The Astrophysical Journal, 649:428–435, 2006 September 20

A KECK HIRES DOPPLER SEARCH FOR PLANETS ORBITING METAL-POOR DWARFS. I. TESTING GIANT PLANET FORMATION AND MIGRATION SCENARIOS

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Received 2006 March 17; accepted 2006 May 25

ABSTRACT

We describe a high-precision Doppler search for giant planets orbiting a well-defined sample of metal-poor dwarfs in the field. This experiment constitutes a fundamental test of theoretical predictions, which will help discriminate between proposed giant planet formation and migration models. We present details of the survey, as well as an overall assessment of the quality of our measurements, making use of the results for stars that show no significant velocity variation.

Subject headings: planetary systems: formation — stars: abundances — stars: statistics — techniques: radial velocities

1. INTRODUCTION

With a present-day catalog of ∼180 extrasolar planets,[6] several important statistical properties of the sample are beginning to emerge (for a review see, e.g., Marcy et al. 2005; Udry et al. 2006). Some of the most intriguing features unveiled so far include gas giant planets in few-day orbits, eccentricities spanning the entire range of possible values, the existence of a "brown dwarf desert," correlations among planetary orbital and physical parameters, evidence for a wide variety of dynamical interactions in multiple-planet systems, and a dependence of the frequency and properties of planetary systems on some of the characteristics of the parent stars (mass, metallicity).

The largely unexpected properties of extrasolar planets have boosted theoretical research in the field of planetary system formation and evolution. Recently, improved understanding of some of the complex aspects of the underlying physical processes governing planet formation in gaseous protoplanetary disks has enabled us to move from attempts to explain already known features of the exoplanet sample to more refined models making testable predictions. In turn, surveys for planets with a variety of techniques have started targeting more carefully defined and selected stellar samples, with the aim of providing the observational evidence required to address a specific scientific question (rather than simply focusing on the discovery of extrasolar planets), and thus helping to discriminate between different theoretical planet formation models.

This is the first of a series of papers in which we present results from a spectroscopic search for giant planets orbiting a sample of metal-poor stars in the field. The two competing mechanisms for gas giant planet formation, core accretion, and disk instability produce significantly different distributions of planet masses and orbital elements (e.g., Rice et al. 2003; Ida & Lin 2004a), and they predict a very different dependence of planetary frequency on stellar metallicity and mass (Boss 2002, 2006; Ida & Lin 2004b, 2005; Laughlin et al. 2004). In order to determine whether core accretion or disk instability is the dominant formation mode for giant planets, or to verify the existence of bimodal planet formation, one should then compare the frequency of gas giant planets and their properties between metal-rich and metal-poor stars. However, the low-metallicity stellar sample that has been searched for planets is at present too small to test any but the most outstanding differences between such hypothetical populations. It is now crucial to provide a statistically significant, unbiased sample of metal-deficient stars screened for giant planets.

We have arranged this first paper as follows. In § 2 we present the scientific case for a Doppler survey for giant planets orbiting field metal-poor dwarfs. We describe in § 3 some of the technical aspects of our Keck HIRES radial-velocity survey. We present in § 4 preliminary results from the first 3 years of observations, focusing on the detailed assessment of the quality of our measurements, making use of the results for all the stars that show no significant velocity variation. We provide in § 5 a brief summary and conclusions.

2. TESTING GIANT PLANET FORMATION AND MIGRATION MODELS

2.1. *Stellar Metallicity and Planets: Observations*

The connection between the presence of giant planets and the metal content of the parent stars has been the subject of a significant number of studies in the past (see, e.g., Gonzalez 2003, and references therein). The average of the metallicity distribution of planet-hosting stars is $[\mathrm{Fe/H}] \simeq 0.14$ (e.g., Fischer & Valenti 2005), whereas the mean value for the solar neighborhood is $[\mathrm{Fe/H}] \simeq -0.1$ (Nordström et al. 2004). With improved statistics, in recent years the hypothesis that supersolar metallicity could correspond to a higher likelihood that a given star will harbor a planet has been conclusively proved (e.g., Santos et al. 2001, 2004a; Fischer & Valenti 2005). As of today, the frequency of giant planets around metal-rich ($[\mathrm{Fe/H}] \gtrsim 0.3$) dwarfs (integrating over the F-G-K spectral types) is $f_p \gtrsim 20\%$, while this fraction decreases to $f_p \simeq 3\%$ for metal-poor stars ($-0.5 \lesssim [\mathrm{Fe/H}] \lesssim 0.0$). For metallicities below solar, f_p appears to be roughly constant (Santos et al. 2004a; Fischer & Valenti 2005).

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[6] See, for example, http://www.obspm.fr/encycl/encycl.html and http://www.dtm.ciw.edu/boss/iauindex.html.

Many authors have debated whether the observational evidence is an indicator of primordial high metallicity in the planet-host stellar sample (Santos et al. 2001; Reid 2002), or if the trend with [Fe/H] could be due to pollution by ingested planetary material (Laughlin 2000; Gonzalez et al. 2001; Israelian et al. 2001; Murray & Chaboyer 2002). The idea of pollution is losing credit among the scientific community, primarily due to the lack of any correlation between [Fe/H] and effective temperature $T_{\rm eff}$, or convective envelope mass $M_{\rm conv}$, for the planet host sample (e.g., Pinsonneault et al. 2001; Fischer & Valenti, 2005; Santos et al. 2003, 2004a, and references therein). Results on this specific issue are not yet conclusive, however. For example, Vauclair (2004) has recently pointed out that the absence of an [Fe/H]-$M_{\rm conv}$ correlation does not automatically imply that stars with planets have not been polluted.

