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

XVII. Super-Earth and Neptune-mass planets in multiple planet systems HD 47 186 and HD 181 433

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ABSTRACT

We report on the detection of two new multiple planet systems orbiting solar-like stars HD 47 186 and HD 181 433. The first system contains a hot Neptune of 22.78 $M_\oplus$ with a 4.08-day period and a Saturn of 0.35 $M_{\rm JUP}$ with a 3.7-year period. The second system contains a Super-Earth of 7.5 $M_\oplus$ with a 9.4-day period, a 0.64 $M_{\rm JUP}$ with a 2.6-year period, and a third companion of 0.54 $M_{\rm JUP}$ with a period of about 6 years. These detections increase to 20 the number of close-in low-mass exoplanets (below 0.1 $M_{\rm JUP}$) and strengthen the fact that 80% of these planets are in multiple planetary systems.

Key words. stars: planetary systems – techniques: radial velocities – stars: individual: HD 47 186 – stars: individual: HD 181 433

1. Introduction

The HARPS spectrograph based on the 3.6-m ESO telescope at La Silla Observatory has been in operation since 2003. The HARPS consortium started 5 years ago as an ambitious and comprehensive Guaranteed Time Observations (GTO) program of high-precision systematic searches for exoplanets in the Southern sky (Mayor et al. 2003, 2009). Significant efforts were made to search for very low-mass planets. Our consortium have been assigned 50% of the GTO time on HARPS since 2003 to monitor about 200 nearby non-active stars. Due to a radial velocity accuracy of higher than 1 m s^{-1} (Pepe et al. 2004; Lovis et al. 2007), HARPS has discovered several Neptune-mass and Super-Earth exoplanets around solar-type stars (Santos et al. 2004; Udry et al. 2006; Lovis et al. 2006; Melo et al. 2008; Mayor et al. 2009) and M dwarfs (Bonfils et al. 2005; Udry et al. 2007a; Bonfils et al. 2007, Forveille et al. 2009). Such efficiency originates in the following factors: 1) a careful and frequent monitoring of instrumental performances; 2) a continuous improvement of the data reduction software (e.g. Lovis & Pepe 2007); 3) a dedicated and careful observing strategy to deal with stellar seismic noise (e.g. Bouchy et al. 2005); 4) a long-duration monitoring of non-active stars; and 5) an accumulation of measurements to identify multi-planetary systems. Our large program is now leading to an increasing list of close-in low-mass exoplanets, which will improve our knowledge of the planet distribution in the mass-period diagram and allow comparisons with theoretical predictions. Furthermore, this increasing number of close-in low-mass planets stimulates dedicated photometric follow-up to detect transiting Neptunes such as GJ436b (Gillon et al. 2007). Indeed we expect statistically that 5–10% of these close-in low-mass exoplanets offer the appropriate configuration for transiting their parent stars. In that case, a direct measurement of the planetary radius as well as the exact mass will be provided. In this paper, we present the discovery of two new multiple planet systems, including one hot Neptune and one Super-Earth orbiting the stars HD 47 186 and HD 181 433, respectively.

2. Parent-star characteristics of HD 47 186 and HD 181 433

The basic photometric and astrometric properties of HD 47 186 and HD 181 433 were taken from the Hipparcos catalogue (ESA 1997). Accurate spectroscopic stellar parameters of the HARPS GTO "high-precision" program were determined by Sousa et al. (2008) using high-quality, high-resolution, and high-S/N HARPS spectra. Stellar parameters for HD 47 186 and HD 181 433 are summarized in Table 1.

3. Radial-velocity data and orbital solutions

The observations were carried out using the HARPS spectrograph (3.6-m ESO telescope, La Silla, Chile). We derived 66 and 107 measurements for HD 47 186 and HD 181 433, respectively, spanning more than 4 years. The exposure time was fixed

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

⋆⋆ Tables of radial velocities are only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/496/527

Table 1. Stellar parameters of HD 47 186 and HD 181 433. The rotational period is derived from the activity index log R'_{HK}.

