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A Hot Saturn Planet Orbiting HD 88133, from the N2K Consortium[1]

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ABSTRACT

The N2K consortium is carrying out a distributed observing campaign with the Keck, Magellan and Subaru telescopes, as well as the automatic photometric telescopes of Fairborn Observatory, in order to search for short-period gas giant planets around metal-rich stars. We have established a reservoir of more than 14,000 main sequence and subgiant stars, closer than 110 pc, brighter than

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[1] 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.

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V=10.5 and with $0.4 < B - V < 1.2$. Because the fraction of stars with planets is a sensitive function of stellar metallicity, a broadband photometric calibration has been developed to identify a subset of 2000 stars with [Fe/H] > 0.1 dex for this survey. We outline the strategy and report the detection of a planet orbiting the metal-rich G5IV star HD 88133 with a period of 3.41 days, semi-velocity amplitude, K=35.7 m s^{-1}and $M \sin i = 0.29$ M$_{\rm JUP}$. Photometric observations reveal that HD 88133 is constant on the 3.415-day radial velocity period to a limit of 0.0005 mag. Despite a transit probability of 19.5%, our photometry rules out the shallow transits predicted by the large stellar radius.

Subject headings: planetary systems – stars: individual (HD 88133)

1. Introduction

The Doppler Radial Velocity (RV) technique is an effective tool that has resulted in the detection of 136 extrasolar planets over the last decade. Ongoing Doppler projects in the U.S. and Europe are currently surveying almost 3000 of the closest and brightest stars ($V < 8$). These surveys now detect Jupiter-like extrasolar planets in wider orbits analogous to our own solar system (Marcy *et al.* 2002) and Neptune-mass planets with orbital periods of a few days (Butler *et al.* 2004, McArthur *et al.* 2004, Santos *et al.* 2004). Because planets with short orbital periods are so easily detected with Doppler RV measurements, virtually all planets with $M \sin i > 0.5$ M$_{\rm JUP}$ and orbital periods less than 14 days (the so-called "hot Jupiters") have already been harvested from current Doppler surveys.

The observation of a hot Jupiter planet transiting the star HD 209458 (Charbonneau *et al.* 2000, Henry *et al.* 2000) provided an important direct detection of an extrasolar planet. The quality of physical information for HD 209458b exceeds that of any other known exoplanet because the intrinsic brightness of the host star enables the efficient collection of high-precision (3 ms^{-1}) radial velocities which allow precise determination of the mass and orbital parameters (e.g. Butler et al 1996), as well as high temporal resolution HST photometry (Brown *et al.* 2001) and spectroscopic observations of the atmospheric constituents in the planet atmosphere (Charbonneau *et al.* 2002, Vidal-Madjar *et al.* 2003). The intrinsic brightness of HD 209458 also contributed to the precision with which stellar characteristics ($T_{\rm eff}$, metallicity, $v \sin i$, M$_\star$, R$_\star$) could be derived and an accurate parallax measurement is available from Hipparcos. Since only the ratio of the planet radius to the stellar radius can be determined, knowledge of the stellar parameters is key to deriving the radius and density of the transiting planet.

The recent spate of discoveries of planets transiting faint stars (Alonso *et al.* 2004, Bouchy *et al.* 2004, Konacki *et al.* 2003, Pont *et al.* 2004) indicates that HD 209458b is in fact a rather anomalous planet, with a radius 40% larger than expected both from theory. The radius of HD 209458 is also apparently larger than the radii of the other transiting planets. The radius discrepancy observed for HD 209458b has spawned controversy regarding the nature of the mechanism responsible for the planet's bloated condition (Guillot & Showman, 2002, Baraffe *et al.* 2003, Burrows *et al.* 2003, Bodenheimer, Laughlin & Lin 2003).

Since the detection of HD 209458b, more than twenty photometric transit searches have been started (Horne 2003). Unfortunately, these surveys cannot detect the 90% of hot Jupiter planets that do not transit their host stars. Non-transiting hot Jupiters are important objects in their own right and the detection of a large number of these objects could provide powerful constraints on theories of planet formation and evolution. For example, these planets can exhibit non-Keplerian interactions with sibling planets on timescales of just a few years. In addition, the eccentricity distribution of short-period planets could reveal whether hot Jupiters have solid cores. The detection of a large number of new hot Jupiters could also shed light on the puzzling concentration of planets in the period range between roughly 2.5 d and 3.5 d (9 out of 20 objects with $P < 10\,\mathrm{d}$). This orbital pile-up at 3 days is seemingly at odds with the detection of 3 out of 4 transiting planets with orbital periods of about 1.5 days ("very hot Jupiters") from the OGLE survey (Konacki *et al.* 2004). There is no observational bias against the Doppler detection of $P = 1.5$ day planets by the Doppler technique, suggesting that these very hot Jupiters must be much less common than gas giant planets in 3 day orbits.

