/2} = 1.46$  for this Keplerian fit. Adopting a stellar mass of  $1.14 M_{\odot}$ , we derive  $M \sin i = 1.08 M_{\text{Jup}}$  and a semimajor axis of

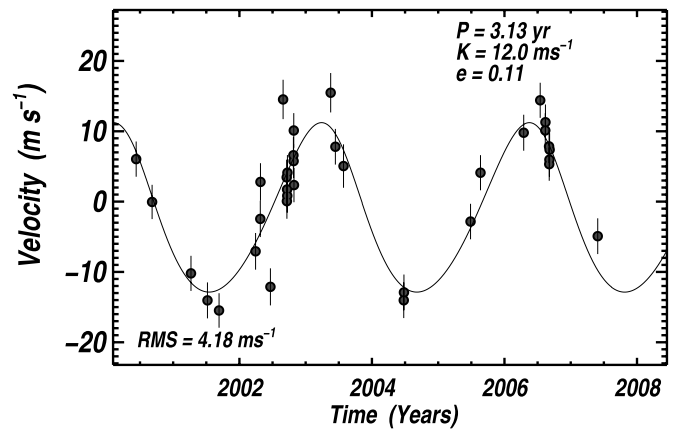


FIG. 5.—Keck radial velocities for HD 170469, including  $2.0 \text{ m s}^{-1}$  added in quadrature with the internal error bars listed in Table 7. With the added jitter, the Keplerian fit has  $(\chi^2_{\nu})^{1/2} = 1.59$ . The assumed stellar mass of  $1.14 M_{\odot}$  yields a planet mass of  $M \sin i = 0.67 M_{\text{Jup}}$  and a semimajor axis of about 2 AU.

TABLE 9  
RADIAL VELOCITIES FOR HD 231701

JD-2440000.	Radial Velocity (m s <sup>-1</sup> )	Uncertainties (m s <sup>-1</sup> )
13190.98047.....	1.98	3.41
13198.03808.....	-2.44	4.00
13199.02309.....	-11.19	3.74
13199.95689.....	-16.16	3.62
13603.87134.....	40.18	3.32
13928.04498.....	-38.57	2.90
13931.08095.....	-32.84	2.93
13932.02123.....	-36.55	3.38
13961.87814.....	-31.29	3.34
13981.76292.....	5.66	3.18
13983.77988.....	5.49	3.11
14023.71873.....	25.79	3.53
14083.69519.....	-39.18	2.43
14085.70009.....	-37.48	2.83
14217.13510.....	-40.18	2.99
14250.07410.....	-15.89	2.90
14286.00169.....	31.17	2.86

0.53 AU. The Keplerian orbital solution is listed in Table 8, and the phased RV data are plotted with the best-fit Keplerian model in Figure 6 (*solid line*).

## 7. DISCUSSION

Here, we present the detection of five new exoplanets detected with Doppler observations. For each of the Keplerian models, we also carried out a Markov Chain Monte Carlo (MCMC) analysis to better estimate the orbital parameters and their uncertainties, following the algorithm described by Ford (2003). Unlike the Levenberg-Marquardt algorithm that we generally use to determine a best-fit Keplerian orbit, the MCMC analysis provides the full posterior probability density distribution for each parameter. This approach is particularly useful for data sets where the Levenberg-Marquardt algorithm can minimize  $(\chi^2_\nu)^{1/2}$  with a model that fits a sparse data set. The MCMC algorithm explores a wider range of parameter space, because it is not driven solely by  $(\chi^2_\nu)^{1/2}$  minimization. However, MCMC does not explore an exhaustive range of parameter space. For example, solutions with very different orbital periods might be missed. For each of the models presented here, we began with the input parameters found with Levenberg-Marquardt fitting, and confirmed that the orbital

