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The HARPS search for southern extra-solar planets⋆,⋆⋆

XIII. A planetary system with 3 super-Earths (4.2, 6.9, and 9.2 $M_\oplus$)

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ABSTRACT

We report the detection of a planetary system with three Super-Earths orbiting HD 40307. HD 40307 is a K2 V metal-deficient star at a distance of only 13 parsec, which is part of the HARPS GTO high-precision planet-search programme. The three planets on circular orbits have very low minimum masses of 4.2, 6.9, and 9.2 Earth masses and periods of 4.3, 9.6, and 20.5 days, respectively. The planet with the shortest period is the lowest mass planet detected to-date orbiting a main sequence star. The detection of the correspondingly low amplitudes of the induced radial-velocity variations is secured completely by the 135 high-quality HARPS observations illustrated by the radial-velocity residuals around the 3-Keplerian solution of only 0.85 ms^{-1}. Activity and bisector indicators exclude any significant perturbations of stellar intrinsic origin, which supports a planetary interpretation. In contrast to most planet-host stars, HD 40307 has a significantly sub-solar metallicity ([Fe/H] = −0.31), which suggests that very light planets might have a different dependence on host star metallicity than gas giant planets. In addition to the 3 planets close to the central star, a small drift in the radial-velocity residuals implies the presence of another companion in the system, the nature of which is still unknown.

Key words. stars: individual: HD 40307 – stars: planetary systems – techniques: radial velocities – methods: observational

1. Introduction and context

The planet-search programme conducted at high precision with the HARPS spectrograph on the ESO 3.6-m telescope at La Silla is attempting to detect very low-mass planets orbiting solar-type stars. The stars selected have already been studied to check for the presence of giant planets with CORALIE on the 1.2-m Swiss telescope at the same site. About 50% of the HARPS GTO time is dedicated to this survey. After 4.5 years of the programme, we are starting to see a large population of Neptune-mass and super-Earth planets emerging from the data, including the system presented here.

Several reasons motivate our interest to search for very low-mass planets, with masses in the range of the Neptunes or the so-called Super-Earths ($\sim 2\ M_\oplus \leq m_2 \sin i \leq 10\ M_\oplus$).

Several statistical distributions of the orbital elements of gaseous giant planets have emerged from the nearly 300 detected planetary systems (see e.g. Udry & Santos 2007; Marcy et al. 2005). These statistical properties provide constraints on complex physical scenarios of planetary system formation. Planetary formation theory and observations can be compared directly, for example, in terms of the planetary mass versus semi-major axis ($m_2 - a$) diagram (Ida & Lin 2004a; Mordasini et al. 2008). Comparison can be made for specific categories of host stars by selecting different primary masses (m_1) or metallicities ([Fe/H]). In all cases, global features of planet formation directly affect the overall topology of the ($m_2 - a$) diagram. In particular, the location of the significant population of very low-mass planets predicted by the models (Mordasini et al. 2008; Ida & Lin 2008) depends on the amount of migration experienced by planets during their formation. Detection of a significant number of planets with masses lower than about 25 $M_\oplus$ close to their parent star is therefore a key indicator of the efficiency of type I migration, assuming that the planets are not sufficiently close for evaporation to be important.

Despite the limited number of planets that have been detected to have approximately Neptune masses, a few interesting characteristics are however already emerging (Mayor & Udry 2008). We find that the distribution of planetary masses appears as bimodal. A new population of light planets, although more difficult to detect, distinguish itself from the distribution of giant-planet masses. The Neptune- and super-Earth mass distribution does not appear to be the extrapolation towards lower masses of

⋆ Based on observations made with the HARPS instrument on the ESO 3.6 m telescope at La Silla Observatory under the GTO programme ID 072.C-0488.

⋆⋆ The table with the individual radial velocities is available in electronic form at the CDS anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via
http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/493/639

the distribution for gaseous giant planets. The very strong correlation observed between the host star metallicity and occurrence frequency of giant planets (Santos et al. 2001, 2004; Fischer & Valenti 2005) appears to vanish or at least be reduced (Udry et al. 2006). Neptune-mass planets and Super-Earths are found most of the time in multiplanetary systems (>80% of known candidates).