Parameters	HD 47 186	HD 181 433	Reference
Spectral type	G5V	K3IV	Hipparcos
Parallax [mas]	26.43	38.24	Hipparcos
Distance [pc]	37.84	26.15	Hipparcos
m_v	7.6	8.4	Hipparcos
$B-V$	0.71	1.01	Hipparcos
M_v	4.74	6.31	Hipparcos
Luminosity [$L_\odot$]	1.08 ± 0.029	0.308 ± 0.026	Sousa et al. (2008)
Mass [$M_\odot$]	0.99	0.78	Sousa et al. (2008)
$T_{\rm eff}$ [K]	5675 ± 21	4962 ± 134	Sousa et al. (2008)
log g	4.36 ± 0.04	4.37 ± 0.26	Sousa et al. (2008)
[Fe/H]	0.23 ± 0.02	0.33 ± 0.13	Sousa et al. (2008)
$v \sin i$ [km s^{-1}]	2.2	1.5	this paper
log R'_{HK}	–5.01	–5.11	this paper
$P_{\rm ROT}$ [days]	33	54	this paper

to 900 s to average out the stellar seismic noise. The spectra have typical S/N per pixel in the range 120–250 for HD 47186 and 80–160 for HD 181 433, reflecting the difference in magnitude. Radial velocities (available in electronic form at CDS) were obtained directly using the HARPS pipeline. Their uncertainties, including photon noise, wavelength-calibration uncertainty and spectrograph drift uncertainty, are in the range 0.3–0.6 m s^{-1} and 0.4–1.0 m s^{-1} for HD 47 186 and HD 181 433, respectively.

3.1. HD 47186

Radial velocity measurements of HD 47 186 as a function of Julian Date are shown in the top panel of Fig. 1. Analysis of these data reveals the presence of a clear and stable 4-day period signal in addition to a long-term modulation of 3.7-year period. The phase-folded curves of the two planets, with points representing the observed radial velocities, after removing the effect of the other planets are displayed in Fig. 1 (middle and bottom panels). The reduced χ^2 per degree of freedom is 2.25 and the residuals around the solution is 0.91 m s^{-1}. The derived orbital parameters imply a minimum mass of 22.8 $M_\oplus$ and a separation $a = 0.05$ AU for the close-in exoplanet, and a minimum mass of 0.35 $M_{\rm JUP}$ and a separation $a = 2.4$ AU for the second exoplanet. Orbital and physical parameters derived from the 2-planet Keplerian models are presented in Table 2. The close-in planet has an almost significant eccentricity (0.038 ± 0.020). If we define the eccentricity to be zero, all parameters remain the same, apart from the periastron epoch $T_{\rm peri} = 54566.261 \pm 0.028$. In that case, the reduced χ^2 is 2.28 and the residual about the solution is 0.94 m s^{-1}. Orbital parameters of the long-period planets may still be improved. Although more than 1 orbital period was covered, no measurements were completed in-between the phases –0.1 and 0.3, and we assume here that there is no long-term trend. Additional measurements should significantly improve the determination of the orbital parameters and place constraints on a possible third companion of longer period. We ensured that the bisector shape of the cross-correlation function (see Queloz et al. 2001) shows no variations down to the photon noise level, providing strong support to the planetary interpretation of the 2 RV signals.

3.2. HD 181 433

Our radial-velocity measurements as a function of Julian Date are shown in the top panel of Fig. 2. It first shows a clear signal at period 2.6 years plus an additional long-term trend. Analysis of the residuals reveals an additional signal at 9.4 days. We tested a linear, a quadratic and a Keplerian solution for the long-term trend. It does not affect the solution for the short-period planet but affects slightly the orbital parameters of the panet with period of 2.6 years. With a linear trend of 1.70 ± 0.26 m s^{-1}/year, the reduced χ^2 fit is 3.3 and the residual about the solution is 1.66 m s^{-1}. A quadratic trend with a slope of 2.98 ± 0.38 m s^{-1}/year and a curve of 1.30 ± 0.22 m s^{-1}/year^2

