The HARPS search for southern extra-solar planets*

XIII. A planetary system with 3 Super-Earths (4.2, 6.9, & 9.2 M⊕)

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Abstract. This paper reports on 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, part of the HARPS GTO high-precision planet-search programme. The three planets on circular orbits have very low minimum masses of respectively 4.2, 6.9 and 9.2 Earth masses and periods of 4.3, 9.6 and 20.5 days. The planet with the shortest period is the lightest planet detected to-date orbiting a main sequence star. The detection of the correspondingly low amplitudes of the induced radial-velocity variations is completely secured by the 135 very 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 the planetary interpretation. Contrary to most planet-host stars, HD 40307 has a marked sub-solar metallicity ([Fe/H] = −0.31), further supporting the already raised possibility that the occurrence of very light planets might show a different dependence on host-star metallicity compared to the population of gas giant planets. In addition to the 3 planets close to the central star, a small drift of the radial-velocity residuals reveals 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 – techniques: spectroscopy

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 aims at the detection of very low-mass planets in a sample of solar-type stars already screened for giant planets at a lower precision with CORALIE on the 1.2-m Swiss telescope on the same site. About 50 % of the HARPS GTO time is dedicated to the detection of the orbital elements of gaseous giant planets have emerged 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 (≤ 2 M⊕ ≤ m sin i ≤ 10 M⊕).

i) Over the past decade, 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 to complex physical scenarios of planetary system formation. One of the most obvious example of that dialogue between planetary formation theory and observations is illustrated by the comparison of the planetary mass vs semi-major axis (m₂ − a) diagram (Ida & Lin2004a, Mordasini et al. 2008). Comparison can be made for specific categories of host stars by selecting different primary masses (m₁) or metallicities ([Fe/H]). In all cases, global features of planet formation directly affect the overall topology of the (m₂ − a) diagram. In particular, the location of the large population of very low-mass planets predicted by the models (Mordasini et al. 2008, Ida & Lin 2008) depends upon the extend of migration undergone by the planets during their formation. The detection of a large sample of planets with masses less than roughly 25 M⊕ at relatively close distances is therefore an important indicator of the efficiency of type I migration (assuming that the planets are not too close so that evaporation can be neglected). Despite the still very limited number of planets detected in the range of Neptune masses, already a few interesting characteristics are emerging (Mayor & Udry 2008).

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- The distribution of planetary masses appears as bimodal. A new population of light planets, although more difficult to detect, is differentiating itself from the distribution of giant-planet masses. The Neptune- and super-Earth mass distribution seems not to be the extrapolation towards lower masses of 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) seems to be vanishing or at least to be reduced (Udry et al. 2006).

- Neptune-mass planets and Super-Earths are found most of the time in multiplanetary systems (> 80% of the known candidates).

ii) Simulations of planetary formation do not only provide the 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 the planet at the end of the 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 variable percentages of these ingredients. The predicted distributions of the planetary internal composition, as a function of the different significant parameters (\(m_1, m_2, a, [\text{Fe/H}]\)) can be observed in the corresponding radius-mass (\(m_2 - R\)) diagrams. These predicted (\(m_2 - R\)) distributions can then be compared to the observed distributions derived from combined radial-velocity and transit searches. The coming soon results from space missions searching for planetary transits combined with ground-based, high-precision, radial-velocity follow-up, will provide rich observational constraints to the planetary formation theory via the \(m_2 - R\) distributions of low-mass planets.

iii) In a more distant future, space missions will be developed to search for life signatures in the atmosphere of terrestrial-type planets. Before the detailed design of such ambitious missions, it would be wise to have first insights in the occurrence frequency of terrestrial planets and on the statistical properties of their orbits. Still more valuable is the detection of planets in the habitable zone of our closest neighbours, initiating the preparation of an “input catalogue” for these future missions.