Simulations of planetary formation do not only provide statistical distributions of masses and semi-major axes. For every planet, we have, in addition, a prediction of its internal structure. The internal composition of a planet at the end of its formation/migration process carries a fossil signature of the system history. The end-state diversity is broad: rocky planets, icy planets, ocean planets, evaporated gaseous giant planets, or possibly objects with varying fractions of these ingredients. The predicted distributions of the planetary internal composition, as a function of the different significant parameters (m_1, m_2, a, [Fe/H]), can be observed in the corresponding radius-mass (m_2–R) diagrams. These predicted (m_2–R) distributions can then be compared with the observed data distributions derived from combined radial-velocity and transit searches. The soon-to-be-announced results from space missions searching for planetary transits, combined with ground-based, high-precision, radial-velocity follow-up, will provide rich observational constraints of planetary formation theory by means of the $m_2 - R$ distributions of low-mass planets.

In the more distant future, space missions will be developed to search for signatures of life in the atmosphere of terrestrial-type planets. Before completing detailed designs of these ambitious missions, it would be invaluable to gain first insights into the occurrence frequency of terrestrial planets and the statistical properties of their orbits. The detection of planets in the habitable zone of our closest neighbours is even more invaluable, initiating the preparation of an "input catalogue" for these future missions.

Already a few planets have been detected with masses between 3 and 10 $M_\oplus$. From precise timing, Wolszczan & Frail (1992) discovered two planets with masses of 2.8 and 3.4 $M_\oplus$ orbiting the pulsar PSR 1257+12 in almost perfect circular orbits. Microlensing technique has also demonstrated its potential to detect low-mass planets. Two planets with masses possibly in the range of super-Earths have been announced: a planet of about 5.5 $M_\oplus$ orbiting a low-mass star (Beaulieu et al. 2006), and a still less massive object, of only 3.3 $M_\oplus$, probably gravitationally bound to a brown dwarf (Bennett et al. 2008). Doppler spectroscopy also revealed a fair number of planets with $m_2 \sin i$ less than 10 $M_\oplus$: GJ 876 d, $m_2 \sin i = 5.9\ M_\oplus$ (Rivera et al. 2005); GJ 581 c and d, with $m_2 \sin i$ of 5.1 and 8.2 $M_\oplus$, respectively (Udry et al. 2007); HD 181433 b with $m_2 \sin i = 7.5\ M_\oplus$ (Bouchy et al. 2009). GJ 876 and GJ 581 are both stars at the bottom of the main sequence with spectral types M4 V and M3 V, respectively. HD 181433 and HD 40307 are, on the other hand, both K dwarfs. The detection of planetary systems around bright stars with Doppler spectroscopy is important because this technique is used to study mostly nearby stars for which we are able to determine interesting further information (e.g. about their orbital, planetary, and stellar properties), opening the possibility of productive follow-up studies. This is in particular true when the planet is transiting in front of its parent star (see for illustration the wealth of studies concerning GJ 436).

In this paper, we characterize the orbits of three new super-Earth planets on short-period trajectories orbiting the main sequence star HD 40307. Section 2 briefly describes the improvement of the HARPS radial velocities in terms of observational strategy and software developments. The stellar characteristics of HD 40307 are presented in Sect. 3. Section 4 deals with the derived orbital solution while our summary and conclusion are given in Sect. 5.

2. Challenges to high-precision radial velocities

2.1. Star sample and observational strategy

About 50% of the HARPS GTO (guaranteed time observation) time is devoted to the search for very low-mass planets orbiting G and K dwarfs of the solar vicinity, in the southern sky. A companion programme is focused on the same goal but for planets around M-dwarf stars. HARPS is a vacuum high-resolution spectrograph fiber-fed by the ESO 3.6-m telescope at La Silla Observatory (Mayor et al. 2003). HD 40307 is part of our G–K survey. The stars in this programme were selected from the volume-limited sample (1650 stars) measured since 1998 with the CORALIE spectrograph on the EULER telescope, also at La Silla (Udry et al. 2000). In a first step, we selected some 400 G and K dwarfs with $v \sin i$ less than 3 km s^{-1} and removed known spectroscopic binaries. In a second step, using the high quality HARPS spectra, we concentrated our efforts on the less active stars of the sample ($\log R'_{HK} < -4.8$). The remaining ~200 stars of rather low chromospheric activity constitute the core of the programme to search for Neptune-mass and super-Earth planets.

