A KECK/HIRES DOPPLER SEARCH FOR PLANETS ORBITING METAL-POOR DWARFS

A. Sozzetti[1,2], D.W. Latham[2], G. Torres[2], R.P. Stefanik[2], A.P. Boss[3], B.W. Carney[4], J.B. Laird[5]

[1]Department of Physics & Astronomy, University of Pittsburgh, Pittsburgh, PA 15260 USA
[2]Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138 USA
[3]Carnegie Institution of Washington, 5241 Broad Branch Road, NW, Washington, DC 20015 USA
[4]Department of Physics & Astronomy, University of North Carolina at Chapel Hill, Chapel Hill, NC 27599 USA
[5]Department of Physics & Astronomy, Bowling Green State University, Bowling Green, OH 43403 USA

ABSTRACT

We present results from our ongoing spectroscopic search for giant planets within 1 AU around a well-defined sample of metal-poor stars with HIRES on the Keck 1 telescope. We have achieved an rms radial velocity precision of ~ 8 m s^{-1} over a time-span of 1.5 years. The data collected so far build toward evidence of the absence of very short-period (< 1 month) giant planets. However, about 7% of the stars in our sample exhibit velocity trends indicative of the existence of companions. We place preliminary upper limits on the detectable companion mass as a function of orbital period, and compare them with the performance of ESA's future space-borne high-precision astrometric observatory Gaia.

Key words: Planetary systems; Radial velocity; Astrometry; Stars: statistics.

1. INTRODUCTION

With a present-day catalogue of well over 130 extra-solar planets[1], several important statistical properties of the sample are beginning to emerge. One of the most intriguing features unveiled so far, however, concerns the parent stars rather than the planets themselves. In particular, both the probability of a star to harbour a planet and some orbital properties of the latter appear to depend on the metallicity of the former.

The metallicity distribution of stars with planets peaks at [Fe/H] $\simeq$ 0.3, showing evidence of moderate metal-enrichment with respect to the average metallicity ([Fe/H] $\simeq -0.1$) of field dwarfs in the solar neighbourhood (Santos et al. 2001; Fischer et al. 2003; Santos et al. 2004). The evidence for higher planetary frequency around metal-rich stars has been confirmed based on observationally unbiased stellar samples. This trend seems to agree with the predictions from theoretical models of gas giant planet formation by core accretion (e.g., Ida & Lin 2004). However, the alternative scenario of giant planet formation by disc instability (Boss 2002) is insensitive to the primordial metallicity of the protoplanetary disc, and, although not statistically significant, the possible evidence for bi-modality of the planet frequency distribution as a function of metallicity (Santos et al. 2004) suggests the existence of two different mechanisms for forming gas giant planets.

Furthermore, despite potential biases introduced by the small-number statistics, the orbital periods of extra-solar planets seem to correlate with the metallicity of their parent stars (Sozzetti 2004, and references therein). In particular, close-in planets, on few-day orbits, are more likely to be found around metal-rich stars. If true, the correlation could reflect a dependence of migration rates on the amount of metals present in the disc (Livio & Pringle 2003). Alternatively, it might be indicative of longer timescales for giant planet formation around metal-poor stars, and thus reduced chances for the protoplanets to undergo significant migration before the disc evaporates (Ida & Lin 2004).

Such questions can be addressed by comparing the frequency of gas giant planets and their properties between metal-rich and metal-poor stars. However, the low-metallicity stellar sample is at present too small to test but the most outstanding differences between such hypothetical populations. It is then crucial to provide a statistically significant, unbiased sample of metal-poor stars screened for giant planets. This can be achieved by means of both Doppler (Sozzetti et al. 2003a) and astrometric (Sozzetti et al. 2001, 2002, 2003b) surveys.

2. SELECTION CRITERIA OF THE SAMPLE

In this project we are using the HIRES spectrograph on the Keck 1 telescope (Vogt et al. 1994) to search for planetary companions within 1 AU orbiting a sample of 200 metal-poor 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). The stars have been selected not to have close orbiting