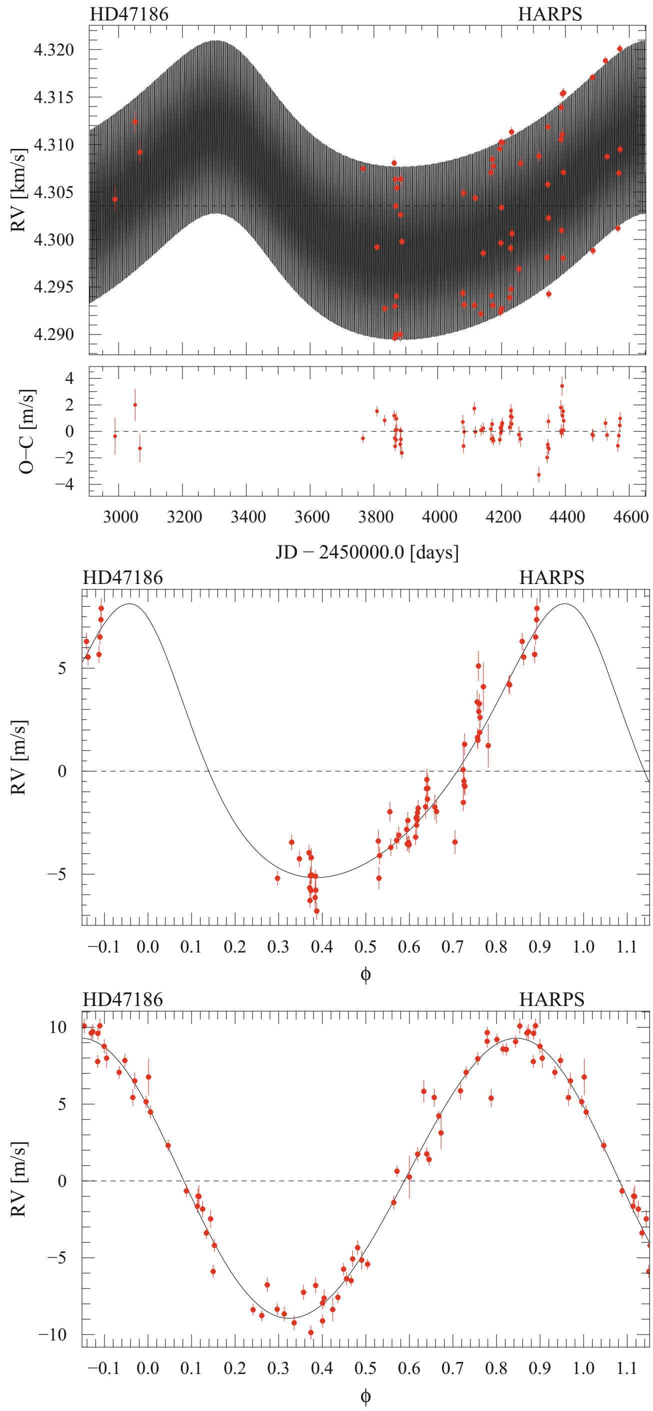

Fig. 1. 2-planet Keplerian model for the HD 47 186 radial-velocity variations. *The upper panel* display the RVs as a function of Julian Date. *The middle and bottom panels* display the phase-folded curve of the 3.7-year and the 4-day period planet respectively, with points representing the observed RVs, after removing the effect of the other planets.

Table 2. Orbital and physical parameters of the 2-planet system orbiting HD 47 186.

Parameters	HD 47 186b	HD 47 186c
P [days]	4.0845 ± 0.0002	1353.6 ± 57.1
$T_{\rm peri}$ [BJD-2400000]	54566.95 ± 0.36	52 010 ± 180
e	0.038 ± 0.020	0.249 ± 0.073
ω [deg]	59 ± 32	26 ± 23
V [km s^{-1}]	4.3035 ± 0.0014	
K [m s^{-1}]	9.12 ± 0.18	6.65 ± 1.43
msin i [$M_{\rm JUP}$]	0.07167	0.35061
msin i [$M_{\oplus}$]	22.78	111.42
a [AU]	0.050	2.395
$N_{\rm meas}$	66	
Data span [days]	1583	
σ (O – C) [m s^{-1}]	0.91	
$\chi^2_{\rm red}$	2.25	