2. N2K Consortium

Current Doppler surveys have identified about 20 extrasolar planets with orbital periods shorter than 14 days, however after an initial burst of discoveries, the rate of hot Jupiter detections has trailed off. The known set of hot Jupiters is a stagnant set; virtually all of these easily-detected planets have been harvested from current RV surveys. In order to find a substantial number of new hot Jupiters, we have established a consortium of U.S., Chilean and Japanese astronomers to carry out a distributed observing program. Using the Keck, Magellan and Subaru telescopes, we will observe the next 2000 (N2K) closest, brightest, and most metal-rich FGK stars not on current Doppler surveys.

We first established a reservoir of more than 14,000 main sequence and subgiant stars drawn from the Hipparcos catalog (ESA 1997). Considerable information is available for this large aggregate of candidate stars including B and V colors, 2MASS JHK photometry, parallaxes, luminosity, proper motions, photometric variability, and information regarding the presence of companions. Our reservoir stars all have $0.4 < B - V < 1.2$ and $V < 10.5$ and all are closer than 110 pc.

The N2K program actively tracks stars as they are drawn out of the reservoir and distributed to a particular telescope for an observing run. At each telescope, we use an iodine cell to provide a wavelength reference spectrum and our standard Doppler pipeline to analyze all stars identically. A spectral synthesis modeling pipeline has also been established at each telescope so that spectroscopic analysis (Valenti & Fischer 2004) is carried out identically for all stars. Our strategy is to observe a set of star three times over a period of a few days to detect short period RV variations consistent with a hot Jupiter. Monte Carlo simulations show that with a Doppler precision of 7 m s^{-1} , more than 90% of the planets with $M \sin i > 0.5$ $\mathrm{M_{JUP}}$ and orbital periods between 1.2 and 14 days will show $> 3\sigma$ RV scatter. Spectroscopic binaries typically show RMS scatter of several hundred m s^{-1} on this timescale and can be immediately dropped. In fact, our Doppler velocities generally have a better-than-target precision of 4-5 m s^{-1} and any stars with significant RV variations obtain immediate RV and photometric follow-up at the telescopes available to the consortium members. Over the next 2 years, the N2K consortium should detect $\sim$60 new planets with $M \sin i > 0.5$ $\mathrm{M_{JUP}}$ and orbital periods shorter than 14 days and flag stars having longer period exoplanets.

All stars with significant short-term RV variations will also be observed with the automatic photometric telescopes (APTs) at Fairborn Observatory (Henry 1999, Eaton, Henry & Fekel 2003). As outlined in Butler et al. (2004), the precise photometric measurements from the APTs are useful for establishing whether the RV variations are caused by photospheric features such as spots and plages or by planetary-reflex motion. Also, the efficiency and flexibility of the APTs make them ideal for searching for possible transits that would allow the determination of planetary radii and true masses. The high precision of the APT photometry renders transits of hot Jupiters easily visible, even for the subgiant stars in our sample with radii of up to 2.0 $R_\odot$ (e.g., Henry 2000; §5 below).

2.1. Synthetic Templates

In the past 6 months we have been testing the use of synthetic templates for our Doppler analysis pipeline. The advantage to a synthetic template is that it eliminates one RV observation, traditionally taken without iodine. To create the synthetic template we first divide the stellar observation (with I2) by a featureless B star observation (also with I2). This division is never perfect; residual 1% iodine lines are left in the spectrum and our first tests showed that this resulted in unacceptable drifts in the wavelength scale as the barycentric velocities change with time. To try to eliminate this velocity drift, we morphed the National Solar Observatory (NSO) solar spectrum (Wallace *et al.* 1993) to match our iodine-divided stellar spectra. The morphing process involves rotationally broadening the solar absorption lines and then globally rescaling with a pseudo optical depth. Additional fine-tuning is accomplished by multiplying the morphed spectrum by the remaining smoothed residuals. The morphed-NSO templates provide reliable short-term RV precision of about 7 m s^{-1} and help to identify spectroscopic binaries that should be dropped from the N2K program. However, the standard Doppler technique employing an extra template observation still yields the highest precision and is used for stars that warrant long-term RV follow up.