Furthermore, theoretical calculations (Montalbán & Rebolo 2002; Boesgaard & King 2002) suggest that detection of anomalous abundances of rare elements such as lithium (Li) or beryllium (Be) could be interpreted as evidence for recent accretion of planets onto the atmosphere of a star. The abundances of Li isotopes in the spectral region around the 6707 Å line in planet-host stars have recently been investigated by several authors (Gonzalez & Laws 2000; Ryan 2000; Israelian et al. 2001, 2003, 2004; Reddy et al. 2002; Mandell et al. 2004), and similar studies have been conducted for the Be II lines at 3130 Å and 3131 Å (García López & Pérez de Taoro1998; Deliyannis et al. 2000; Santos et al. 2002, 2004b). While the presence of the ^{6}Li isotope has actually been detected in some planet-harboring stars (Israelian et al. 2001, 2003, 2004; Laws & Gonzalez 2001), suggesting that accretion of planetary material can indeed take place in some stars, generally stars with planets have normal light-element abundances, typical of field stars. It thus seems unlikely that pollution effects can be responsible for the overall metallicity enhancement of the planet-host stellar sample.

In addition, analyses of over a dozen other elements have been carried out in recent years (Santos et al. 2000; Gonzalez et al. 2001; Smith et al. 2001; Takeda et al. 2001; Sadakane et al. 2002; Zhao et al. 2002; Bodaghee et al. 2003; Ecuvillon et al. 2004a, 2004b, 2006b; Beirão et al. 2005; Gilli et al. 2006; Sozzetti et al. 2006), and the general evidence is that the abundance distributions in stars with planets are an extension of the observed behavior for [Fe/H], a result quantified by trends of decreasing [X/Fe] with decreasing [Fe/H]. The absence of any statistically significant trend of metallicity [X/H] with condensation temperature T_c (e.g., Sozzetti et al. 2006; Ecuvillon et al. 2006a; Gonzalez 2006) is one more piece of circumstantial evidence that the best explanation for the metallicity excess in stars with planets is that the enhanced [Fe/H] is primordial in nature.

Several studies have also focused on possible correlations between stellar metallicity and planet properties. While no significant trend was found between [Fe/H] and planet mass or orbital eccentricity (e.g., Udry et al. 2002; Santos et al. 2001, 2003; Fischer et al. 2002), evidence (albeit weak) for a correlation between the metallicity of planet-harboring stars and the orbital periods P of the planets has been pointed out (e.g., Sozzetti 2004, and references therein; Santos et al. 2006). This correlation is highlighted by an excess of close-in planets, on few-day orbits, around the metal-rich ($[{\rm Fe/H}] \gtrsim 0.0$) sample of planet hosts.

2.2. *Stellar Metallicity and Planets: Theory*

Within the framework of the scenario of gas giant planet formation by core accretion (e.g., Lissauer 1993; Pollack et al. 1996; Alibert et al. 2004), recent studies have successfully reproduced the strong dependence of planetary frequency on stellar metallicity, in qualitatively good agreement with the observed trend (Kornet et al. 2005; Ida & Lin 2004b). The probability of forming giant planets according to the disk instability model (e.g., Boss 1997, 2000; Mayer et al. 2004), however, is remarkably insensitive to the primordial surface density of solids of the protoplanetary disk (Boss, 2002; Rice et al. 2003); thus planet occurrence should not be hampered around metal-poor stars. On the one hand, the observed trend suggests that giant planet formation by core accretion predominates in the metal-rich regime ($[{\rm Fe/H}] \gtrsim 0.0$). On the other hand, f_p appears to be rather flat in the metal-poor regime ($[{\rm Fe/H}] \lesssim 0.0$). The possible evidence for bimodality of the planet frequency distribution as a function of metallicity (Santos et al. 2004a; Fischer & Valenti 2005) suggests the existence of two different mechanisms for forming gas giant planets. However, due to the low numbers of metal-poor stars ($[{\rm Fe/H}] \lesssim -0.5$) surveyed to date, no definitive conclusion can be drawn, except that maybe both mechanisms operate (Beer et al. 2004).

If real, several possible explanations can be put forth for the existence of a P-[Fe/H] correlation. For example, migration rates might be slowed down in metal-poor protoplanetary disks (Livio & Pringle 2003; Boss 2005), although the predicted dependence of migration timescales on [Fe/H] appears to be somewhat weak. The correlation may also arise as a consequence of longer timescales for giant planet formation around metal-poor stars, and thus reduced migration efficiency before the disk dissipates (Ida & Lin 2004b; Alibert et al. 2005). Another possibility (Santos et al. 2006) is related to planetary internal-structure arguments: if planets formed in low-metallicity disks have small rocky cores (e.g., Pollack et al. 1996; Ida & Lin 2004b), their low density might hamper survival against evaporation (Baraffe et al. 2004; Lecavelier des Etangs et al. 2004) once they have migrated to very close-in orbits. However, even in this case small-number statistics in the low-metallicity regime prevent one from reaching a clear conclusion.

One way or another, in order to unambiguously determine the role of metallicity in gas giant planet formation (for example, is f_p a truly monotonic function of [Fe/H], or is planetary frequency constant in the metal-poor regime?), and consequently discriminate between proposed explanations for the observed trends in the data, it is crucial to provide a statistically significant, unbiased sample of metal-poor stars screened for giant planets.