Already a few planets have been detected with masses between 3 and 10 \(M_\oplus\). In 1992, from precise timing, Wolszczan & Frail (1992) have discovered two planets with masses of 2.8 \(M_\oplus\) and 3.4 \(M_\oplus\) orbiting the pulsar PSR1257+12 on almost perfect circular orbits. Microlensing technique has demonstrated as well 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 quite a few 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. 2008). GJ 876 as well as 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 by Doppler spectroscopy is very important because it concerns mostly nearby stars for which we can obtain interesting further information (e.g. on their orbital, planetary and stellar properties), opening the possibility of rich complementary studies. This is even more 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 will briefly describe the improvement of the HARPS radial velocities in term 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 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 time (guaranteed time observation) 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 have selected some 400 G and K dwarfs with \(v \sin i\) less than 3 \(\text{km/s}\) and removing the known spectroscopic binaries. In a second step, using the high quality HARPS spectra, we have concentrated our efforts on the less active stars of the sample (\(\log R'_{\text{HK}} < -4.8\)). The remaining ~200 stars with 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 measure of very precise radial velocities requires that all steps 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 still 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 time scales, 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 as much as possible our observational strategy to these corresponding time scales, in such a way that averaged radial-velocity values will be much less sensitive to the mentioned effects. For example, long integrations (~15 minutes) are sufficient to damp the radial-velocity variations due to stellar oscillations well below 1 \(\text{ms}^{-1}\). To damp the granulation noise several measurements spread over a few hours will probably be...
required. Test observations with HARPS are ongoing to better characterize this point. We finally are trying to avoid activity effects by selecting the less active stars, as mentioned above.

### 2.2. Precision improvements through software developments

Recently the precision of the HARPS measurements has been notably improved thanks to three major upgrades of the reduction software:

- The precision of radial velocity measurements depends on many factors, but 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 lines positions based on many thousand HARPS spectra has allowed Lovis & Pepe (2007) to significantly improve the precision of thorium line wavelengths. Immediately a drastic increase of the stability of spectrographic software:

  - Aging of the thorium-argon calibration lamp can be observed producing a small wavelength shift of the emission lines due to the changing pressure inside the lamp. Such an effect is much larger for argon lines than for thorium lines. This differential effect can be used to correct for the lamp aging effect (Lovis, in prep).

  - The ADC (Atmospheric Dispersion Corrector) in the Cassegrain adaptor is designed to maintain the stellar image at any wavelengths precisely centered on the entrance of the optical fiber, for the different grating orders, is depending on the airmass. The used cross-correlation technique provides the mean velocities of stellar lines order by order. Mean radial velocities of the different orders are not exactly identical due to the random distribution of the line blurring, etc. To correct for this secondary effect on the Doppler velocity, we must normalized the flux received in the different orders to a given value and compensate for the seeing chromatic dependence with airmass.

All the spectra obtained on the full span of HARPS measurements have been reprocessed taking into account these new developments. The net effect is a clear improvement of the long term stability of the HARPS measurements (better than a fraction of a m/s over 5 years) as well as a significant decrease of 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 to detect very low-mass planets is then directly related to the progress done to improve the sensitivity and stability of spectrograph. Ice giants and super-Earths induce RV amplitudes smaller than 3 m/s. This makes the quest for the highest possible RV precision critical to detect this population.

### Table 1. Observed and inferred parameters of HD 40307

| Parameter | HD 40307 |
|-----------|----------|
| Sp        | K2.5 V   |
| V         |          |
| B − V     | [mag]    | 7.17 |
| π         | [mas]    | 0.92 |
| M_V       | [mag]    | 77.95 ± 0.53 |
| T eff     | [K]      | 6.63 |
| log g     | [cgs]    | 4.47 ± 0.16 |
| [Fe/H]    | [dex]    | -0.31 ± 0.03 |
| L         | [L⊙]     | 0.23 |
| M_⊙       | [M⊙]     | 0.77 ± 0.05 |
| v sin i   | [km s⁻¹] | < 1 |
| log R_{H'K} |         | -4.99 |
| P_rot(log R_{H'K}) | [days] | ~ 48 |