improves the global solution and provides a reduced χ^2 fit of 2.4 and residual of 1.22 m s^{-1}. Finally, a Keplerian orbit with a period of about 6 years improves the global solution significantly and provides a reduced χ^2 of 1.3 and residuals of 1.06 m s^{-1}. The parameters of this long-period planet are not well constrained by our span coverage of 4.8 years. However, long-term observations of HD 181 433 completed with the spectrograph CORALIE over 9 years confirm this signal. The phase-folded curves of the three planets, with points representing the observed radial velocities, after removing the effect of the other planets, are displayed in Fig. 2. The derived orbital parameters correspond to a minimum mass of 7.5 $M_{\oplus}$ and a separation a = 0.08 AU for the close-in exoplanets, and a minimum mass of 0.64 $M_{\rm JUP}$ and a separation a = 1.76 AU for the second exoplanets. The derived parameters of the third exoplanet indicate a minimum mass of 0.54 $M_{\rm JUP}$ and a semi-major axis close to 3 AU. Additional CORALIE observations and dynamical analysis of this system will be presented in a forthcoming paper. Orbital and physical parameters derived from the 3-planet Keplerian models are presented in Table 3. We confirmed that the bisector shape of the CCF exhibits no variation and no correlation with any of the 3 RV signals. The significance of the detection of the 9.4-day planet was confirmed using a Monte Carlo approach in which the residuals of the two external planet fit were scrambled and then analyzed to determine the periodicity. Figure 3 represents the Lomb-Scargle periodiogram of these residuals. The 9.4-day signal is clearly evident above the false alarm probability limit.

4. Discussion and conclusion

Figure 4 presents data of the ~300 known exoplanets[1] in the mass-separation diagram. The triangles indicate exoplanets found by radial velocities, the dark triangles refer to transiting exoplanets, the circles are for exoplanets found by microlensing, and the bold triangles correspond to HARPS discovered exoplanets including 5 described in this paper and 3 detected orbiting HD 40 307 (Mayor et al. 2009). HARPS is completing an ongoing survey of close-in low-mass exoplanets with minimum mass below 0.1 $M_{\rm JUP}$. One expects that a few percent of these exoplanets exhibit the appropriate configuration to transit their parent stars. In that case, a direct measurement of the planetary radius as well as the exact mass will be done providing crutial information about and constraints on their composition. This was the case for the to-date unique transiting Neptune

[1] from The Extrasolar Planets Encyclopedia (http://exoplanet.eu) June 2008.