[1]See for example http://www.obspm.fr/encycl/encycl.html

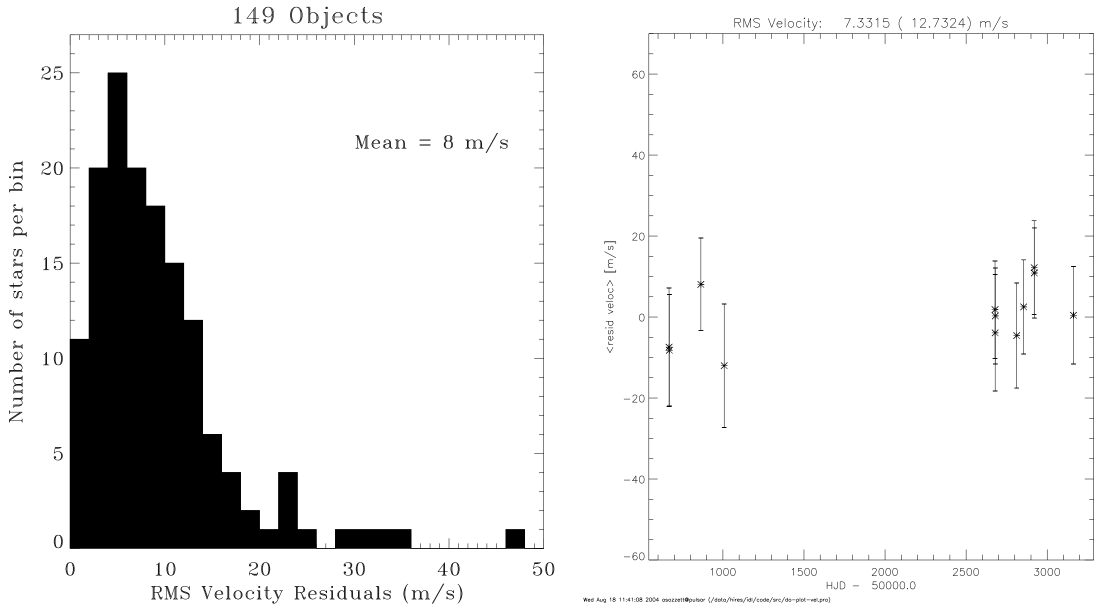

Figure 1. Left: rms velocity distribution for the full sample. A number of objects exhibiting significant radial velocity variations (> 50 m s^{-1}) is not shown. Right: radial velocity as a function of time for a quiet star in our sample.

companions in the stellar mass regime that might hamper the formation or survival of planets (Carney et al. 2001; Latham et al. 2002).

Old stars have the advantage that they rotate slowly and have low levels of chromospheric activity. All of the stars in our sample exhibit rotational velocities $V_{\rm rot} \leq 10$ km s^{-1}. Thus, velocity jitter due to astrophysical phenomena is not expected to be a problem for this sample. 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 as a function of stellar metallicity [Fe/H], effective temperature $T_{\rm eff}$, and visual magnitude V (assuming non-rotating, inactive stars), we have run simulations utilizing the CfA library of synthetic stellar spectra (Sozzetti et al. 2003a). In light of those results, we have refined our sample of 200 metal-poor dwarfs from the Carney-Latham and Ryan surveys by selecting objects in the metallicity range $-2.0 \leq$[Fe/H]≤ -0.6, and utilized the following magnitude and temperature cut-offs: $V \leq 11.5$, $T_{\rm eff} \leq 6250$ K.

Based on our experience with solar neighbourhood G dwarfs observed with HIRES for the G Dwarf Planet Search Program (Latham 2000), we have set an initial threshold of 20 m s^{-1} precision for planet detection, and have computed the relative exposure times needed to achieve such precision, for each star in our sample.

Finally, our sample-size is large enough that a null result, i.e., no detections, would be significant. The frequency of giant planets within 1 AU around F-G-K dwarfs is $f \simeq$3–4% (e.g., Santos et al. 2004). 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 $(1-f)^N = 0.0027$, which is satisfied for $N =$ 194–145. Our sample of 200 metal-poor stars should eventually provide a robust 3-σ null result in case of no detections.

3. RESULTS

Our analysis pipeline encompasses the full modelling of temporal and spatial variations of the instrumental profile of the HIRES spectrograph (Valenti et al. 1995) and is conceptually similar to that described by Butler et al. (1996). This analysis technique has allowed us to significantly improve upon our initial estimates of achievable radial velocity precision. In Figure 1, left panel, we show the histogram of the rms velocity residuals of the first 1.5 years of precise radial velocity measurements with HIRES for about 75% of our sample. The rms velocitity residuals distribution of the *full* sample (excluding variables with rms $\geq$30 m s^{-1}) averages $\sim$8 m s^{-1}. For about two dozen of the stars in our sample, in common with the G dwarf planet survey of Latham (2000), we could establish the long-term stability of the velocity zero-point over time-scales of up to seven years (Figure 1, right panel). This demonstrates the true radial-velocity precision we are obtaining on the sample of metal-poor stars, with a significant improvement of $\sim$60% 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. One possible matter of concern would be the evidence of systematic trends in the rms velocity distribution as a function of these three parameters. However, as shown in Figure 2, 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.