### 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 [1997]. They are recalled in Table 1, together with inferred quantities like the absolute magnitude (M_V = 6.63) and the stellar physical characteristics derived from the HARPS spectra by Sousa et al. (2008). These authors provide for the complete high-precision HARPS sample (including HD 40307) homogeneous estimates for the effective temperature (T_eff = 4977 ± 59 K), metallicity ([Fe/H] = −0.31 ± 0.03), and surface gravity (log g = 4.47 ± 0.16) of the stars.

Very interestingly HD 40307 has a substellar metallicity with [Fe/H] = −0.31 unlike most of 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 hamper the formation of low-mass planets (Lin & Ida 2004). Mordasini et al. (2008) Taking into account its subsolar metallicity, Sousa et al. (2008) also derived for the star a mass of 0.77 M⊙. From the colour index, the derived effective temperature, and the corresponding bolometric correction, we estimated the star luminosity to be 0.23 L⊙.

HD 40307 is among the least active stars of our sample with an activity indicator log R_{H'K} of -4.99. No significant radial-velocity jitter is thus expected for the star. From the activity indicator we also derive a stellar rotation period P_rot = ~ 48 days (following Noyes et al. 1984).

### 4. The HD 40307 planetary system

#### 4.1. Radial velocity observations

HD 40307 has been measured with the HARPS spectrograph during 4.5 years. 135 measurements have been obtained. During the last 3 seasons (128 measurements, span of 878 days), we have adopted a measurement strategy aiming at minimizing the effect of stellar acoustic modes. Despite the bright-
ness of the star the integration time per epoch has always been set to 15 minutes. Over such an integration time, covering a few periods of the p-modes, the residual effect of these modes is estimated to be less than 20 cms\(^{-1}\). For most of the measurements, the photon noise after 15 minutes is typically of the order of 0.3 ms\(^{-1}\) (corresponding to S/N of the order of 150-200 at \(\lambda = 550\) nm, depending on seeing conditions). The mean uncertainty of the 128 velocities obtained during the last 3 seasons is 0.32 ms\(^{-1}\). As already mentioned, HD 40307 presents 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 but, due to the low level of calcium reemission, this effect is by comparison with other similar stars less than 1 ms\(^{-1}\). The observed raw rms for the 135 measurements spread over 1628 days is 2.94 m/s, much in excess of the above-mentioned different sources of noise.

End of 2006 we noticed that the observed radial-velocity variation could be explained by the effect of 3 low-mass planets. A first preliminary solution was already obtained. But 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 for these 3 planets, we preferred to postpone the final analysis and accumulate more measurements during the next 2 seasons. Extending by such amount the span and number of measurements has permitted to confirm and check the robustness of the preliminary solution.

Using the now available data, three peaks are clearly identified in the Fourier spectrum of the velocity measurements, they correspond to periods of 4.2, 9.6 and 20.5 days (Fig. 1). Fitting three Keplerians to the radial velocity measurements, we obtain a solution close to the one listed in Table 2, with periods corresponding to the 3 mentioned peaks. Note here that the conventional approach of iteratively determining the solution for the different planets one after the other is very difficult because of the short periods at play, moreover close to resonances. To find the final solution we rather followed a genetic-algorithm approach to blindly probe the complete parameter space.