3. Targeting Metal-Rich Stars

Butler *et al.* (2001) have shown that 0.75% of the stars on current Doppler surveys have hot Jupiter companions with orbital periods between 3–5 days. However, we expect a higher detection rate because we are exploiting an observed correlation between stellar metallicity and the rate of occurrence of gas giant planets. Fischer & Valenti (2004) show that stars with [Fe/H] > 0.2 have at least 3 times as many extrasolar planets as solar metallicity stars and we will bias our sample with metal-rich stars. In addition, our observing strategy will flag orbital periods out to 14 days so our detectable parameter space extends beyond the orbits considered to be hot Jupiters by Butler *et al.* (2001). We expect to find close-in gas giant planets around at least 3% of the stars surveyed by the N2K consortium.

Of key importance to the success of this project, a photometric calibration using broadband filters was developed (Ammons *et al.* 2004) to provide $T_{\rm eff}$ and metallicity estimates for every star in our reservoir using Tycho BV and 2MASS JHK photometry. Our ability to produce a Hipparcos-2MASS-metallicity calibration was made possible by our possession of a high-quality "training set" of spectroscopic metallicities for more than 1100 FGK stars (Valenti & Fischer 2004). Figure 1 shows a histogram of the subset of super-solar metallicity stars from our reservoir sample. This set of more than 2000 stars with [Fe/H] > 0.1 dex comprises the core target sample for the N2K program. We are also obtaining low resolution spectroscopy to check the broadband photometry metallicity calibration. The low resolution spectroscopy employs a set measured spectral line equivalent widths, recently re-calibrated (Robinson *et al.* 2004) using the same training set of spectroscopic metallicities (Valenti & Fischer 2004). These indices provide a spectroscopic abundance that agrees to better than 0.1 dex (Figure 2).

4. The First N2K Run

The first set of N2K stars were observed during a 3 night observing run at Keck in the 2004A semester. After a single observation on the first night, we determined the chromospheric activity of the observed stars (Wright *et al.* 2004, Baliunas *et al.* 1997, Noyes *et al.* 1984) and ran the spectra through our spectral synthesis pipeline to determine metallicity, $\log {\rm g}$, $v \sin i$ and to identify double-lined spectroscopic binaries (SB2s). As a result of this "morning after" screening, 12 stars were identified as SB2's or rapid rotators and were dropped before a second observation was obtained. All information regarding every observed star, including RV measurements, information from spectral synthesis modeling, information about the presence of stellar companions and chromospheric activity measurements will be appearing in a subsequent catalog paper.

We obtained three or more RV measurements for 211 stars at Keck in the 2004A semester with a typical precision of 4 m s^{-1} for stars with standard templates and 7 m s^{-1} for stars with synthetic templates. The RV variations fell into three categories: 1) 148 stars showed less than 3σ RV scatter and were retired from the N2K program, 2) 19 stars were spectroscopic binaries with RV variations > 500 m s^{-1} - these spectroscopic binaries were also retired from the N2K program, 3) 35 stars (16% of the 211 star sample) showed RMS scatter $> 3\sigma$ consistent with the presence of a short-period planet.

The distribution of RMS scatter for these stars is shown in Figure 3. The cross-hatched bins in Figure 3 represent the 35 stars having radial velocity scatter between 20 – 80 m s^{-1}. These are the stars that warrant RV follow-up to search for short-period planets. One of these stars, HD 88133, showed an initial RMS scatter of 24 m s^{-1}. This star now has enough RV measurements to characterize an orbiting hot Jupiter planet, described below.

Spectral synthesis modeling was carried out for all 211 stars yielding [Fe/H], $T_{\rm eff}$, $\log {\rm g}$ and $v \sin i$ with uncertainties of 0.04 dex, 23K, 0.05 dex and 0.3 m s^{-1} respectively, as discussed in Valenti & Fischer (2004). Figure 4 shows that the spectroscopic metallicities agree well with the broadband metallicity estimates (Ammons *et al.* 2004), confirming that the broadband photometric calibration is an excellent way to identify metal-rich target stars for the N2K program.

5. HD 88133

HD 88133 is a G5 IV star with $V = 8.0$ and $B - V = 0.81$. The Hipparcos parallax (ESA 1997) of 13.43 *mas* places the star at a distance of 74.5 pc with an absolute visual magnitude, $M_V = 3.65$. Our spectroscopic analysis yields $T_{\rm eff} = 5494 \pm 23$ K, [Fe/H] = 0.34 ± 0.04, $\log {\rm g} = 4.23 \pm 0.05$ and $v \sin i = 2.2$ km s^{-1}. From the bolometric luminosity and $T_{\rm eff}$ we derive a stellar radius of 1.93 R$_\odot$ and evolutionary tracks of Girardi *et al.* provide a stellar mass estimate of 1.2 M$_\odot$. The chromospheric activity of HD 88133 is $S_{HK} = 0.138$ and $\log R'_{HK} = -5.16$. Using the relation between rotation period and the S_{HK} index (Noyes *et al.* 1984) we estimate a rotational period of 48 days for this star. Stellar parameters are summarized in Table 1.