2.3. *Searching for Planets around Field Metal-Poor Stars*

The absence of short-period ($P \leq 8.3$ days) transiting planets in the moderately metal-deficient ($[{\rm Fe/H}] \simeq -0.7$) globular cluster 47 Tucanæ has been used by Gilliland et al. (2000) and Weldrake et al. (2005) to argue that low-metallicity stars are less likely to harbor giant planets. However, the claims by these authors suffer from some ambiguity, because in the cluster core investigated by Gilliland et al. (2000) with *HST* transit photometry, crowding could play a significant role in giant planet formation, migration, and survival (e.g., Davies & Sigurdsson 2001; Bonnell et al. 2001; Hurley & Shara 2002; Fregeau et al. 2006). The outer regions of the cluster monitored by Weldrake et al. (2005) are less affected by crowding. However, the lower occurrence rate of hot Jupiters in a metal-poor environment does not rule out the existence of a population of giant planets at wider radii. Indeed, this possibility has recently been supported by the findings of Sigurdsson et al. (2003), who, using *HST* data, were able to infer a mass of a few Jupiter masses for the third, long-period component orbiting the white dwarf-pulsar system

B1620−26 in the globular cluster M4, 5 times more metal-poor than 47 Tuc. Their results provide the first evidence for planet formation in very metal-poor environments. In light of the M4 announcement, the 47 Tuc results could be reinterpreted as follows: dynamical disruption in dense clusters is not sufficient to completely destroy any planetary population, and the lack of transiting planets on short-period orbits might be due to other processes, such as a metallicity dependence in the migration mechanism, or suppression of migration (but not formation) in globular clusters.[7]

By addressing the field population of metal-poor stars directly, it is then possible to eliminate dynamical interactions in dense stellar environments as a possible source of interference with planet formation, or with migration to close-in orbits, or with planet survival.

3. THE KECK HIRES DOPPLER SURVEY OF METAL-POOR DWARFS

In 2003, we began a high-precision radial-velocity survey of ∼200 metal-poor stars, using HIRES on the Keck I telescope (Vogt et al. 1994) and its I_2 gas absorption cell as the reference velocity metric (Butler et al. 1996). The goal of this project is to carry out an initial reconnaissance for gas giant planets orbiting within 1 AU of a statistically significant sample of low-metallicity dwarfs.

The sample has been drawn from the Carney-Latham and Ryan samples of metal-poor, high-velocity field stars (e.g., Carney et al. 1994; Ryan 1989; Ryan & Norris 1991). The initial combined database totaled 1558 objects. A number of selection criteria have been adopted in order to finalize our list of targets. First, a key advantage of the Carney-Latham and Ryan samples is that we have monitored the radial velocities of the stars in these samples, most for more than 3000 days, using the CfA digital speedometers (Latham 1992). This has allowed us to identify most of the stars with stellar companions that would interfere with the formation or survival of planets in the habitable zones (Carney et al. 2001; Latham et al. 2002). All stars included in the final list of targets showed no sign of velocity variation at the 0.5 to 1.0 km s^{-1} level. Second, significant chromospheric activity (quantified, for example, through the chromospheric emission ratio $R'_{\rm HK}$) and large values of stellar rotational velocity $v \sin i$ should be avoided, as they constitute sources of intrinsic radial velocity "jitter" that can mask, and sometimes even mimic, the presence of orbital reflex motion due to planetary mass companions (Saar et al. 1998; Santos et al. 2000; Queloz et al. 2001; Paulson et al. 2004). Fortunately, old stars have the advantage of rotating slowly and having low levels of chromospheric activity. All of the stars in our sample exhibit rotational velocities $v \sin i \leq 10$ km s^{-1}, and most have rotations below the resolution limit of the CfA digital speedometers (8.5 km s^{-1}), so that a value of $v \sin i$ could not be determined. Thus, we do not expect velocity jitter due to astrophysical phenomena to be a problem for this sample.

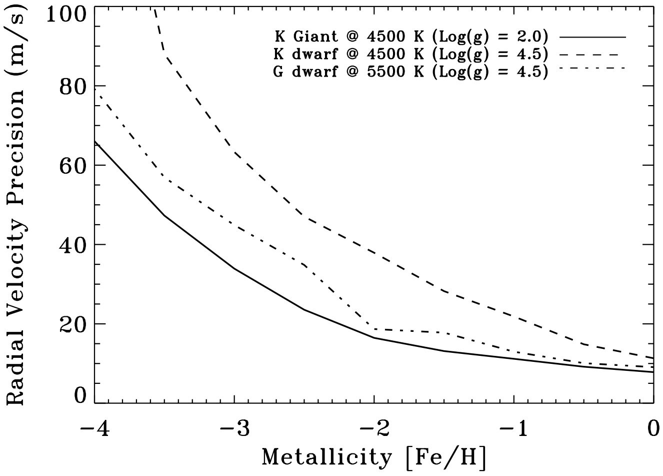

FIG. 1.—Degradation in the radial-velocity precision $\sigma_{\rm RV}$ as a function of stellar metallicity, effective temperature, and gravity, for fixed exposure time. The zero point of $\sigma_{\rm RV}$ for solar values of [Fe/H], $T_{\rm eff}$, and $\log g$ is arbitrarily scaled to 10 m s^{-1}.