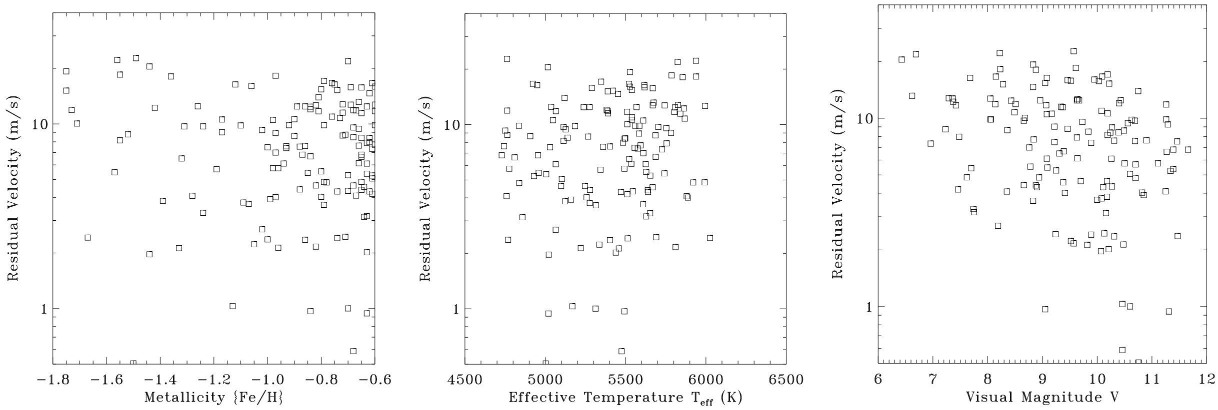

Figure 2. Radial velocity residuals (excluding variables) as a function of [Fe/H] (left), $T_{\rm eff}$ (center), and V (right).

We have provided an important confirmation of our ability to derive high-precision radial velocities for stars 2 to 5 mag fainter than the typical targets in Doppler surveys of nearby stars by determining the spectroscopic orbit for the recently announced (Alonso et al. 2004) transiting extra-solar planet TrES-1 (Figure 3). As recently determined by means of detailed abudance analyses (Sozzetti et al. 2004), its parent star is a relatively cool ($T_{\rm eff} \simeq 5250$ K), moderately faint (V = 11.79) solar-metallicity dwarf. The rms of the post-fit velocity residuals is ~ 14 m s^{-1}, in good agreement with the average of the internal errors. This is a remarkable result if we consider that this star is 2 mag fainter than the faintest stars with planets for which spectroscopic orbits with similar velocity precision have ever been derived.

None of the 149 metal-poor dwarfs screened for planets so far (with an average number of 5 observations per target spanning 1.5 years), exhibits short-term, low-amplitude variations. However, $\sim 7\%$ of the stars in the sample appear to be long-period candidates. In Figure 4 we show radial velocities as a function of time for one of the objects with a large rms velocity value. The star shown in Figure 4 exhibits a linear radial-velocity trend which is indicative of the existence of a companion, and thus, together with another handful of objects, will become a primary target for follow-up observations.

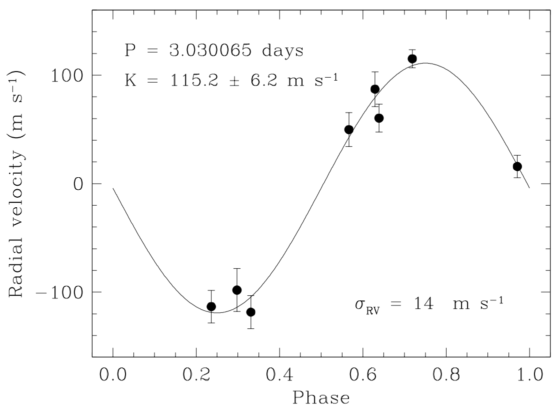

Figure 3. Radial velocity observations of TrES-1, overplotted with the best-fit orbit.

We have run Monte Carlo simulations to obtain a first estimate of the sensitivity of our survey to planetary companions of given mass and orbital period. In Figure 5, left panel, we show the minimum detectable planet mass $M_{\rm p}$ as a function of orbital period P, assuming a 0.69 $M_\odot$ primary (the average stellar mass of our sample) and a single-measurement precision $\sigma_{\rm RV} = 8$ m s^{-1}. For a typical observing strategy consisting of five observations spanning 1.5 years, the two curves identify the loci in the $M_{\rm p} - P$ discovery-space diagram for 50% and 95% probability of a 3-σ detection, respectively. If present, essentially all Jupiter-sized objects on very-short periods (<1 month) would have been detected. The data collected so far thus build toward evidence of the absence of close-in planets around metal-poor stars.