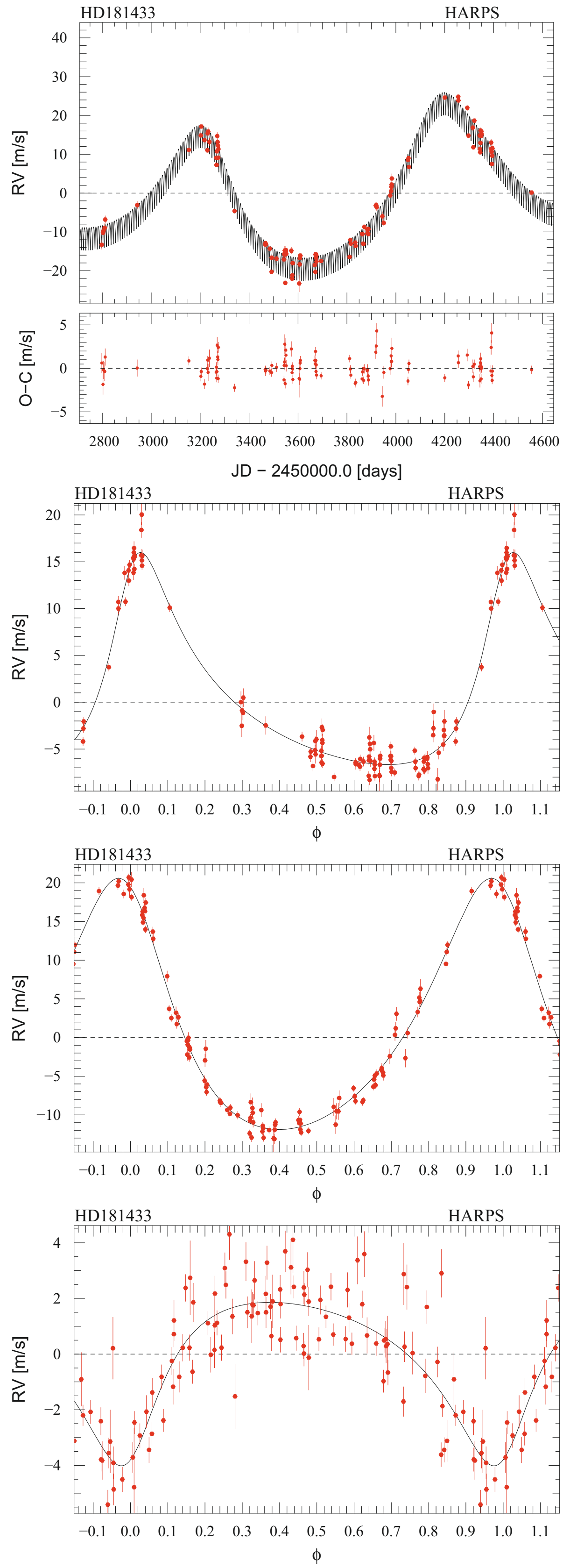

Fig. 2. 3-planet Keplerian model for the HD 181 433 radial-velocity variations. *The upper panel* displays the RVs as a function of Julian Date. The 3 *bottom panels* (*from top to bottom*) display the phase-folded curve of the 6-years, 2.6-years, and the 9.4-days period planets, respectively, with points representing the observed RVs, after removing the effect of the other planets.

Table 3. Orbital and physical parameters of the 3-planet system orbiting HD 181 433.

Parameters	HD 181 433b	HD 181 433c	HD 181 433d
P [days]	9.3743 ± 0.0019	962.0 ± 15	2172 ± 158
T_{peri} [BJD-2400000]	54 542.0 ± 0.26	53 235.0 ± 7.3	52 154 ± 194
e	0.396 ± 0.062	0.28 ± 0.02	0.48 ± 0.05
ω [deg]	202 ± 10	21.4 ± 3.2	–30 ± 13
V [km s^{-1}]		40.2125 ± 0.0004	
K [m s^{-1}]	2.94 ± 0.23	16.2 ± 0.4	11.3 ± 0.9
msin i [M_{JUP}]	0.024	0.64	0.54
msin i [$M_{\oplus}$]	7.5	203	171
a [AU]	0.080	1.76	3
N_{meas}		107	
Data span [days]		1757	
σ (O – C) [m s^{-1}]		1.06	
χ^2_{red}		1.29	

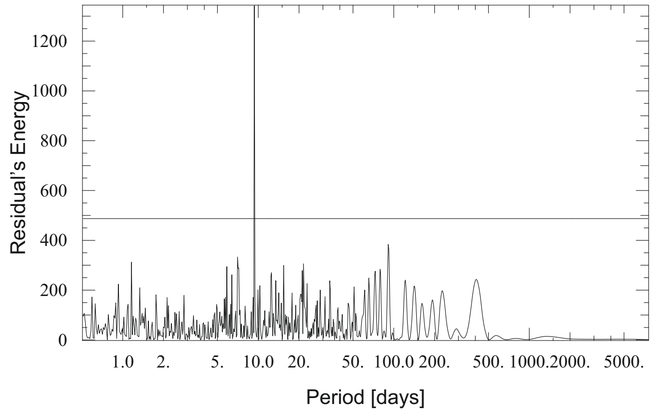

Fig. 3. Lomb-Scargle periodogram of the radial velocities of HD 181 433, after substraction of the two long-period signals. The horizontal line corresponds to a false alarm probability of 10^{-4}.