In a first fit the orbital eccentricities were let free. The derived solution showed respectively non-significant eccentricities of 0.008 ± 0.065, 0.033 ± 0.052 and 0.037 ± 0.052 for the 3 planets. The residuals of the observed velocities around the best 3-planet solution is 0.94 ms\(^{-1}\). With circular orbits, the residuals stay unchanged as well as the other orbital parameters. The solution with 3 circular orbits is then the preferred one. Additionally, the residuals (O-C) also exhibit a well defined linear drift over the span of our measurements. The best

Fig. 1. Lomb-Scargle periodogram (top) of the 135 HARPS radial velocities of HD 40307. Clear peaks are found 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 of the effect of the 2 other planets and of the drift. Curves related to planets b,c and d are illustrated from top to bottom, respectively.
solution is finally obtained by fitting 3 Keplerian circular orbits plus a linear drift to our 128 better measurements. The phase distribution of the radial velocities for the 3 planets are shown on 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 with regards to 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. But we also have to consider the possibility of additional planets. Several potential additional signals are present in the Fourier spectrum. Although they are non-significant, we have nevertheless tried a blind search for 4 Keplersians plus a drift, without finding a convincing case for a fourth planet. Additional measurements are foreseen on the coming seasons to explore such a possibility and also to gain more insight on the companion responsible of 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 rather large number of measurements, all three amplitudes are rather precisely determined. The masses of these super-Earths are determined with a precision of the order of 6% or better.

The ratios of periods $P_2/P_1 = 2.23$ and $P_3/P_2 = 2.13$ are probably sufficiently distant to a rational value to exclude resonances.

5. Summary and discussion

We report 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. The high precision radial velocities acquired with the HARPS spectrograph on the ESO 3.6-m telescope enabled this discovery. The 3-Keplerian fit reveals the presence of 3 low-mass planets. The closest one 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, with masses of 6.9 and 9.2 $M_{\oplus}$ also belong to the category of super-Earths. All the 3 planets are on circular orbits. It is amazing to notice that the global rms of the 135 measurements, before fitting any planets, was only 2.94 ms$^{-1}$. The sigma(O-C) after the 3-planet Keplerian fit and drift is 0.85 ms$^{-1}$. We will continue the velocity monitoring to better characterize 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 $\mu$m region of the spectra (Augereau, private communication). No warm dust disk is thus detected in the inner regions of the system, unlike the case of HD 69830, the star harbouring a trio of Neptune planets (Lovis et al. 2006) and for which an observed IR excess indicates the presence of a debris disk, possibly under the form of an asteroid belt (Beichman et al. 2005).

The characterization of multi-planetary systems with very low-mass planets require a rather large number of measurements. After 4.5 years of the HARPS programme and with the improved reduction software, several dozens of planets with masses less than 30 Earth-masses and period less than 50 days have been detected. Coming observations will confirm these detections and allow us to fully characterize the systems. The domain of Neptune-type and rocky planets will be drastically boosted in a near future with these detections. In particular we expect to have enough systems to revisit the emerging properties for these low mass planets as tentatively discussed by Mayor & Udry (2008):

- is the mass-distribution of exoplanets bimodal?
- Is the correlation between host star metallicity and occurrence frequency of Neptune-type planets (or smaller) still existing?
- What is the frequency of multiplanetary systems with
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-2400000] | 54562.77 ± 0.08  | 54551.53 ± 0.15  | 54532.42 ± 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$^{-1}$]| 31.33 ± 0.11    |                  |                  |
| drift [m s$^{-1}$/yr]| 0.51 ± 0.10 |                  |                  |
| $f(m)$ [10$^{-12}$M$_{⊙}$]| 0.35       | 1.53             | 3.59             |
| $m_2\sin i$ [M$_{⊕}$]| 4.2         | 6.8              | 9.2              |
| $a$ [AU]        | 0.047            | 0.081            | 0.134            |
| $N_{meas}$      | 135              |                  |                  |
| Span [days]     |                  | 1628             |                  |
| $σ$ (O-C) [ms$^{-1}$]| 0.85        |                  |                  |
| $χ^2_{red}$     |                  |                  | 2.57             |

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 possibility offered by this large emerging population of low-mass planets with short orbital periods is the related high probability to have transiting super-Earths among the candidates. If detected and targeted for complementary observations, these transiting super-Earths would bring a tremendous contribution to the study of the expected diversity of the structure of low-mass planets.

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