The planetary minimum mass estimated from Doppler measurements is directly proportional to the amplitude of the reflex motion of the primary star. The measurement of precise radial velocities requires that all points along the light path, from the star to the detector, are well understood. If photon supply is no longer a problem (e.g. for bright stars), there remain two main limitations to the achieved radial-velocity precision: intrinsic stellar variability and spectrograph stability. The stellar noise groups error sources related to stellar intrinsic phenomena acting on different timescales, from minutes (p modes), to hours (granulation) and even days or weeks (activity). To minimize their effects on the measured radial velocities, we have to adapt our observational strategy as much as possible to these corresponding timescales, in such a way that averaged radial-velocity values will be far less sensitive to the aforementioned effects. For example, long integrations (~15 min) are sufficient to dampen the radial-velocity variations due to stellar oscillations to well below 1 ms^{-1}. To dampen the granulation noise, several measurements spread over a few hours are probably required. Test observations with HARPS to characterize this point more accurately are ongoing. We finally attempt to avoid activity effects by selecting the least active stars, as mentioned above.

2.2. Precision improvements by software developments

The precision of the HARPS measurements has been improved by three major upgrades on the reduction software.

We firstly considered the precision of radial velocity measurements, which depends on many factors in particular on the quality of the relation between wavelengths and position on the CCD detector. This relation is established before the beginning of each night by using the numerous thorium lines of a thorium-argon hollow cathode lamp. A global reanalysis of thorium line positions based on many thousands of HARPS spectra has allowed Lovis & Pepe (2007) to improve significantly the precision of thorium line wavelengths. A drastic increase in the stability of the HARPS dispersion relation was immediately observed.

Ageing of the thorium-argon calibration lamp can be observed producing a small wavelength shift in the emission lines due to the changing pressure inside the lamp. This effect is far more significant for argon lines than thorium lines. This differential effect can be used to correct for the lamp ageing effect (Lovis, in prep.).

The ADC (Atmospheric Dispersion Corrector) in the Cassegrain adaptor is designed to maintain the stellar image at any wavelengths centred precisely on the entrance of the optical fiber feeding the spectrograph. Since the seeing is chromatically dependent on the airmass, the relative amount of light entering in the optical fiber, for the different grating orders, is however dependent on airmass. The cross-correlation technique provides the mean velocities of stellar lines order by order. Mean radial velocities of the different orders are not identical because of the random distribution of the line blending and to the line-to-line dependence of for example the stellar convective blueshift. To correct for this secondary effect on the Doppler velocity, we must normalize the flux for the different orders to a particular value and compensate for the seeing chromatic dependence with airmass.

All spectra acquired to derive the complete set of HARPS velocities were reprocessed taking into account these new developments. The net effect is a clear improvement in the long-term stability of the HARPS measurements (better than a fraction of a m/s over 5 years) and a significant decrease in the observed radial-velocity rms of the stable stars. The planetary mass estimated from Doppler measurements is directly proportional to the amplitude of the stellar reflex motion. Our progress in detecting very low-mass planets is therefore directly related to the improvements in the sensitivity and stability of spectrographs. Ice giants and super-Earths induce RV amplitudes smaller than 3 m/s. This implies that the highest possible RV precision is critical to detecting this population.

3. Stellar characteristics of HD 40307

The basic photometric (K2.5V, $V = 7.12$, $B - V = 0.92$) and astrometric (π = 77.95 mas) properties of HD 40307 were taken from the Hipparcos catalogue (ESA 1997). They are presented in Table 1 with inferred quantities such as the absolute magnitude (M_V = 6.63) and stellar physical characteristics derived from the HARPS spectra by Sousa et al. (2008). For the complete high-precision HARPS sample (including HD 40307), these authors provide homogeneous estimates of the effective temperature ($T_{\rm eff}$ = 4977 ± 59 K), metallicity ([Fe/H] = −0.31 ± 0.03), and surface gravity ($\log g$ = 4.47 ± 0.16) of the stars.

