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Probing structural and evolutionary properties of exoplanets

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Abstract. We summarise the results of a) a Keck/HIRES Doppler search for planets orbiting metal-poor dwarfs, and b) a new spectroscopic and photometric analysis of the transiting planet systems TrES-3 and TrES-4. These two experiments have allowed us to address important issues related to the correlation between planet frequencies and properties and the metallicity of the hosts. Our results can usefully inform formation, structural, and evolutionary models of gas giant planets.

Key words. stars: individual (TrES-3) – stars: individual (TrES-4) – stars: abundances – stars: fundamental parameters – planetary systems

1. Introduction

The planet-metallicity connection is one of the most important aspects of the close relationship between characteristics and frequencies of planetary systems and the physical properties of the host stars which have been unveiled by the present sample of over 200 extrasolar planets. In particular, the likelihood of finding a planet around a given star rises sharply with stellar metallicity (Santos et al. 2004; Fischer & Valenti 2005, e.g.). Furthermore, a correlation may also exist between estimated inner core masses of transiting giant planets and the hosts' metal content (Guillot et al. 2006; Burrows et al. 2007). In both cases, the evidence collected so far appears to strongly support the more widely accepted mechanism of giant planet formation by core accretion (e.g. Pollack et al. 1996), as opposed to the alternative formation mode by disk instability (e.g. Boss 1997). However, the relatively small numbers of metal-poor stars screened for planets so far, and the large uncertainties often present in the determination of both planet and stellar properties in transiting systems prevent one from drawing conclusions. We describe two experiments designed to put the observed trends on firmer observational

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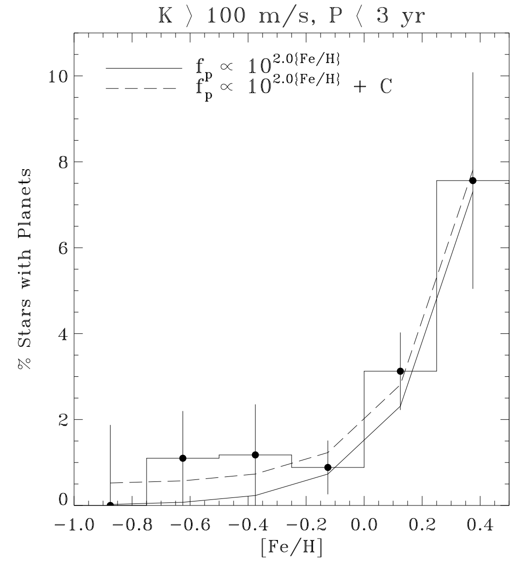

Fig. 2. Percentage of planet hosting stars as a function of metallicity (0.5 dex bins) for the sample constructed combining our survey stars with those of Fischer & Valenti (2005). The increasing trend in the fraction of stars with planets as a function of metallicity is well fitted with a power law, but the data are compatible with a constant occurrence rate $f_p \simeq 1\%$ for [Fe/H]$\lesssim$ 0.0.

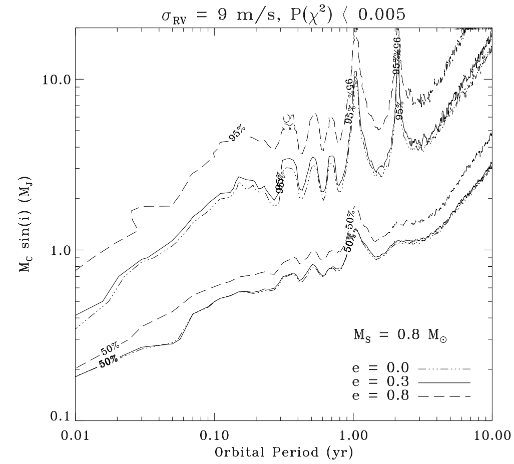

Fig. 1. Survey completeness for companions of given mass, orbital period, and eccentricity.

grounds, thus ultimately helping to discriminate between proposed planet formation models. The first is a Doppler survey for giant planets orbiting within 2 AU of a well-defined sample of 200 field metal-poor dwarfs. Our data can help to gauge the behaviour of planet frequency in the metal-poor regime. The second consists of a novel method for improving on the knowledge of stellar and planetary parameters of transiting systems through a careful analysis of spectro-photometric measurements. With this approach, structural and evolutionary models of irradiated planets can be better informed, allowing for refined estimates of the heavy-element content of transiting planets and for improved understanding of the core mass-stellar metallicity correlation.