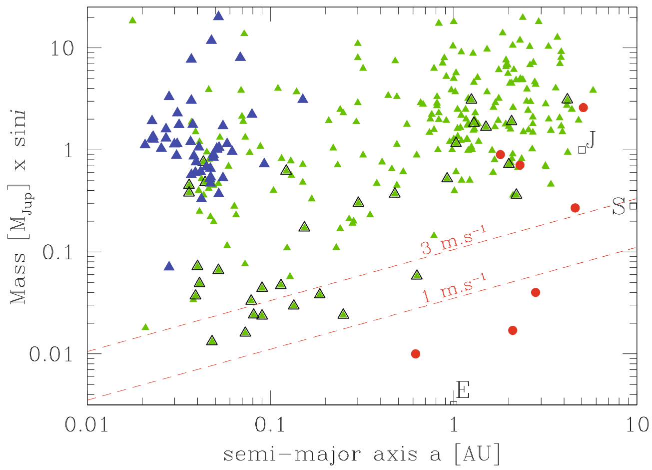

Fig. 4. Mass-separation diagram of the 300 known exoplanets. The triangles refer to exoplanets found by radial velocities. The dark triangles refer to transiting exoplanets. The circles refer to exoplanets found by microlensing. The bold triangles correspond to HARPS discovered exoplanets. Lines of radial-velocity semi-amplitude of 1 and 3 m s^{-1} have been added by assuming a 1 solar-mass star.

GJ436b (Gillon et al. 2007), which was first discovered by radial velocity (Butler et al. 2004). These close-in low-mass planets are expected to have radii of a few $R_{\oplus}$, which means a transit depth in the sub-millimagnitude regime. Although impossible to detect in ground-based photometric surveys, these small transiting exoplanets may be detected in specific high-precision ground-based photometric follow-up, especially in case of small stellar radius (K and M dwarves), or using spaced-based facilities. One advantage is that these planets orbit around nearby bright stars, which enables accurate characterization.

The two new planetary systems described here strengthen the fact that low-mass exoplanets are found in multiple planetary systems. Indeed, from the 20 known exoplanets of masses lower than 0.1 M_{JUP}, 16 are in a multiple planetary systems, hence 80%. This fraction should be compared to the 23% of the ~300 known exoplanets that are in multiple planetary systems. If we restrict our analysis to planetary periods shorter than 50 days, which correspond to the detectability period cutoff of low mass explanets, the conclusion remains that 19% of exoplanets and 72% of low mass explanets are in multiple systems. We note that of the 4 low-mass planets that have not been identified to date to be part of multiple planetary systems, 3 orbit a M-dwarf (GJ674b, GJ436b, and HD 285 968b).

It is interesting to discuss the discoveries presented in this paper from a theoretical point of view. In the planet population-synthesis calculations of Mordasini et al. (2008a) based on the core accretion scenario, a large number of hot-Neptunian and Super-Earth planets similar to those presented here, are predicted to exist at small distances from the host star. These low mass planets form a distinct sub-population of planets that have not experienced gas runaway accretion, in contrast to the sub-population of Hot Jupiters. In the predicted initial mass function (IMF) of the close-in planets, a local minimum is found between the two groups, occurring for solar type stars at a mass of about 30 $M_{\oplus}$. Figure 4 indicates that the high precision program of HARPS has started to explore this new sub-population of close-in, low-mass planets. One might even tentatively recognize in Fig. 4, a bimodal mass distribution of the "Hot" planets. The bimodal shape of the mass distribution from gaseous giant planets to the super-Earth regime was already pointed out by Mayor & Udry (2008), and bimodality is also evident in the mass distribution of detected planets with periods shorter than 50 days (see Fig. 5). Planetary formation simulations based on the core-accretion scenario, completed by Ida & Lin (2004a, 2008) also predict a bimodal distribution from gaseous giants to Super-Earth planets, and furthermore a paucity of extrasolar planets with masses in the range 10–100 $M_{\oplus}$.