However, metal-poor stars have weak absorption lines in comparison to their solar-metallicity counterparts. The lines also grow weaker as the effective temperature rises. Furthermore, very metal-poor stars are rare, and therefore they tend to be distant and faint. In order to characterize the behavior of the radial velocity precision $\sigma_{\rm RV}$ as a function of stellar metallicity, effective temperature $T_{\rm eff}$, and visual magnitude V (assuming nonrotating, inactive stars), we have run simulations utilizing the CfA library of synthetic stellar spectra (e.g., Nordström et al. 1994; Latham et al. 2002). We show in Figure 1 how $\sigma_{\rm RV}$ degrades as a function of [Fe/H] and $T_{\rm eff}$, assuming a fixed exposure time and a typical measurement precision of 10 m s^{-1} for [Fe/H] = 0.0. For a solar-type star, [Fe/H] = −1.0 corresponds to a degradation in $\sigma_{\rm RV}$ of a factor ∼2, while for a significantly cooler star, with a more complex spectrum,[8] the effect is less severe (in addition, surface gravity constitutes only a higher order effect). This result confirms the empirical findings of Santos et al. (2003) and Fischer & Valenti (2005), based on the analyses of the achieved velocity precision as a function of metallicity carried out with the stellar databases of their respective Doppler planet surveys. Those studies were aimed at ruling out possible observational biases that might contribute to the observed correlation between f_p and [Fe/H]. In both cases, Santos et al. (2003) and Fischer & Valenti (2005) conclude that, given the typical single-measurement precision $\sigma_{\rm RV} \simeq 3$–5 m s^{-1} achieved for bright objects (typically $V \lesssim 8.0$), a velocity degradation of a factor 1.5–2 does not imply that a fraction of the giant planets orbiting low-metallicity stars might have gone undetected (at least in the orbital period range currently covered by Doppler surveys). However, not many bright metal-poor stars ($-0.5 \lesssim$ [Fe/H] $\lesssim 0.0$) are found in the solar neighborhood ($d \lesssim 50$ pc). In order to create a statistically significant database (hundreds of stars) of metal-poor ([Fe/H] $\lesssim -0.5$) dwarfs, one must then include more distant, and fainter, objects. For the purpose of optimizing the trade off between number of objects surveyed and total observing time required, we have refined our sample of metal-poor dwarfs from the Carney-Latham and Ryan surveys by adopting magnitude and temperature cut offs ($V \leq 12.0$ and

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[7] Notably, the lack of any apparent correlation in the plane defined by minimum mass $M_p \sin i$ and orbital period P for planets in binary and triple stellar systems (as opposed to the observed $M_p \sin i$–P correlation in the case of planets orbiting single stars) is interpreted as evidence for enhanced migration efficiency for planets formed in stellar systems (Zucker & Mazeh 2002; Udry et al. 2003; Eggenberger et al. 2004). However, the birthplaces for such systems are stellar groups and clusters with much lower stellar densities than globular clusters. Thus, both the impact on planet formation and migration efficiency as well as the evolutionary history of dynamical interactions are likely not the same in these two different environments (e.g., Davies & Sigurdsson 2001; Adams et al. 2006).

[8] The velocity information content depends on the mean absolute value of the slope of the spectrum, which increases for later spectral types (e.g., Butler et al. 1996; Bouchy et al. 2001).

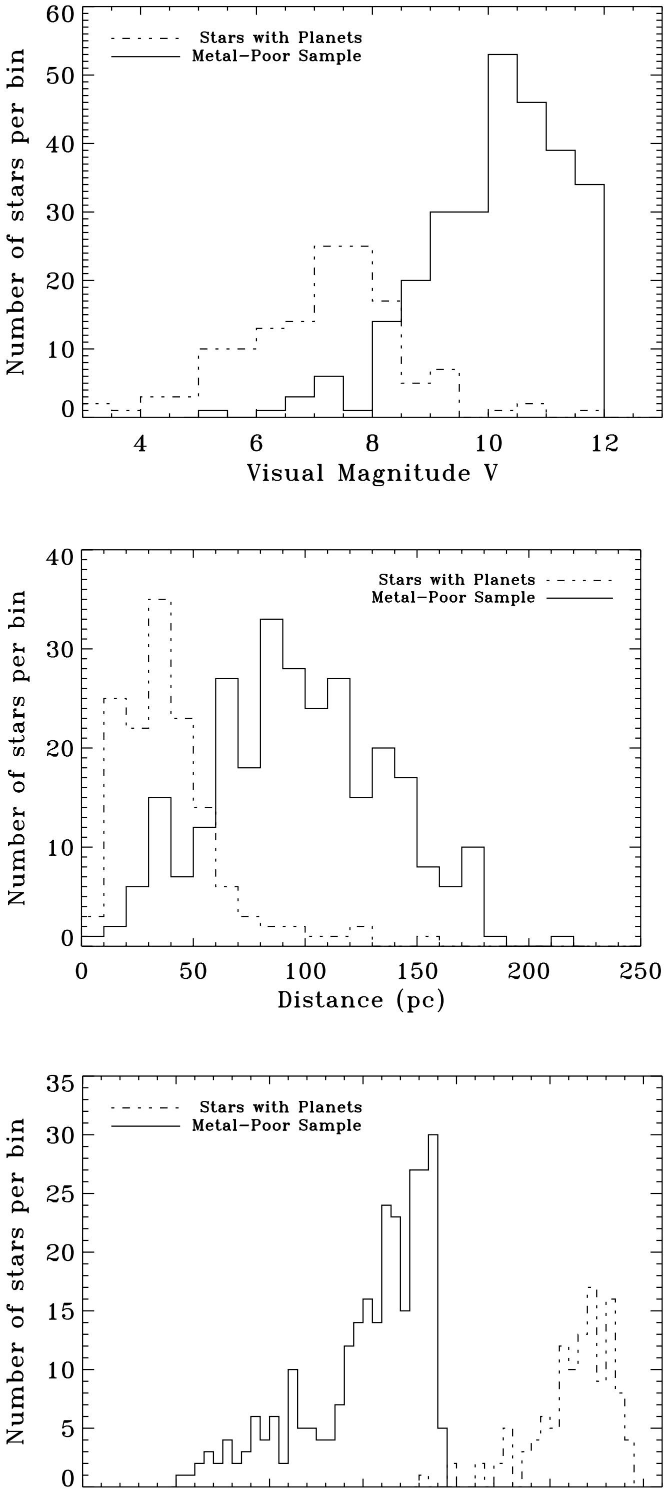

FIG. 2.—Distributions of visual magnitudes (*top*), distances from the Sun (*center*), and metallicities (*bottom*) for a sample of 278 metal-poor stars selected with the criteria detailed in the text. For comparison, the same distributions for a large sample of 119 planet hosts are also shown (data from Santos et al. 2004a, 2005; Sozzetti et al. 2004).