Based on an analysis of over 3 yr of precision radial velocity measurements of ~ 200 metal-poor stars observed with HIRES on the Keck 1 telescope (Sozzetti et al. 2006),

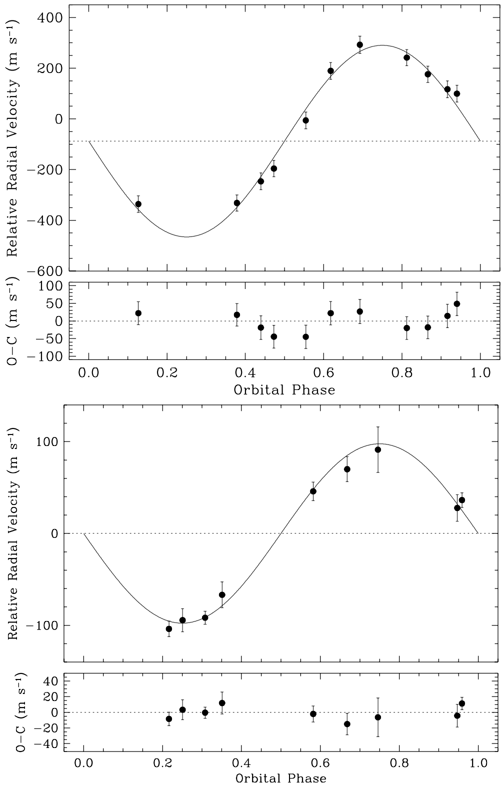

Fig. 3. Left: Revised spectroscopic orbital solution for TrES-3 (top), and post-fit residuals (bottom). Right: The same for TrES-4.