The observation dates, radial velocities and RV uncertainties for HD 88133 are listed in Table 2. We estimate the stellar jitter for this star to be 3.2 m s^{-1} and add this jitter in quadrature with the formal RV errors when fitting the data with a Keplerian and calculating $\sqrt{\chi^2_\nu}$. Our best fit orbital parameters are listed in Table 3 and the Keplerian fit is overplotted on the phased RV data in Figure 5. The orbital period is 3.41 days, with a velocity semi-amplitude of 35.7 m s^{-1} and eccentricity of 0.11 ± 0.05 with RMS scatter of 5.26 m s^{-1} and $\sqrt{\chi^2_\nu}$ of 1.26. With the stellar mass of 1.2 M$_\odot$, we derive $M \sin i = 0.29$ M$_{\rm JUP}$ and $a_{rel} = 0.046$ AU. Uncertainties were estimated by running 100 Monte Carlo trials, fitting in the orbital parameters listed in Table 3. The models of Bodenheimer, Laughlin & Lin (2003) predict a planetary radius for HD 88133b of $0.97 R_{\rm JUP}$ if the planet has a core, and $1.12 R_{\rm JUP}$ if it does not.

The best fit eccentricity of 0.11 is unusual since giant planets with orbital periods shorter than 5 days are expected to be tidally circularized. Fixing the eccentricity to zero yields a slightly increased $\sqrt{\chi^2_\nu}$ of 1.48 and an RMS to the fit of 6.3 m s^{-1}. Again, we have added jitter in quadrature to the formal RV errors. This constitutes an acceptable fit, however this star warrants additional RV follow-up to determine the eccentricity more accurately and to check for any additional planetary companions.

In addition to the radial velocity observations, we have collected 161 photometric measurements between 2004 March and June with the T12 0.8 m automatic photometric telescope at Fairborn Observatory. The transit probability is given by the ratio of the stellar radius to the semi-major axis of the orbit: $R_*/a = 19.5\%$. The telescope, photometer, observing procedures, and data reduction techniques are described briefly in Butler *et al.* (2004) and the references therein. Our photometric comparison star was HD 88270 ($V = 6.64$, $B - V = 0.36$, F2 V), which has been shown to be constant to 0.002 mag or better from intercomparison with additional comparison stars.

The 161 combined $(b + y)/2$ differential magnitudes of HD 88133 were phased with the planetary orbital period and a time of inferior conjunction (computed from the orbital elements in Table 3) and plotted in Figure 6. The standard deviation of the observations is 0.0029 mag, slightly larger than the typical precision with this telescope, most likely because HD 88133 is somewhat fainter than most program stars. Period analysis does not reveal evidence of any periodicity between 1 and 60 days. A least-squares sine fit of the observations phased to the radial velocity period gives a semi-amplitude of 0.00054 ± 0.00030 mag, so starspots are unlikely to be the cause of the radial velocity variations. The solid curve in Figure 6 approximates the predicted transit light curve (assuming central transits) computed from the orbital elements, the stellar radius, and an adopted planetary radius equal to Jupiter's. The horizontal bar below the predicted transit window represents the approximate uncertainty in the time of mid transit, based on Monte Carlo simulations and the uncertainties in the orbital elements. The predicted transit depth is only 0.0031 mag, due to the large stellar radius. However, the mean of the 8 observations within the transit window agrees with the mean of the 153 observations outside the window to within 0.0005 mag, just as expected from the precision of the observations. Thus, central (non-grazing) transits are ruled out by our photometry.

6. Discussion

The N2K consortium was established to survey "the next 2000" closest and brightest high metallicity stars using a distributed observing program and a quick-look strategy to identify stars with RMS velocity scatter consistent with the presence of a hot Jupiter companion. Over the next two years, this program should identify 60 new gas giant planets in short period orbits, quadrupling the number of hot Jupiters that have been discovered and providing 6 new transiting planets around stars brighter than $V = 10.5$.

Observations of the first 211 stars at Keck have identified 35 stars with velocity variations consistent with the presence of an extrasolar planet. Follow-up RV observations on one of these stars (HD 88133) has confirmed the presence of a planet in a 3.41 day orbit with

$M \sin i$ = 0.29 $\mathrm{M_{JUP}}$. Our photometric observations have established that HD 88133 is highly constant on the radial velocity period and that it does not undergo transits at the predicted times.