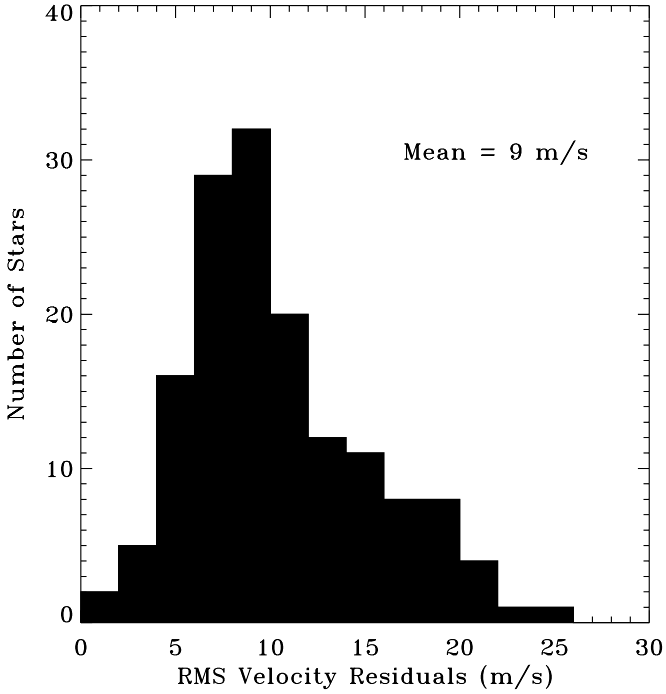

FIG. 3.—The rms velocity distribution for ~80% of the stars in our sample, for which uniform temporal coverage has been obtained (see text for details). Objects exhibiting significant radial velocity variations (>30 m $\mathrm{s^{-1}}$) are not shown.

$T_{\rm eff} \leq 6000$ K, respectively), and by selecting objects in the metallicity range $-2.0 \leq [\mathrm{Fe/H}] \leq -0.6$.

In the empirical error model we have obtained using the simulations with the CfA database of synthetic spectra, the radial-velocity uncertainty is

$$\sigma_{\rm RV} = \left(\frac{t_0}{t_{\rm exp}} 10.0^{(V-V_0)/2.5}\right)^{1/2} F([\mathrm{Fe/H}],\ T_{\rm eff}), \qquad (1)$$

where $F([\mathrm{Fe/H}], T_{\rm eff})$ is an empirical function of temperature and metallicity based on the simulation results shown in Figure 1, and t_0 and V_0 are reference integration time and magnitude for a star with the temperature and metallicity of the Sun. Based on our experience with solar neighborhood G dwarfs observed with HIRES for the G Dwarf Planet Search Program (Latham 2000), we have set a threshold of 20 m $\mathrm{s^{-1}}$ precision for planet detection, and computed the relative exposure times needed to achieve such precision, for each star in our sample. Furthermore, we decided to limit the maximum exposure times to 15 minutes, to minimize uncertainties in the barycentric correction. We show in Figure 2 the distribution of [Fe/H], V, and distance estimates (for those objects with *Hipparcos* parallaxes, photometric otherwise) for the sample of 278 metal-poor stars derived after adopting all the selection criteria described above. In order to highlight the different ranges of metallicity, magnitude, and distance spanned by our survey, the same distributions for a large fraction of the present-day sample of planet hosts are also shown. Given that the average stellar mass in our sample is $\sim 0.69\ M_\odot$, setting a velocity precision threshold at 20 m $\mathrm{s^{-1}}$ is sufficient to detect (at the 5 σ level) velocity variations of planetary companions with minimum mass in the average range $0.59 M_{\rm J} \leq M_{\rm p} \sin i \leq 2.75 M_{\rm J}$, or higher, for orbital periods in the range $0.01 \leq P \leq 1$ yr.

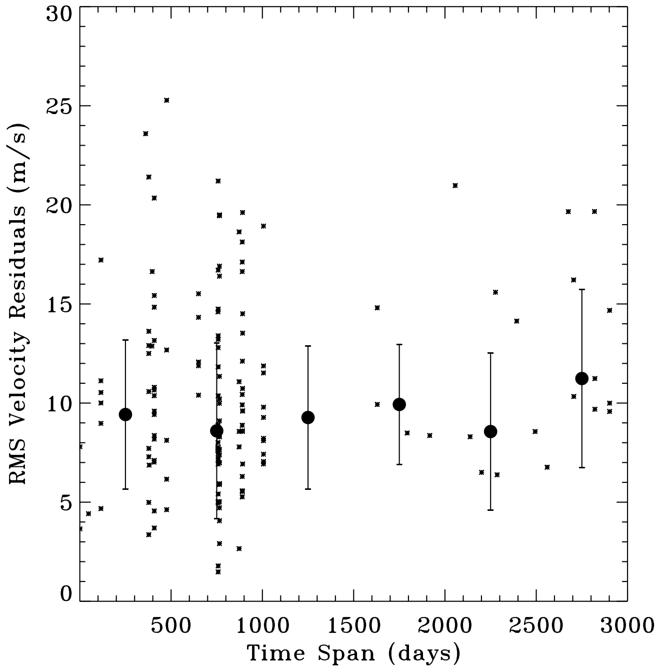

FIG. 4.—The rms velocity residuals as a function of the timespan of the observations. Overplotted are the median (*large filled circles*) and standard deviation in 500 day bins. Variables with rms >30 m s^{-1} are not taken into account.

