

The *Spitzer* search for the transits of HARPS low-mass planets

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Abstract. Radial velocity, microlensing and transit surveys have revealed the existence of a large population of low-mass planets in our Galaxy, the so-called ‘Super-Earths’ and ‘Neptunes’. The understanding of these objects would greatly benefit from the detection of a few of them transiting bright nearby stars, making possible their thorough characterization with high signal-to-noise follow-up measurements. Our HARPS Doppler survey has now detected dozens of low-mass planets in close orbit around bright nearby stars, and it is highly probable that a few of them do transit their host star. In this context, we have set up an ambitious *Spitzer* program devoted to the search for the transits of the short period low-mass planets detected by HARPS. We present here this program and some of its first results.

Keywords. planetary systems, eclipses, techniques: photometric, techniques: radial velocities

1. Introduction

Transiting exoplanets are definitely key objects for our study of planetary systems. Except for the planets of our own solar system, they are the only planets we can accurately estimate for mass, radius, and, by inference, constrain the internal composition. Furthermore, the geometry of their orbit relative to Earth makes possible the study of their atmospheric properties without having to resolve them from their host star (see contribution by Charbonneau, this volume). About 100 transiting planets have been detected so far, most of them by dedicated photometric surveys. Among them, the ‘hot Jupiters’ HD 209458b and HD 189733b are certainly the ones that have been best characterized so far (see contribution by Tinetti, this volume), thanks to the brightness of their host stars ($K=6.3$ and 5.5). The galore of results obtained for these two planets and a few others have opened a new field of astronomy: exoplanetary science.

Radial velocity (RV) and microlensing surveys have revealed the existence of a large population of planets with a mass of a few to ~ 20 Earth masses (Lovis *et al.* 2009; Sumi *et al.* 2009). Based on their mass (or minimal mass for RV planets), these planets are loosely classified as ‘super-Earths’ ($M_p \leq 10 M_{\oplus}$) and ‘Neptunes’ ($M_p > 10 M_{\oplus}$). This classification is based on the theoretical limit for gravitational capture of H/He, $\sim 10 M_{\oplus}$ (Rafikov 2006), and thus implicitly assumes that ‘Neptunes’ are predominantly ice giants with a significant H/He envelope, and that most ‘super-Earths’ are massive

terrestrial planets. In fact, the exact nature of these low-mass planets remains mysterious. A few of them transit their parent star, but only the ‘hot Neptune’ GJ 436b (Gillon *et al.* 2007) and the ‘mini-Neptune’ GJ 1214b (Charbonneau *et al.* 2009) are good targets for a thorough characterization with existing or near-to-come instruments, thanks to the small size and infrared brightness of their parent M-dwarf stars. It is now desirable to extend our understanding of low-mass planets towards solar-type host stars, and it requires the detection of a few ‘hot Neptunes’ and ‘super-Earths’ transiting bright nearby FGK-dwarf stars. Doppler surveys target such bright solar-type stars, and searching for the transits of the low-mass planets detected by RV measurements is thus an obvious method of detecting transiting low-mass planets suitable for a thorough characterization.

Our HARPS Doppler survey has now detected a few dozens short-period low-mass planets, enough to make highly probable that a few of them do transit. Detecting these shallow transits could not be done from the ground, and requires a space-based instrument that not only can reach extremely high photometric precisions, but also that can monitor the same star for a few dozens of hours (see discussion in Gillon *et al.* 2010). Indeed, the small amplitude of the RV signals of low-mass planets, their tendency to be found in multiple-planet systems (Lovis *et al.* 2009), and also the RV low-frequency noise of the host star itself, make extremely difficult a precise estimation of the transit timings, and rather large time windows have to be probed. In this context, we have concluded that the best instrumental choice for our transit search was the *Spitzer Space Telescope*. Due to its heliocentric orbit, it can monitor most of the stars for weeks to months during their visibility window, and it has demonstrated on many instances its capacity to detect eclipses with an amplitude of a few hundreds of ppm (e.g. Stevenson *et al.* 2010). We have thus set up a *Spitzer* program devoted to the search for the transits of HARPS low-mass planets. This program has been presently divided in a cycle 5 (cryogenic) *Spitzer* program that targeted the ‘super-Earth’ HD 40307b (Mayor *et al.* 2009), and a cycle 6 100-hr *Warm Spitzer* program targetting nine other low-mass planets. The results of our HD 40307b program were presented in Gillon *et al.* (2010), and we present here preliminary results for our *Warm Spitzer* program.