Spectroscopic analysis of the program stars requires about one CPU hour to run, so it is possible to analyze $\sim$ 300 stars in one 24 hour period on our computer cluster at San Francisco State University. This pipeline analysis makes it possible to check every star the morning after the first observation is obtained. Unsuitable stars (SB2s, rapid rotators) are immediately dropped and the observing list is backfilled with new stars.

In addition to the 250 stars observed in the 2004A semester at Keck, we have completed 3 or more observations of 130 stars at Subaru. All of these stars have spectroscopic and Doppler analysis completed and we are obtaining follow-up observations on those stars with RMS velocity scatter greater than 3σ and less than 100 m $\mathrm{s^{-1}}$. At Magellan, 90 stars have multiple observations and we are beginning the Doppler analysis of those stars. So, the first 500 of 2000 metal-rich stars are now beginning to be processed by the N2K consortium.

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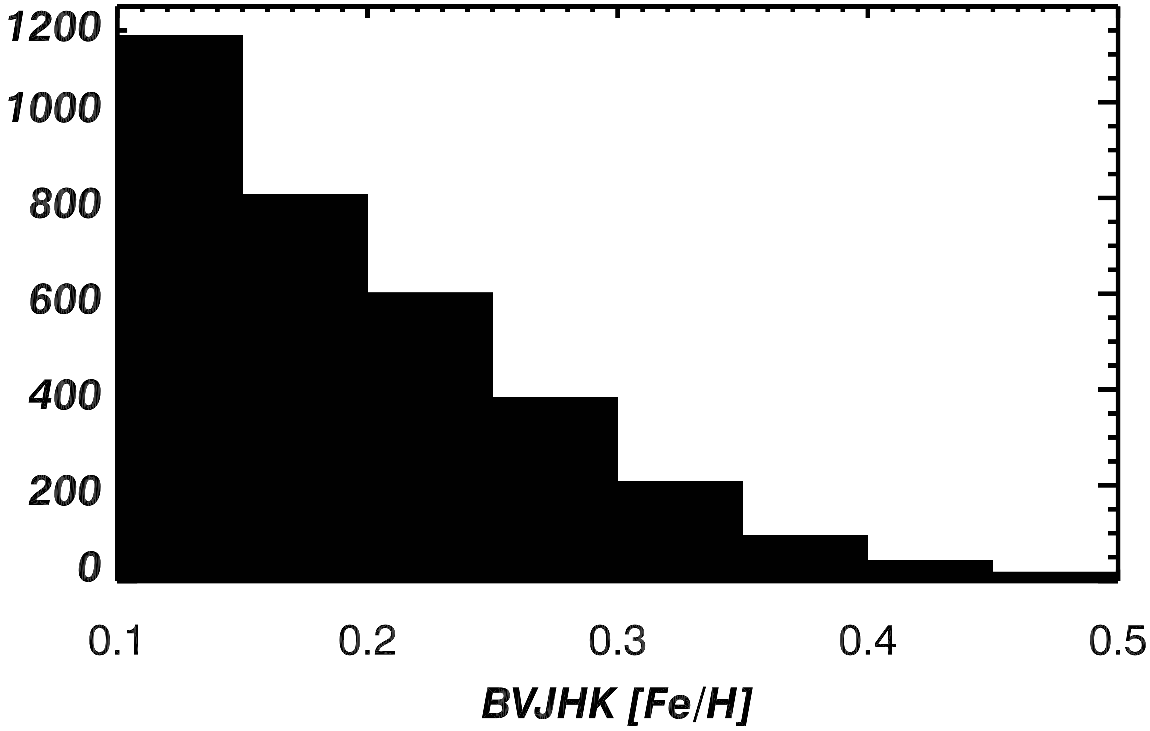

Fig. 1.— The metal-rich tail of the [Fe/H] distribution for our N2K reservoir sample of more than 14,000 stars. Broadband photometry (B_T, V_T, JHK) was used to estimate the metallicity for all main sequence and subgiant stars closer than 110 pc, brighter than $V = 10.5$, with color $0.4 < B - V < 1.2$ and not on current Doppler programs. The 2000 stars shown here have [Fe/H] > 0.1 dex and are the primary targets for the N2K program