Interestingly, HD 40307 has a substellar metallicity of [Fe/H] = −0.31 unlike most gaseous giant-planet host stars (Santos et al. 2004). According to simulations of planet formation based on the core-accretion paradigm, moderate metal-deficiency does not affect the formation of low-mass planets (Ida & Lin 2004b; Mordasini et al. 2008). Taking into account its subsolar metallicity, Sousa et al. (2008) also derived a mass of 0.77 $M_\odot$ for the star. From the colour index, derived effective temperature, and corresponding bolometric correction, we estimated the star luminosity to be 0.23 $L_\odot$.

HD 40307 is among the least active of stars in our sample with an activity indicator $\log R'_{HK}$ of −4.99. No significant radial-velocity jitter is therefore expected for the star. From the activity indicator, we also derive a stellar rotation period of $P_{\rm rot}$ = ~48 days (following Noyes et al. 1984).

Table 1. Observed and inferred parameters of HD 40307. Photometric and astrometric parameters were taken from the Hipparcos catalogue (ESA 1997) and the stellar physical quantities from Sousa et al. (2008).

Parameter		HD 40307
Sp		K2.5 V
V	[mag]	7.17
$B - V$	[mag]	0.92
π	[mas]	77.95 ± 0.53
M_V	[mag]	6.63
$T_{\rm eff}$	[K]	4977 ± 59
$\log g$	[cgs]	4.47 ± 0.16
[Fe/H]	[dex]	−0.31 ± 0.03
L	[$L_\odot$]	0.23
M_*	[$M_\odot$]	0.77 ± 0.05
$v \sin i$	[km s^{-1}]	<1
$\log R'_{HK}$		−4.99
$P_{\rm rot}(\log R'_{HK})$	[days]	~48

4. The HD 40307 planetary system

4.1. Radial velocity observations

HD 40307 was monitored by the HARPS spectrograph for 4.5 years, during which time 135 measurements were obtained. During the final 3 seasons (128 measurements, and time span of 878 days), we adopted a measurement strategy to minimize the effect of stellar acoustic modes. Despite the brightness of the star, the integration time per epoch was always set to 15 min. Over this integration time corresponding to a few periods of the p-modes, the residual effect of these modes is estimated to be less than 20 cm s^{-1} (Pepe & Lovis 2008). For most of the measurements, the photon noise after 15 min is typically of the order of 0.3 ms^{-1} (corresponding to S/N of the order of 150–200 at λ = 550 nm, depending on seeing conditions). The mean uncertainty in the 128 velocities obtained during the last 3 seasons is 0.32 ms^{-1}. As already mentioned, HD 40307 has a very low level of chromospheric activity ($\log R'_{HK} = -4.99$).

The radial velocity intrinsic variability, including the noise due to stellar granulation (Kjeldsen et al. 2005) and any effect related to the stellar magnetic activity, is not known. However, due to the low level of calcium reemission and by comparison with other similar stars, this effect is estimated to be lower than 1 ms^{-1}. The observed raw rms for the 135 measurements spread over 1628 days is 2.94 m/s, far in excess of the above mentioned different sources of noise.

At the end of 2006, we noticed that the observed radial-velocity variation could be explained by the effect of 3 low-mass planets and a first preliminary solution was obtained. Due to the complicated pattern of the radial velocities, the number of parameters required for a 3-planet fit (16 free-parameters), and the low velocity semi-amplitudes of these 3 planets, we preferred to postpone the final analysis and accumulate more measurements during the next 2 seasons. Extending the span and number of measurements has permitted us to confirm and check the robustness of the preliminary solution.