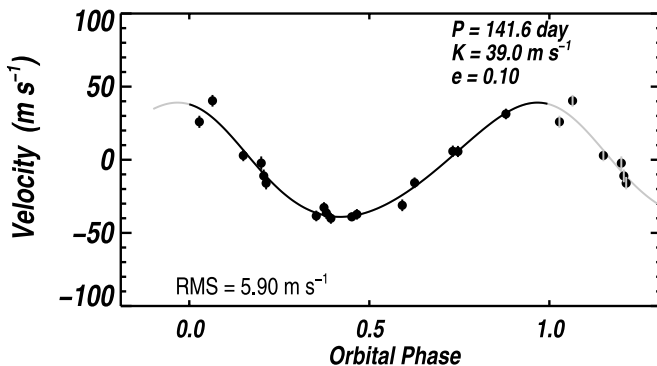


FIG. 6.—Phase-folded radial velocities for HD 231701, including stellar jitter of 2.2 m s<sup>-1</sup> added to the errors listed in Table 9, giving  $(\chi^2_\nu)^{1/2} = 1.46$ . The stellar mass of 1.14  $M_\odot$  implies a planet mass of  $M \sin i = 1.08 M_{\text{Jup}}$  and an orbital radius of 0.53 AU.

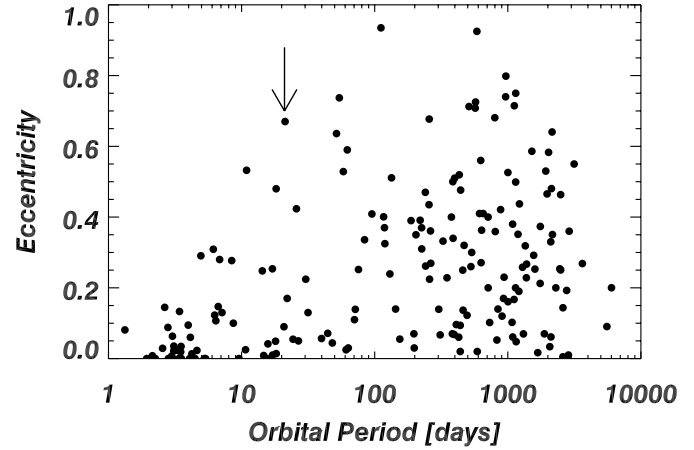


FIG. 7.—Orbital eccentricity distribution for exoplanets. A rising envelope defines the distribution for planets with periods between 2 and 100 days. The distribution peaks for periods between 100 and 1000 days. The arrow points to the dot representing HD 17156b. With an orbital period of 21 days and eccentricity of 0.67, HD 17156b still fits within the envelope of this eccentricity distribution.

elements were recovered with strongly peaked probability distributions using MCMC.

HD 170469 is a star on the regular planet search at Keck that has a planet of  $M \sin i = 0.66 M_{\text{Jup}}$  in a  $\sim 3$  yr orbit, with eccentricity 0.23. The host star is metal-rich with  $[\text{Fe}/\text{H}] = 0.3$ . The remaining four exoplanets were initially part of the N2K program at Keck. The N2K program targets metal-rich stars for rapid identification of short-period planets. The first three radial velocity measurements for the stars presented here had rms scatter less than 5 m s<sup>-1</sup> (except HD 17156, with initial rms scatter of 34 m s<sup>-1</sup>), so these stars were not candidates for short-period planets. However, a follow-up program to obtain Doppler observations on N2K-vetted high-metallicity stars with low chromospheric activity and low rms velocity scatter has detected the presence of these longer period planets.

HD 11506b is a fairly massive planet, with  $M \sin i = 4.74 M_{\text{Jup}}$  and a semimajor axis of 2.5 AU. This could well constitute the outer edge of a habitable zone location for putative rocky moons orbiting the planet, depending on the atmospheric properties of any moons. The host star has a luminosity of 2.3  $L_\odot$ . The eccentricity of this system is 0.3, so the temperature at the top of the planet's atmosphere would change by about 50 K between apastron and periastron.