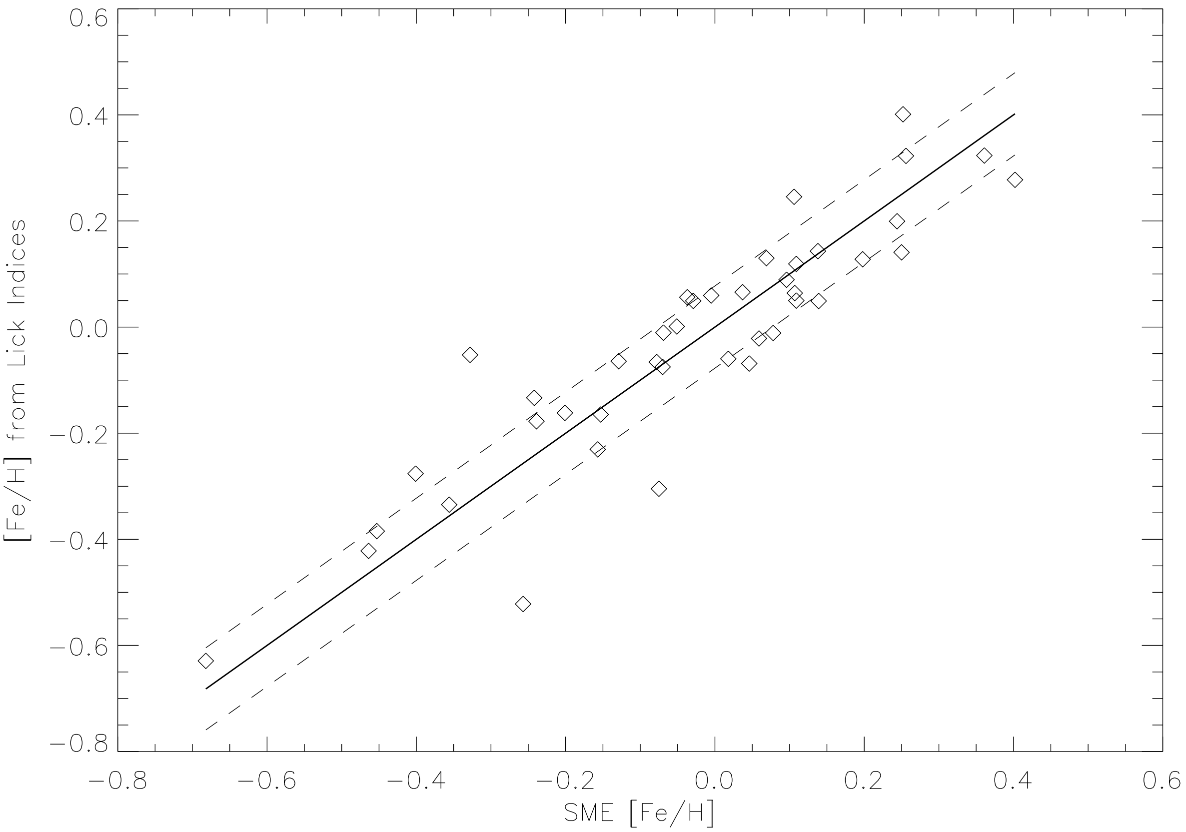

Fig. 2.— Low resolution indices based on equivalent widths of a set of spectral lines have been calibrated to metallicities derived from spectral synthesis modeling of high resolution spectra, and show agreement to better than 0.1 dex