Using the data available today, three peaks are clearly identified in the Fourier spectrum of the velocity measurements, which correspond to periods of 4.2, 9.6, and 20.5 days (Fig. 1). Their false alarm probability estimated from velocity scrambling simulations are below 10^{-4}. Fitting three Keplerians to the radial velocity measurements, we obtain a solution close to that listed in Table 2 with periods corresponding to the

Table 2. Fitted orbital solution for the planetary system around HD 40307: 3 Keplerians plus a linear drift. To better estimate uncertainties on the adjusted parameters, the adopted solution has fixed circular orbits, the derived eccentricities being non-significant (see text).

Parameter		HD 40307 b	HD 40307 c	HD 40307 d
P	[days]	4.3115 ± 0.0006	9.620 ± 0.002	20.46 ± 0.01
T	[JD-2 400 000]	54 562.77 ± 0.08	54 551.53 ± 0.15	54 532.42 ± 0.29
e		0.0	0.0	0.0
ω	[deg]	0.0	0.0	0.0
K	[m s^{-1}]	1.97 ± 0.11	2.47 ± 0.11	4.55 ± 0.12
V	[km s^{-1}]		31.332	
drift	[m s^{-1}/yr]		0.51 ± 0.10	
$f(m)$	[10^{-14} $M_\odot$]	0.35	1.53	3.59
$m_2 \sin i$	[$M_\oplus$]	4.2	6.9	9.2
a	[AU]	0.047	0.081	0.134
$N_{\rm meas}$			135	
Span	[days]		1628	
σ (O–C)	[ms^{-1}]		0.85	
$\chi^2_{\rm red}$			2.57	

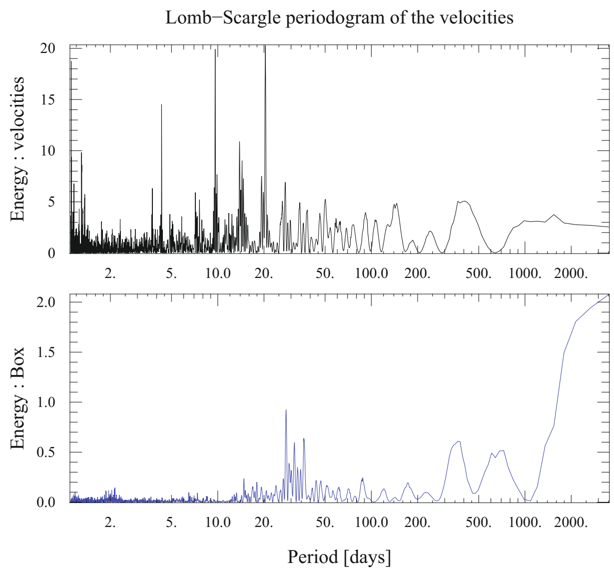

Fig. 1. Lomb-Scargle periodogram (*top*) of the 135 HARPS radial velocities of HD 40307. Clear peaks are evident at frequencies corresponding to periods of 4.2, 9.6, and 20.5 days. *The bottom panel* presents the corresponding window function of the data.