2. Overview

Our nine targets were (or will be) observed with the IRAC instrument, at 3.6 or 4.5 μm , the two only channels that have remained operational after the depletion of *Spitzer’s* cryogen in 2009. Table 1 presents these targets (including HD 40307b). For each of them, Table 1 gives the K -magnitude of the host star, the minimal planetary mass measured from RVs, a minimal value for the expected transit depth assuming a pure iron composition (Seager *et al.* 2007), the geometric transit probability, the used IRAC channel and a reference to the RV discovery paper, if any. Including HD 40307b, the formal *a priori* probability that at least one of these planets transits is $\sim 60\%$. For each of them, our strategy is to deduce from the RVs the $2\text{-}\sigma$ transit window, possibly after getting new RVs at well chosen phases to improve the transit ephemeris, then to monitor continuously the transit window with *Spitzer*. Once *Spitzer* data are gathered, they are analyzed globally with the RVs for the system, using the Bayesian MCMC method described in Gillon *et al.* (2010). In this analysis, a prior on the planet size is used to avoid detecting spurious very low-amplitude transits. The main final output of the analysis is a posterior transit probability for the planet.

The *Warm Spitzer* photometric time-series are affected by systematic effects, and getting a photometric precision high enough to detect a transit of a few hundreds of ppm requires to take them properly into account. The IRAC 3.6 and 4.5 μm InSb detectors

Table 1. Targets observed in our HARPS-*Spitzer* program.

Target	K	$M \sin i$ [M_{\oplus}]	$Min (R_p / R_*)^2$ [ppm]	P_{tr} [%]	IRAC channel [μm]	Obs. duration [hrs]	Reference
HD 10180 c	5.9	13.1 ± 0.5	300	8.5	4.5	10.3	Lovis <i>et al.</i> 2011
HD 40307 b	4.8	4.3 ± 0.3	220	7	8	26.8	Mayor <i>et al.</i> 2009
HD 47186 b	6.0	23.0 ± 0.5	450	10	3.6	5	Bouchy <i>et al.</i> 2009
HD 115617 b	3.0	5.1 ± 0.5	130	9	4.5	12.5	Vogt <i>et al.</i> 2010
HD 125612 c	6.8	18 ± 0.8	400	9	3.6 & 4.5	30.3	Lo Curto <i>et al.</i> 2010
HARPS-19 b	4.8	11.2 ± 0.9	- ¹	21 ¹	3.6	5.9	Lovis <i>et al.</i> , in prep.
HD 215497 b	6.8	5.5 ± 0.6	200	8	4.5	13.4	Lo Curto <i>et al.</i> 2010
HD 219828 b	6.5	19.1 ± 1.2	95	14	4.5	11	Melo <i>et al.</i> 2007
GJ 3634 b	7.5	6.6 ± 1.1	750	6.5	4.5	6.6	Bonfils <i>et al.</i> 2011
55 <i>Cnc</i> e	4.0	9.5 ± 0.9	210	11	4.5	5	Dawson & Fabrycky 2010

Notes:

¹ Because of its high orbital eccentricity ($e \sim 0.45$), the occultation probability for HARPS-19 b is much larger than its transit probability, so we monitored the *occultation* window with *Spitzer*.

show a large intra-pixel variability that, combined to the jitter of the telescope, leads a strong correlation of the measured fluxes with the stellar position on the chip (Knutson *et al.* 2008). Furthermore, we have noticed that some of our 3.6 μm data show a low-frequency *evolution* of the correlation between fluxes and y -positions, and also a sharp increase of the effective gain during the first hour of observation, similar to the well-documented ‘ramp’ effect of 8 μm cryogenic data. We model the combination of all these effects by polynomial functions of the time (and/or its logarithm) and the stellar position on the detector. These models for systematics are part of our global model in the MCMC analysis. We also use the calibration method presented by Ballard *et al.* (2010) to cross-check our results. Fig. 1 shows our *Spitzer* photometric time-series for HD 47186, before and after correction for the systematics.