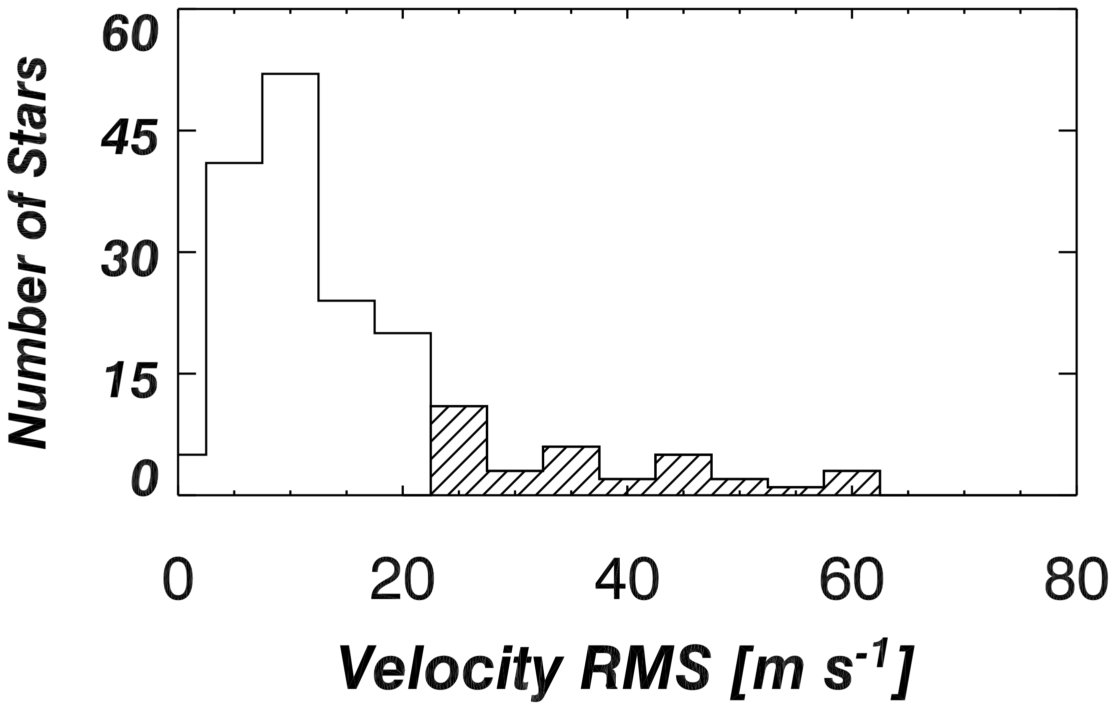

Fig. 3.— Velocity scatter less than 80 m s^{-1} is observed for 175 of 211 stars observed at Keck after 3 or more RV observations. RV scatter $< 3\sigma$ is seen for 148 of these stars. However 35 stars, or 16% of the observed sample (indicated in the cross-hatched bins) show $> 3\sigma$ RV scatter, consistent with the presence of a hot Jupiter. The planet announced in this paper had an initial velocity RMS of 24 m s^{-1}.

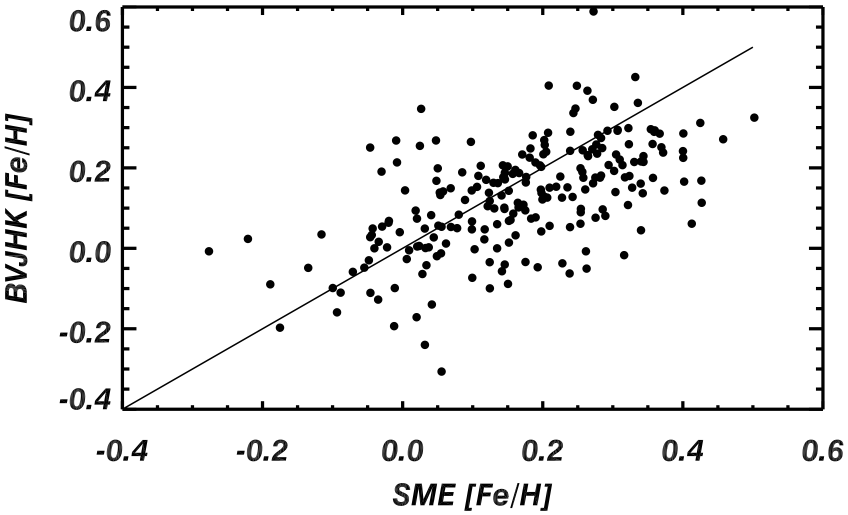

Fig. 4.— A comparison of spectroscopically-derived [Fe/H] with the metallicity estimate from our BVJHK calibration (Ammons *et al.* 2004) for 211 stars observed at Keck. The solid line shows a 1 to 1 correlation.

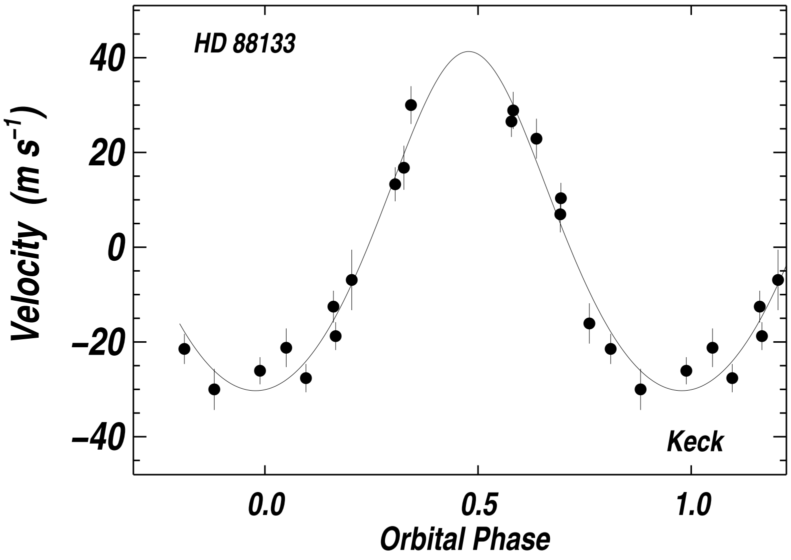

Fig. 5.— Phased radial velocities for HD 88133. With an orbital period of 3.41 d, velocity amplitude of 35.7 m s^{-1} and stellar mass of 1.2 $M_{\odot}$ we derive a planet mass, $M \sin i = 0.29$ $M_{\rm JUP}$ and orbital radius of 0.046 AU.