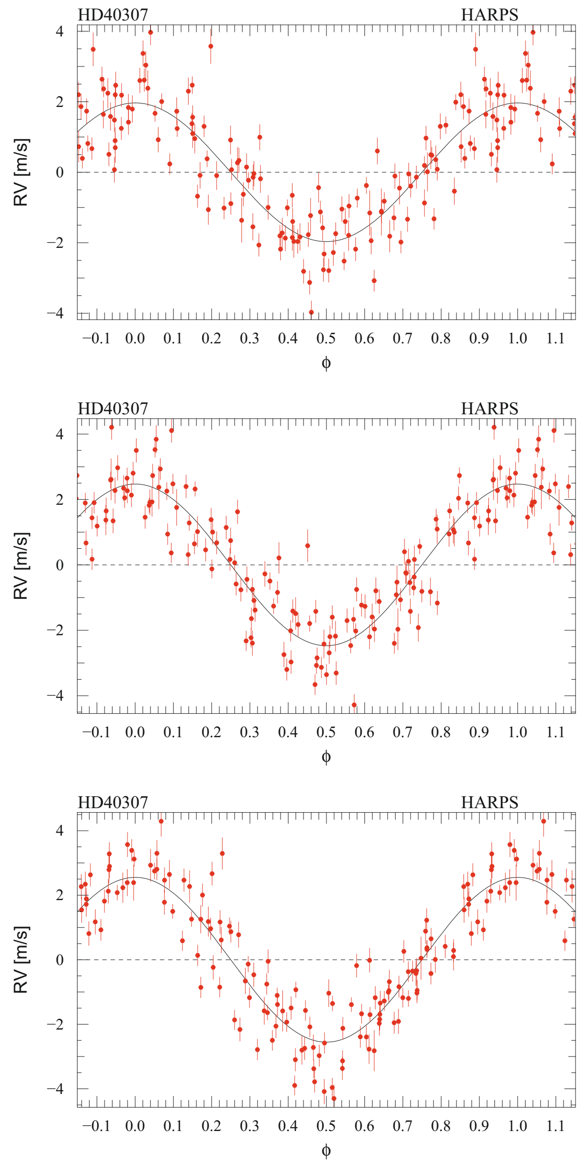

Fig. 2. Phase-folded radial velocities and Keplerian curve for each of the planets, after correction for the effect of the 2 other planets and the drift. Curves related to planets b, c, and d are illustrated *from top to bottom*, respectively.

3 aforementioned peaks. We note that the conventional approach of determining iteratively the solution for the different planets one after the other is difficult because of the short periods, in particular close to resonances. To find the final solution, we rather followed a genetic-algorithm approach to probe blindly the complete parameter space. The ratios of periods $P_2/P_1 = 2.23$ and $P_3/P_2 = 2.13$ probably differ sufficiently from 2 to be able to exclude resonances.

In a first fit, the orbital eccentricities were allowed to be free parameters. The derived solution showed non-significant eccentricities of 0.008 ± 0.065, 0.033 ± 0.052 and 0.037 ± 0.052 for the 3 planets, respectively. The residuals of the observed velocities around the best-fit 3-planet solution was 0.94 ms^{-1}. With circular orbits, the residuals remained unchanged as well as the other orbital parameters. The solution with 3 circular orbits then became the preferred one. Additionally, the residuals (O–C) also exhibited a well defined linear drift during the time span of our measurements. The best-fit solution was finally obtained by fitting 3 Keplerian circular orbits plus a linear drift to our 128 more

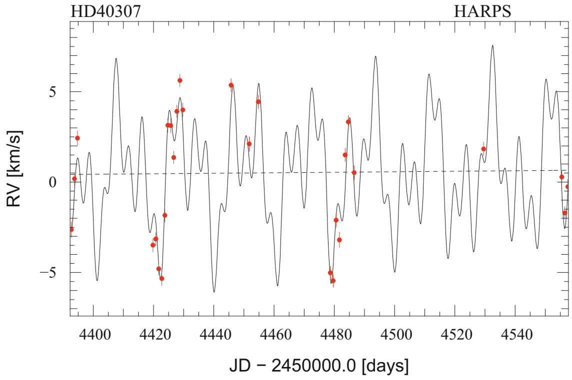

Fig. 3. Partial time window of HARPS relative radial velocities of HD 40307, with the 3-Keplerian model superimposed. Data for only ~6 months are displayed for clarity reasons.

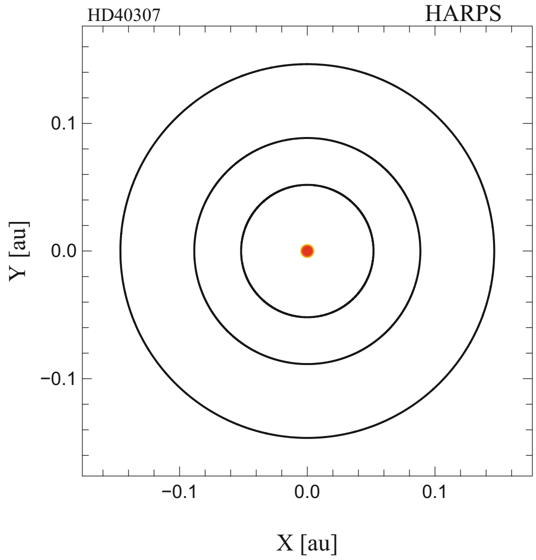

Fig. 4. Pole-on sketch of the 3 circular planetary orbits at the centre of the HD 40307 system.

accurate measurements. The phase distribution of the radial velocities for the 3 planets are shown in Fig. 2, a temporal window of the solution in Fig. 3, and the top view of the system is illustrated in Fig. 4.