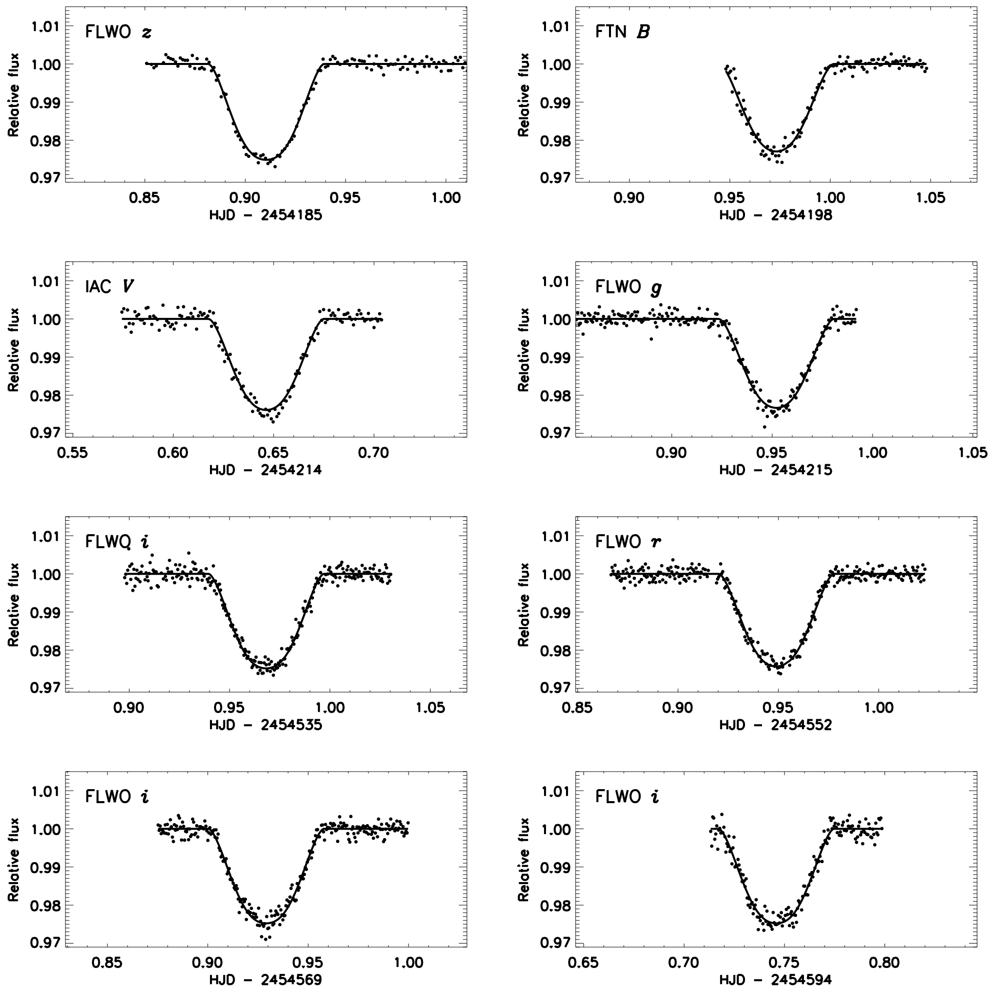

Fig. 4. Relative flux of the TrES-3 system as a function of time from the centre of transit, including a residual colour-dependent extinction correction. Each of these follow-up light curves is labelled with the telescope and filter employed. We have overplotted the simultaneous best-fit solution, adopting the appropriate quadratic limb-darkening parameters for each band pass.

4.1 $M_J(P/yr)^{(1/3)}$, for orbital periods $P \lesssim 3$ yr (Figure 1).

None of the stars in our sample exhibits radial-velocity variations compatible with the presence of Jovian planets with periods shorter than the survey duration. The resulting average frequency of gas giants orbiting metal-poor dwarfs with $-2.0 \lesssim$[Fe/H]$\lesssim -0.6$ is $f_p <$ 0.67%.

We examine the implications of this null result in the context of the observed correlation between the rate of occurrence of giant planets and the metallicity of their main-sequence solar-type stellar hosts. By combining our dataset with the Fischer & Valenti (2005) uniform sample, we confirm that the likelihood of a star to harbour a planet more massive than Jupiter within 2 AU can be expressed as a quadratic function of the host's metallicity (Figure 2). However, the data for stars with $-1.0 \lesssim$[Fe/H]$\lesssim 0.0$ are compatible, in a statistical sense, with a constant occurrence rate $f_p \simeq 1\%$ (see also Santos et al. 2004).

2. Testing the f_p-[Fe/H] correlation

Using high-resolution Keck spectra, we derive improved atmospheric parameters for the parent stars of the recently discovered transiting planets TrES-3 (O'Donovan et al. 2007) and TrES-4 (Mandushev et al. 2007). TrES-3 is a mildly metal-deficient G-dwarf with [Fe/H] $= -0.19 \pm 0.08$, while TrES-4 is a slightly evolved, mildly metal-rich F-star with [Fe/H] = 0.14 ± 0.09. The spectroscopic orbital solutions for both systems are improved with our new radial-velocity measurements (see Figure 3), as are the light-curve parameters for TrES-3 based on newly acquired photometry (see Figure 4). We determine stellar masses and radii using the combined spectro-photometric approach described in Sozzetti et al. (2007), in which $T_{\rm eff}$ and the normalised separation $a/R_\star$ are used in the comparison with stellar evolution models. We obtain $M_\star = 0.924^{+0.012}_{-0.040}\, M_\odot$, $R_\star = 0.813^{+0.012}_{-0.027}\, R_\odot$ for TrES-3 and $M_\star = 1.384_{-0.046}{+0.070}\, M_\odot$, $R_\star = 1.810^{+0.071}_{-0.056}\, R_\odot$ for TrES-4. The improved planetary radius thus inferred confirms TrES-4 as the planet with the largest radius (and lowest density) discovered so far. Given the super-solar metallicity of its host, the TrES-4 system (together with WASP-1 and HAT-P-4) suggests that gas giant planet core mass is not a simple function of host-star metallicity or of radiation environment. We conclude that more definite statements on the relation of the observations and planet structure theories can be made only by reaching higher accuracy in the observed star/planet parameters.

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