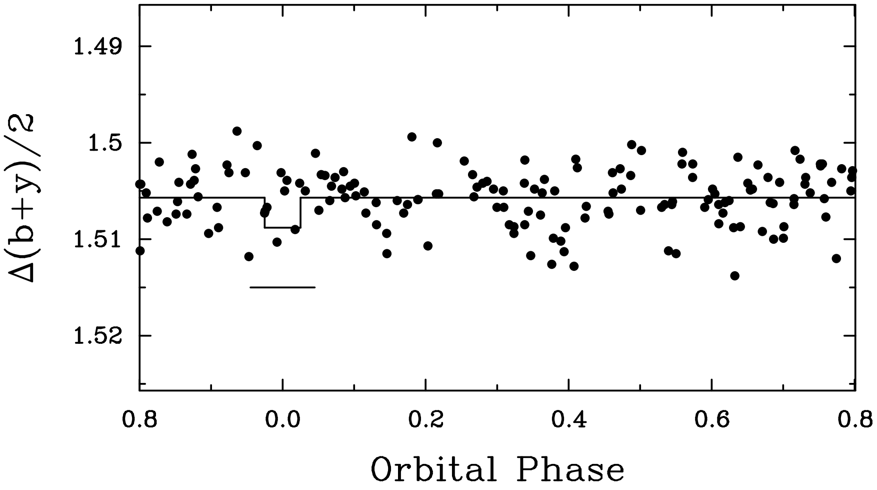

Fig. 6.— Strömgren $(b+y)/2$ photometric observations of HD 88133 acquired with the T12 0.8 m APT at Fairborn Observatory and phased to the radial velocity period. There is no evidence in the observations for any periodicity between 1 and 100 days. The star is constant on the radial velocity period to a limit of 0.0005 mag, supporting the planetary interpretation of the radial velocity variations. Although predicted transit depths are only 0.003 mag due to the large stellar radius, such transits are nonetheless ruled out by the photometry.

Table 1. Stellar Parameters for HD88133

Parameter	
V	8.01
M_V	3.65
B-V	0.81
Spectral Type	G5 IV
Distance (pc)	74.46
[Fe/H]	0.34 (0.04)
T_{eff} (K)	5494 (23)
$v \sin i$ km s^{-1}	2.2 (0.3)
$\log \mathrm{g}$	4.23 (0.05)
M_{STAR} ($\mathrm{M}_\odot$)	1.2 (0.2)
R_{STAR} ($\mathrm{R}_\odot$)	1.93 (0.06)
S_{HK}	0.138
$\log R'_{HK}$	-5.16
P_{ROT} (d)	48.0

Table 2. Radial Velocities for HD88133

JD -2440000	RV (m s^{-1})	Uncertainties (m s^{-1})
13014.948	-14.3	4.09
13015.947	36.9	3.99
13016.953	29.8	4.22
13044.088	35.8	3.92
13044.869	-14.6	3.18
13045.843	-20.7	2.98
13046.081	-11.9	2.94
13069.016	-23.1	4.35
13071.788	13.8	3.82
13072.021	-9.2	4.26
13073.950	23.7	4.66
13076.948	0.0	6.38
13153.760	17.3	3.25
13179.754	20.2	3.59
13195.748	-19.2	2.86
13197.762	33.5	3.27
13199.751	-5.6	3.36

Table 3. Orbital Parameters for HD88133b

Parameter	
P (d)	3.415 (0.001)
T_p (JD)	2453016.4 (1.2)
ω (deg)	10.2 (162.9)
ecc	0.11 (0.05)
K_1 (m s^{-1})	35.7 (2.2)
a (AU)	0.046
$a_1 \sin i$ (AU)	1.11e-05
$f_1(m)$ ($M_\odot$)	1.58e-11
$M \sin i$ (M_{Jup})	0.29
Nobs	17
RMS (m s^{-1})	5.3
Reduced $\sqrt{\chi^2_\nu}$	1.27