Finally, if it turns out to be true that planets did not form around metal-poor dwarfs, then we need to observe a large-enough sample that a null result, i.e., no detections, is significant. The rate at which giant planets with orbits inside 1 AU are being discovered by radial velocities appears to be about $\mathcal{P} \simeq 3\%$ (e.g., Marcy et al. 2005). In order for the failure to detect any planetary companions to be significant at the 3 σ level (corresponding to a probability of 0.0027), we need to survey a sample of N stars, where $(1 - \mathcal{P})^N = 0.0027$, which is satisfied for $N = 194$. We therefore defined our final target list by selecting a subset of 200 metal-poor stars out of the abovementioned larger sample of 278 objects, which will eventually provide a robust 3 σ null result in the case of no detections.

4. PRELIMINARY RESULTS

Our observing program has been awarded an average of two Keck HIRES nights per semester, starting in early 2003. Good temporal coverage is thus a serious issue, as such a scheduling of the observations is good for sampling long-period radial-velocity variations, but rather poor for identifying possible short-period variables. We have tried to obtain at least three velocity measurements per star per year, with at least one set of back-to-back observations (taken in two consecutive nights), in order to mitigate our bias toward poor sampling (and thus significant aliasing and ambiguities) at short orbital periods.

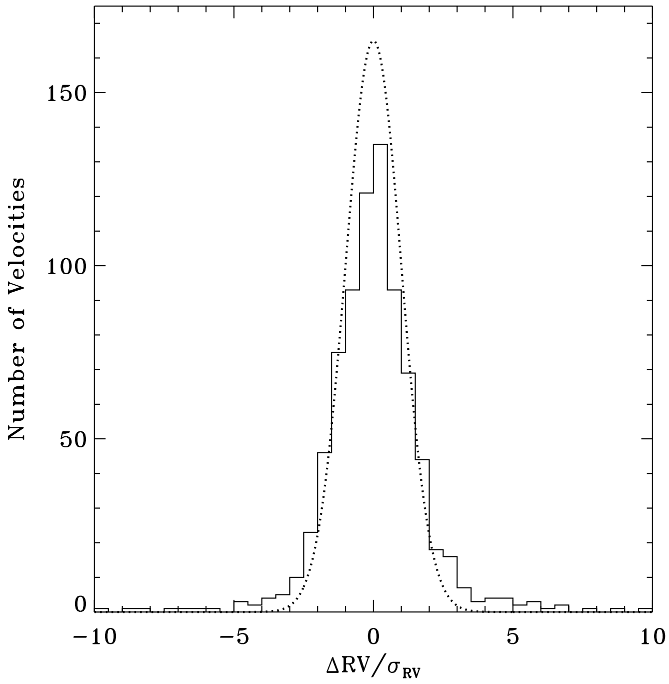

FIG. 6.—Histogram of all the velocity residuals (including variables) normalized by their formal uncertainties. The dotted line represents a reference Gaussian distribution with zero mean and unit dispersion. If, for example, internal errors are over or underestimated, this effect should show up as distortions in the distribution. The width of the distribution is very close to unity, indicating the absence of significant biases. Formal errors are a good estimate of the true underlying uncertainties.

The first important step is to provide an assessment of the long-term stability of the velocity zero point and single-measurement precision achieved for planet detection, in light of the predicted exposure times needed to reach $\sigma_{\rm RV} = 20$ m s^{-1}. Our analysis pipeline incorporates the full modeling of temporal and spatial variations of the HIRES instrumental profile (Valenti et al. 1995),

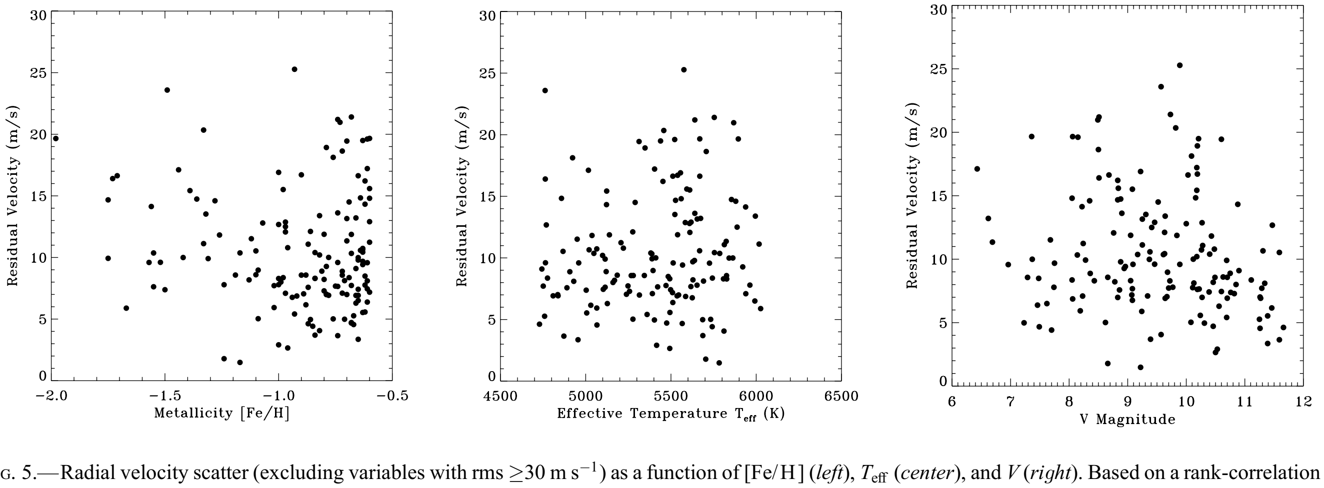

FIG. 5.—Radial velocity scatter (excluding variables with rms ≥30 m s^{-1}) as a function of [Fe/H] (*left*), $T_{\rm eff}$ (*center*), and V (*right*). Based on a rank-correlation test, the probability of no correlation in the three cases is 0.61, 0.14, and 0.09, respectively (i.e., no significant correlation is present).