The right panel of Figure 5 shows the $M_{\rm p} - P$ discovery space for the ESA mission Gaia around a 0.69 $M_\odot$, bright ($V < 13$) metal-poor star in the 50–200 pc distance range. A single-measurement error $\sigma_\psi = 8$ μas on the one-dimensional, along-scan coordinate and a 5-

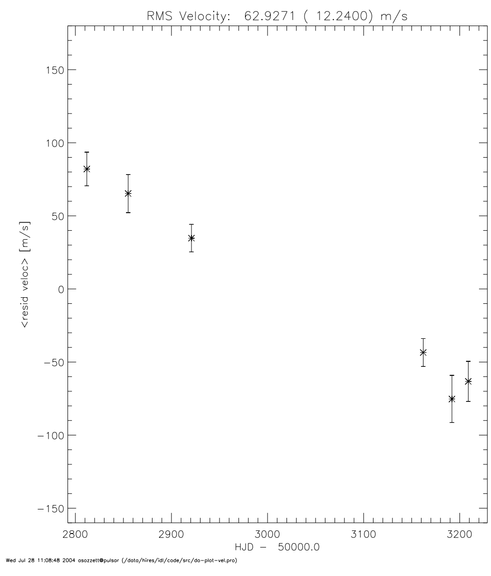

Figure 4. Radial velocity as a function of time for one of the variable objects in our sample.

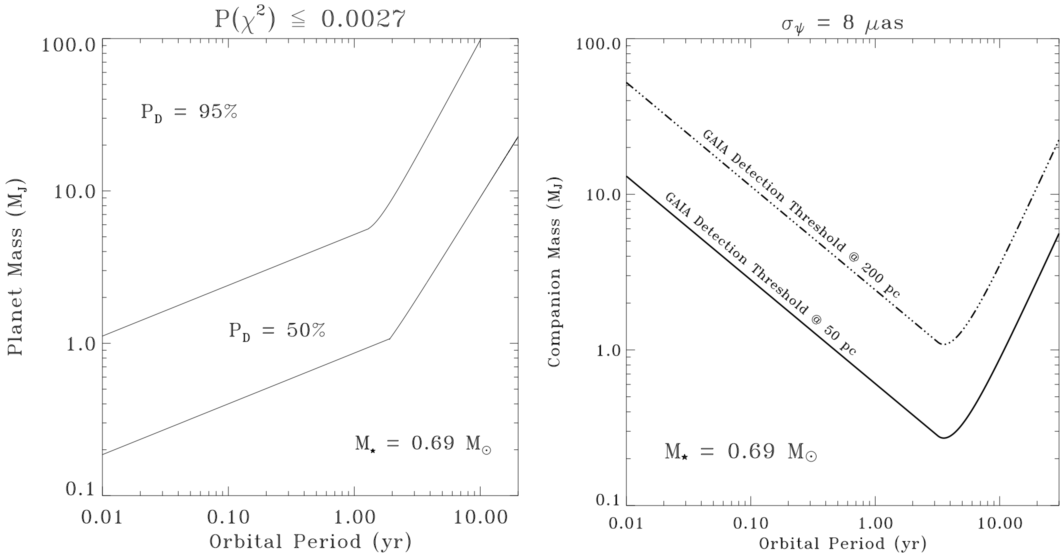

Figure 5. Left: detectable planet mass as a function of orbital period for the sample of 149 metal-poor stars observed so far. Right: Gaia 95% detection thresholds for bright ($V < 13$) metal-poor stars in the 50-200 pc distance range (based on the simulations of Sozzetti et al. 2003c).

yr mission lifetime are assumed. The complementarity between Doppler and astrometric measurements is clearly evident. In particular, by surveying for planets all bright metal-poor dwarfs within 150–200 pc (of order of a few thousands), Gaia will help to understand whether the lack of close-in giant planets around the old stellar population extends also to the long-period regime, thus providing a firm statistical basis in favour of the core-accretion scenario for giant planet formation (e.g., Ida & Lin 2004). Alternatively, the Gaia data, combined with ground-based radial-velocity monitoring, might confirm that metal-poor stars do harbour long-period giant planets (albeit at a reduced rate with respect to the metal-rich population), and thus different formation mechanims might have to be called into play (Boss 2002) and the role of metallicity on giant planet migration rates might have to be revisited (e.g., Sozzetti 2004).

ACKNOWLEDGMENTS

A.S. gratefully acknowledges support from the Smithsonian Astrophysical Observatory through the SAO Predoctoral Fellowship program.

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