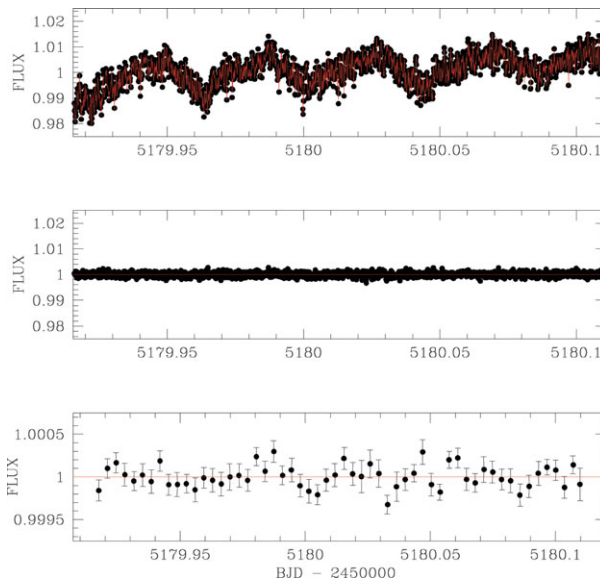


Figure 1. HD 47186 3.6 μm light curve, before (*top*) and after (*middle*) correction for the systematics. *Bottom:* calibrated light curve binned per interval of 5 minutes. Its *rms* is 130 ppm.

3. First results and perspectives

HD 47186 b. This ‘hot Neptune’ was detected by HARPS in 2009 (Bouchy *et al.*). Thanks to the large amplitude of its orbital RV signal ($K \sim 9 \text{ m.s}^{-1}$) and to the high precision of the HARPS measurements, its $2\text{-}\sigma$ transit window was only 5hr. We observed it with *Spitzer*-IRAC at $3.6 \mu\text{m}$. Fig. 1 shows the resulting photometry before and after correction for the systematics. No transit is detected. Our global analysis of the *Spitzer* and HARPS data leads to a posterior transit probability of only 0.4%.

HD 10180 c. This ‘hot Neptune’ was detected recently with six other planets around the nearby solar-type star HD 10180 (Lovis *et al.* 2011). Our *Warm Spitzer* photometry allows us to reject the transiting nature of this planet to a high level of confidence, its posterior transit probability being $\sim 0.7\%$.

GJ 3634 b. GJ 3634 is a M2.5V star at 17.5 parsec from the solar system. This red dwarf is one of the ~ 400 targets of our HARPS M-dwarf program. We recently detected a $6.6 \pm 1.1 M_{\oplus}$ ‘super-Earth’ in very short period orbit around it ($P = 2.64561 \pm 0.0007$ days, Bonfils *et al.* 2011). Our 6-hour long *Warm Spitzer* light curve excludes that a transit occurs within the $2\text{-}\sigma$ transit window, decreasing the probability that GJ 3634 b undergoes transit down to 0.5%.

The data obtained for HARPS-19, HD 115617, HD 125612, HD 215497 and HD 219828 are still under analysis, but unfortunately our preliminary light curves do not show any obvious transit. Our remaining target for our cycle 6 program, 55 *Cnc*, has still to be observed by *Spitzer*. The prior probability that none of our 10 targets transit was $\sim 40\%$. Still, if we consider all the short-period low-mass planets (~ 35 planets) detected by HARPS so far, the prior probability that at least one of them transits is better than 95%, giving us a strong motivation to pursue this program in the future *Spitzer* cycle 7.

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