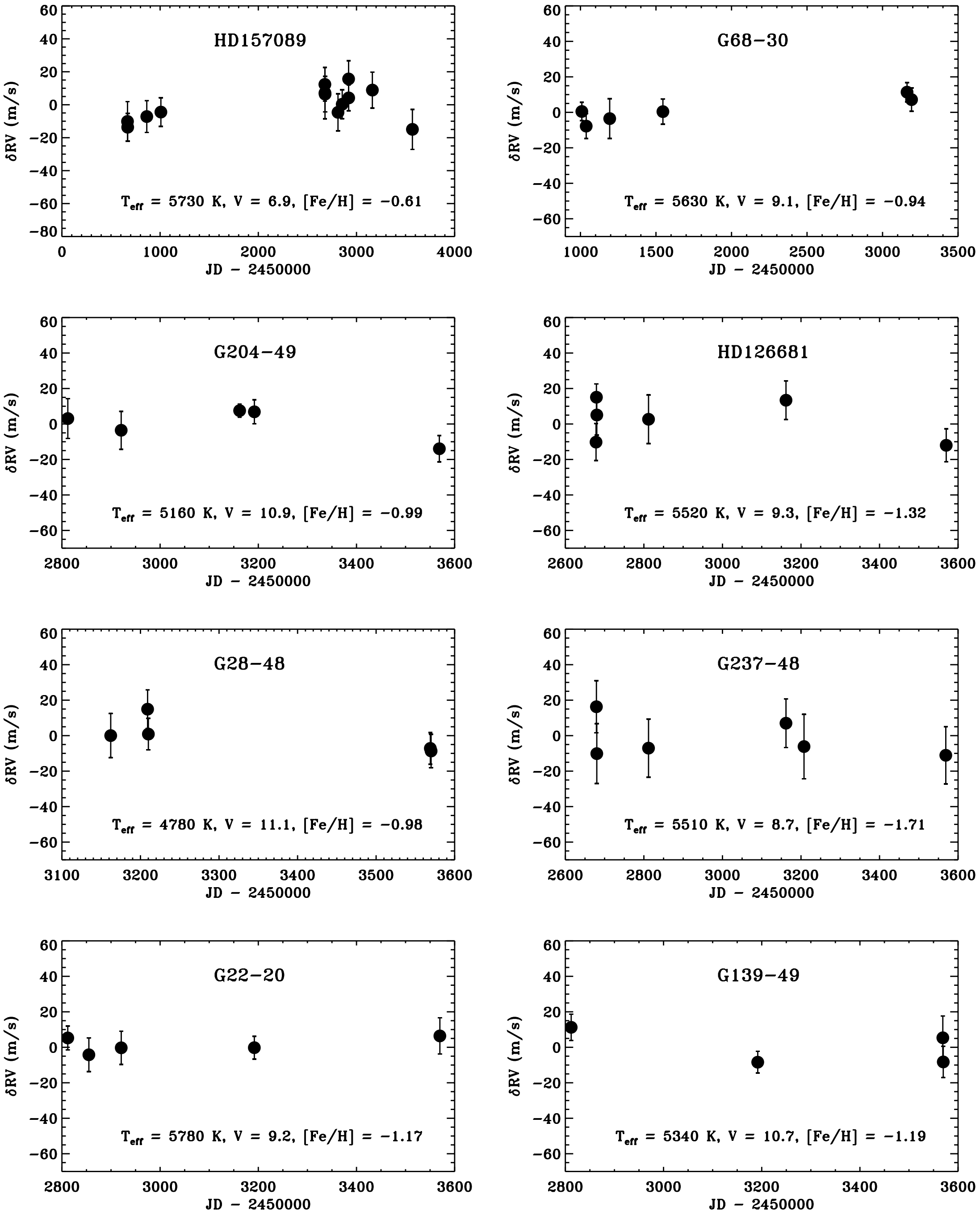

FIG. 7.—Observed relative velocities ΔRV for a sample of stars in our program. The top two panels show objects with constant velocity to ~10 m s^{-1} over a time span of 8 yr, after combining observations taken in the context of the G Dwarf Planet Search program (Latham 2000). The mean rms of the stars shown in the other panels is 9 m s^{-1}, the same as the average of the full sample (excluding variable stars). Comparable precision is achieved over ranges of 1000 K in $T_{\rm eff}$, 4 mag, and 1 dex in metallicity.

similar to the method adopted by other groups (e.g., Butler et al. 1996; Korzennik et al. 2000; Cochran et al. 2002). Spectral modeling of each echelle order containing I_2 lines is carried out independently, and internal uncertainties for each observation are computed from the scatter of the velocities around the mean. This analysis technique has allowed us to significantly improve on our initial estimates of achievable radial velocity precision. In Figure 3, we show the histogram of the rms velocity residuals for about 80% of our sample, for which we have achieved substantially uniform temporal coverage (typically 5–6 observations per star, with at least two back-to-back exposures, over a time span of at least a year). The rms velocity residuals distribution of the *full* sample (excluding variables with rms $\geq$30 m s^{-1}) averages ~9 m s^{-1}. In Figure 4, we show the rms velocity residuals as a function of the timespan of the observations. Overplotted are the median and standard deviation in 500 day bins (again, variable stars are not included). As about two dozen of the stars in our sample are in common with the G dwarf planet survey of Latham (2000), we could establish the longterm stability of the velocity zero-point over timescales of up to 8 years. This demonstrates the true radial-velocity precision we are obtaining on the sample of metal-poor stars, with a significant improvement of over a factor of 2 with respect to the targeted 20 m s^{-1} single-measurement precision.