The rms of the residuals to the fitted orbits (and drift), sigma(O–C) is 0.85 ms^{-1}, still in excess of the mean uncertainty of our observations. Part of the extra noise could result from granulation, jitter related to the low level of chromospheric activity or instrumental effects. We also have however to consider the possibility of additional planets. Several additional signals may also be present in the Fourier spectrum. Although they are non-significant, we have nevertheless attempted a blind search for 4 Keplerians plus a drift, without finding convincing case for a fourth planet. Additional measurements are foreseen for future seasons to explore this possibility and gain insight into the companion responsible for the observed linear drift.

The 3-planet solution is robust and precise. It is worth noticing the rather low amplitudes of the 3 reflex motions induced by these planets (1.97, 2.47, and 2.55 ms^{-1}, respectively). Due to the significant number of measurements, all three amplitudes are determined precisely. The masses of these super-Earths are determined to a precision of approximately 6% or higher.

5. Summary and discussion

We have reported the detection of 3 super-Earth planets orbiting the low metallicity K dwarf HD 40307, a star located at only 13 pc from the Sun. This discovery was achieved with the high precision radial velocities measured from data acquired with the HARPS spectrograph on the ESO 3.6-m telescope. The 3-Keplerian fit reveals the presence of 3 low-mass planets. The closest planet HD 40307 b with $m_2 \sin i = 4.2\ M_\oplus$ is presently the lightest exoplanet detected around a main sequence star. The two other planets of masses 6.9 and 9.2 $M_\oplus$ also belong to the category of super-Earths. All 3 planets are on circular orbits. It is remarkable that the global rms of the 135 measurements, before attempting to include any planets, was only 2.94 ms^{-1}. The sigma(O–C) after the 3-planet Keplerian and drift fitting was 0.85 ms^{-1}. We propose to continue the velocity monitoring to characterize more accurately the longer period 4th object bound to the system, revealed by the additional observed linear drift of the radial velocities.

Available Spitzer IRS data of HD 40307 do not show any IR excess in the 10–40 μm region of the spectra (Augereau, private communication). No warm dust disk is therefore detected in the inner regions of the system; this is unlike the case of HD 69830, the star harbouring a trio of Neptune planets (Lovis et al. 2006) for which an observed IR excess indicated the presence of a debris disk, possibly in the form of an asteroid belt (Beichman et al. 2005).

The characterization of multi-planetary systems with very low-mass planets requires large number of measurements. After 4.5 years of the HARPS programme and with improved data reduction software, several dozens of planets of masses lower than 30 Earth-masses and period shorter than 50 days have been detected. Future observations will confirm these detections and hopefully allow us to characterize these systems in more detail. The domain of Neptune-type and rocky planets will be drastically boosted in the near future with these detections. In particular, we expect to study a sufficient number of systems to revisit the emerging properties for these low mass planets as tentatively discussed by Mayor & Udry (2008). The main outstanding questions in the domain are:

- Is the mass-distribution of exoplanets bimodal?
- Does the correlation between host star metallicity and occurrence frequency of Neptune-type planets (or smaller) still exist?
- What is the frequency of multiplanetary systems with these low mass planets?
- What is the frequency of Neptune or rocky planets orbiting G and K dwarfs? A first estimate based on the HARPS high-precision survey suggests a frequency of 30 ± 10% in the narrow range of periods shorter than 50 days.

One of the most exciting possibilities offered by this large emerging population of low-mass planets with short orbital periods is the related high probability of transiting super-Earths among the candidates. If detected and then targeted in complementary observations, these transiting super-Earths would provide a tremendous contribution to the study of the expected diversity of the structure of low-mass planets.

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