HD 17156b has a mass of  $M \sin i = 3.12 M_{\text{Jup}}$  and an orbital period of 21.2 days, placing it in the so-called period valley between 10 and 100 days (Udry et al. 2003), where a relatively small fraction of exoplanets have been detected. We derive a substantial orbital eccentricity of 0.67 for HD 17156b. At this proximity to the subgiant host star, the planet moves between 0.05 and 0.25 AU, experiencing temperature changes of a few hundred degrees between periastron and apastron. It is possible that these thermal changes could be observed with sensitive IR flux measurements from space, even though the planet is not known to transit its host star.

The distribution of orbital eccentricities for known exoplanets is shown in Figure 7. An upper envelope in the distribution of eccentricities rises steeply from periods of a few days to reach the maximum observed eccentricities (for HD 80606 and HD 20782) at periods of 100–1000 days. Although an orbital eccentricity of 0.67 seems remarkable for HD 17156b, given its orbital period of just 21.2 days, the eccentricity still falls along the upper edge of the observed eccentricity distribution.



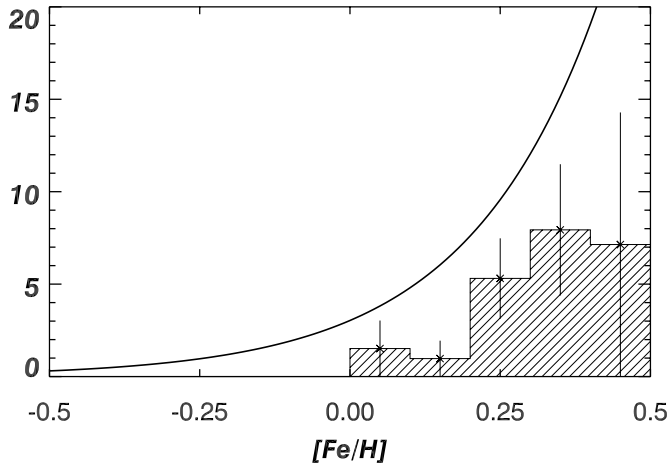


FIG. 8.—Stars with at least four Doppler observations that were observed at Keck as part of the N2K program, binned according to metallicity. In each 0.1 dex metallicity bin, the percentage of stars with detected planets is plotted, and Poisson error bars are shown. Superimposed on this histogram is the curve of planet occurrence as a function of metallicity from Fischer & Valenti (2005). Most stars on the N2K program have only four or five observations; however, the metallicity correlation is still emerging, and is supported in this sample.

HD 125612b has  $M \sin i = 3.5 M_{\text{Jup}}$ , with a semimajor axis of 1.2 AU. This planet has an eccentricity of 0.38. The planet is carried from 0.47 AU at periastron, where the temperature at the top of the atmosphere is about 300 K, to about 2.1 AU, where the temperature falls below the freezing point of water to about 200 K. A single planet model does not appear to adequately describe the velocities of HD 125612, because the rms to that fit is  $10.7 \text{ m s}^{-1}$ ; yet the star is chromospherically quiet and slowly rotating, with  $v \sin i = 2 \text{ km s}^{-1}$ . This star may well have an additional planet orbiting in a relatively short period.

Velocity variations in HD 231701 have been modeled as a planet with  $M \sin i = 1.08 M_{\text{Jup}}$ , a semimajor axis of 0.53 AU, and orbital eccentricity of about 0.1. The MCMC probability dis-

tributions for HD 231701 are consistent with this Keplerian model, but allow for eccentricity solutions that extend to zero. This analysis alerts us that more RV measurements should be taken to better constrain the orbital eccentricity of this system.

We have now obtained three or more Doppler observations for 423 stars at Keck Observatory as part of the N2K program. Spectral synthesis modeling has been carried out for all of these stars, and we plot the percentage of stars with detected planets in each 0.1 dex metallicity bin in Figure 8. Superimposed on this plot is the planet detectability curve from Fischer & Valenti (2005). A planet probability can be assigned based on the stellar metallicity. Integrating planet probabilities, we expect  $27 \pm 5$  exoplanets with masses greater than  $1 M_{\text{Jup}}$  and orbital periods shorter than 4 years. Fourteen, or about half of the expected planets in the sample, have now been detected.

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