The exposure times predicted by the model derived from the simulations with the CfA library of stellar spectra are determined as a function of [Fe/H], $T_{\rm eff}$, and V. However, our program stars are up to 3–4 mag fainter and up to >100 times more metal poor than typical targets of Doppler planet searches. One possible matter of concern would then be the evidence of systematic trends in the velocity scatter as a function of these three parameters. However, as shown in Figure 5, no clear rms velocity trends as a function of [Fe/H], $T_{\rm eff}$, and V are present. This gives us confidence that the model we developed for the dependence of the radial-velocity precision on the above parameters is robust.

A more quantitative, and challenging, test to demonstrate that the character of our errors is well understood can be carried out by studying the distribution of the velocity residuals compared to their formal uncertainties. We define the ratio $\Delta{\rm RV}/\sigma_{\rm RV}$ as the difference between the velocity values and their mean value for each star, divided by their estimated uncertainties. In the ideal case, if internal errors are an accurate tracer of the actual uncertainties in the measurements, this ratio should have a Gaussian distribution with zero mean and unit dispersion. Discrepancies between predicted and actual errors should be reflected in measurable departures from Gaussianity. We show in Figure 6 the histogram of the ratio $\Delta{\rm RV}/\sigma_{\rm RV}$ for all our program stars (including variables). Overplotted is a reference Gaussian with zero mean and unit dispersion. The $\Delta{\rm RV}/\sigma_{\rm RV}$ distribution is very close to Gaussian, with no apparent positive or negative biases. Slightly elevated wings (~6% of the velocity differences are larger than 5 σ) indicate the presence of either non-Gaussian outliers or true variables. The result shown in Figure 6 demonstrates that our internal errors are realistic. The fundamental conclusion is that we achieve sufficient radial-velocity precision in our sample to clearly detect Jupiter-mass objects within 1 AU of metal-deficient dwarfs.

We show in Figure 7 some examples of our velocity measurements of metal-deficient dwarfs. The top two panels show results for two of the stars (HD 157089 and G68-30) in common between our survey and the G Dwarf Planet Search program (Latham 2000). These objects are constant to $\sim$10 m s^{-1} over a timescale of ~8 yr. The examples of velocity timeseries shown in the other panels of Figure 7 cover a range of ~1000 K in $T_{\rm eff}$, ~4 mag, and $\simeq$1 dex in [Fe/H]. The rms of the observations range between 6 and 11 m s^{-1}, with an average of $\sim$9 m s^{-1}. While a large fraction of our sample shows no significant velocity variations over the time span of the observations, a number of objects do exhibit velocity variability indicative of the presence of companions. A thorough analysis of our planet detectability thresholds and a detailed presentation of all our velocity measurements will be the subject of our second paper.

5. CONCLUSIONS

One way to distinguish between proposed models of gas giant planet formation is to confirm or rule out, on an observational basis, their different predictions for planet frequency f_p as a function of the metallicity of the stellar hosts. To address this issue, we have undertaken a Doppler search for giant planets within 1 AU of a sample of 200 metal-deficient ($-2.0 \leq [{\rm Fe/H}] \leq -0.6$) dwarfs in the field. This is the sample size needed to provide a statistically significant result (at the 3 σ level) in the case of no detections. Using the Keck I telescope and its HIRES spectrograph, we have achieved a longterm radial-velocity precision of $\sim$9 m s^{-1}, independently of [Fe/H] and $T_{\rm eff}$, and for stars 2–4 mag fainter than the targets for most other radial-velocity planet surveys. We have provided convincing evidence that our internal error estimates are reliable, and thus demonstrated that we achieve sufficient radial-velocity precision in our sample to clearly detect Jupiter-mass objects within 1 AU of metal-deficient dwarfs. A number of objects with significant radial-velocity trends have been identified, for which we plan to perform followup observations. At the conclusion of our Doppler survey, we will be able to place useful upper limits on the existence of planetary companions of given mass and period around metal-poor stars, and we will then compare the frequency of gas giant planets and their properties in metal-rich and metal-poor stars. These issues will be addressed in future papers.

A. S. acknowledges support from the Keck PI Data Analysis Fund (JPL 1267110). G. T. acknowledges partial support for this work from NASA Origins grant NNG04LG89G. J. L. is partially supported by an NSF grant AST-0307340. B. C. gratefully acknowledges support from an NSF grant AST-0305431. It is a pleasure to acknowledge Mike Kurtz for very stimulating discussions. Special thanks are due to Dimitar Sasselov for lending initial impetus and support to this investigation. The data presented herein were obtained at the W. M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California, and the National Aeronautics and Space Administration. The Observatory was made possible by the generous financial support of the W. M. Keck Foundation. The authors wish to recognize and acknowledge the very significant cultural role and reverence that the summit of Mauna Kea has always had within the indigenous Hawaiian community. Without their generous hospitality, the Keck observations presented here would not have been possible.

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