Discoveries of Hot Neptunes and close-in Super-Earth planets raise questions about how exactly they were formed. In-situ formation seems unlikely for HD 47 186b. because in-situ formation allows the assembly of planets of only a few times the Earth mass even at the supersolar metallicity of about 0.2–0.3 dex of the stars considered here. HD 47 186b has in contrast a clearly larger, Neptunian-like mass and is located at a very small semi-major axis, where only tiny amounts of planetary building blocks are available, if any (due to evaporation of solids close to the star). For HD 181 433b, the planetary mass is only about a third, while the semi-major axis is longer, such that its mass is not out of reach of what might can form in-situ. For reasonable disk masses and profiles, it is unlikely that a such a massive Super-Earth planet can form at its current location. Therefore, some migration process appears to have been operating. Various processes can bring planets closer to the star: planet-disc interaction in the form of types I and II migration (e.g. Terquem & Papaloizou 2007), planet-planet interaction in the form of shepherding (e.g. Mandell et al. 2007), and

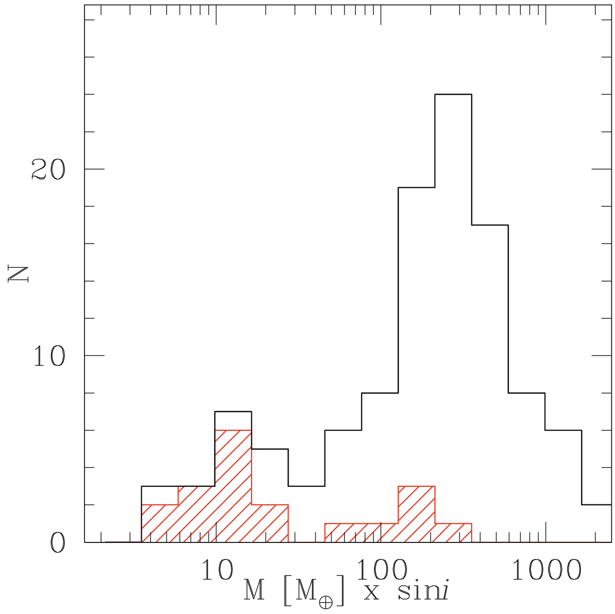

Fig. 5. Distribution of planetary masses from giant gaseous planets to the super-Earth regime for close-in planets ($P \le 50$ days). The hatched histogram represents HARPS detections.

scattering with subsequent circularization or the Kozai mechanism (e.g. Raymond et al. 2008; Zhou & Lin 2008).

It is interesting to discuss the discoveries in the context of the two competing giant-planet formation mechanisms. In the core-accretion mechanism, the formation of a system with both giant and low mass (Neptunian or Super-Earth) planets can be regarded as a natural outcome, which is not necessarily the case in the gravitational instability model. In particular, a planetary system architecture with low mass planets at smaller semi-major axes and one or several giant planets at larger distances is expected in the baseline core-accretion model without long-distance migration, as the increase of the available planetary building blocks with distance facilitates giant planet growth at larger distances, while the smaller amounts available at shorter distances should lead to the formation of low mass planets. This simple picture is reflected in both HD 47 186 and HD 181 433, even if the masses of the inner planets are large compared to those of the Solar System. We therefore regard these systems as cases where some, but not extreme migration of both the low mass planets and the giants occurred. This would indicate an initial disk mass higher than that of the Solar System, but less massive than one leading to the formation of Hot Jupiters.

Population synthesis calculations based on the core-accretion paradigm reproduce the "metallicity effect" (Ida & Lin 2004b) i.e. the strong positive correlation between the stellar metallicity and the planetary detection probability. Discoveries mainly by HARPS have shown that this "metallicity effect" might not exist for close-in low mass planets, even though the data set is currently too small for definitive conclusions (Udry & Santos 2007b). However, the multiple planetary systems such as HD 47 186 and HD 181 433 with both a giant and a low mass planet (55 Cnc, Gl876, HD 160 691, HD 190 360, HD 219 828) all have supersolar metallicities. In the core-accretion scenario, this is understood in the following way: high [Fe/H] stars (disks) are able to produce both giant and low mass planets, while low [Fe/H] systems are able to produce low mass planets only. More discoveries of low mass planets will help clarify the nature of these correlations.

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