Exoplanets: The Road to Earth Twins

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Abstract Recent HARPS discoveries have demonstrated that very quiet stars exist, with intrinsic radial-velocity variations below 1 $\mathrm{m\,s^{-1}}$. These results allow us in particular to characterize an emerging new population of very light planets down to a few Earth masses, as for example the components of a new 3-planet system, with masses between 3.6 and 8 $M_\oplus$. Neptune-mass planets seem to be numerous. Their properties are especially important to constrain planet-formation models. Our HARPS experience also allows us to discuss the limitations of the radial-velocity method and the associated optimistic perspectives for the future detection of Earth-like planets in the Habitable Zone of solar-type stars, especially in the context of the foreseen development of ultra-stable spectrographs for the VLT (ESPRESSO) or the E-ELT (CODEX).

1 A Decade of Giant Planet Detections

The discovery 13 years ago of an extra-solar planet orbiting the solar-type star 51 Peg [8] has encouraged the launch of numerous new search programs, leading now to a steadily increasing number of exoplanet detections. More than 270 other planetary companions have been found to orbit dwarfs of spectral types from F to M and more massive evolved stars. From this sample, we have learned that giant planets are common and that the planetary formation process may produce an unexpectedly large variety of configurations covering a wide range of planetary masses, orbital shapes, and planet-star separations (see e.g. [18]).

The very large majority of the exoplanets have been found through the induced Doppler spectroscopic variations of the primary star (the so-called *radial-velocity (RV) technique*). Most of the candidates are giant gaseous planets similar in nature to Jupiter. With the development of a new generation of very stable spectrographs led by the HARPS spectrograph on the ESO 3.6-m telescope at La Silla, the past few years have known a new step forward in planet discoveries with the detections of lighter (5–20 $M_\oplus$), mainly "solid" planets (Table 1).

The interest for very low mass planets (Neptune masses or super-Earths) follow several motivations: (i) the statistical properties of planetary systems provide constraints to the complex physical scenarios of planet formation, (ii) simulations of planetary formation also furnish information on the planet internal structure closely

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Table 1 Known very low mass planets ($m_2 \sin i < 23$ $M_\oplus$). N_{pl} is the number of planets in the system. O–C are the velocity residuals around the orbital solutions

Planet	P (d)	$m_2 \sin i$ ($M_\oplus$)	K m/s	O–C m/s	N_{pl}	Instr.	Ref.
μ Ara	c 9.64	10.5	3.1	1.4	4	HARPS	[12, 15]
55 Cnc	e 2.81	14.2	6.7	5.4	5	HET	[9]
GJ 436	b 2.64	22.6	18.	5.3	2?	HIRES	[4]
HD 190360	c 17.1	18.1	4.6	3.5	2	HIRES	[19]
GJ 876	d 1.94	5.9	6.3	4.6	3	HIRES	[14]
HD 4308	b 15.6	14.1	4.1	1.3	1	HARPS	[16]
HD 69830	b 8.67	10.2	3.5	0.6	3	HARPS	[6]
	c 31.6	11.8	2.7	0.6	3	HARPS	[6]
	d 197.	18.1	2.2	0.2	3	HARPS	[6]
GJ 581	b 5.4	15.7	12.5	1.2	3	HARPS	[2]
	c 12.9	5.1	3.0	1.2	3	HARPS	[17]
	d 84.0	8.2	2.5	1.2	3	HARPS	[17]
HD 219828	b 3.83	19.8	7.0	1.7	2	HARPS	[10]
GJ 674	b 4.69	11.0	8.7	0.8	1	HARPS	[3]
New HARPS	b 4.31	3.6	1.8	1.2	3	HARPS	Mayor et al., in prep.
	c 9.63	7.0	2.65	1.2	3	HARPS	Mayor et al., in prep.
	d 20.5	8.0	2.3	1.2	3	HARPS	Mayor et al., in prep.

linked to the planet radius, and (iii) in a more distant future, space missions as DARWIN (ESA) or TPF (NASA) will search for life on terrestrial-type planets. Before the detailed design of such ambitious missions, we need a first insight on the frequency of terrestrial planets, and on the properties of their orbits. Planets in the Habitable Zone of our closest neighbors will be especially valuable.

Here, we will concentrate on the mass distribution of exoplanets focusing mainly on its lowest-mass end, and on the prerequisites to the detection of Earth-type planets, in term of RV precision required improvements.

2 Planetary Mass Distribution

The distribution of known planet masses is illustrated on Fig. 1 (left). The low-mass edge of the distribution is poorly defined because of observational incompleteness (smaller RV variations for the lower mass planets). However, in this planet-mass distribution, low-mass planets already start to draw a new population at very low masses. The emerging bimodal aspect of the distribution strongly suggests that the decrease of the distribution for masses less than about one mass of Jupiter is not only the result of the detection bias but should be real, and provides an interesting

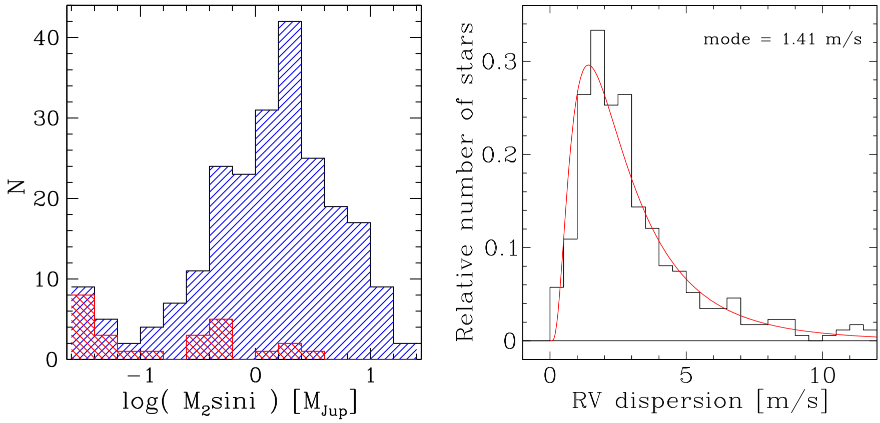

Fig. 1 *Left*. Planetary mass distribution from giant planets to super-Earths. The *double-hatched histogram* represents HARPS detections. *Right*. Histogram of RV rms for stars in the high-precision HARPS subprogram. Part of the "higher"-rms tail results from stellar activity or from still undetected planetary systems. A colour version of this figure is available at dx.doi.org/10.1007/978-1-4020-9190-2_26

constraint for planetary formation scenarios. Because of their small masses and central locations in the systems, these low mass planets are probably mainly composed of rocky/icy material.

The discovery of very low mass planets close to the detection threshold of RV surveys, over a short period of time, suggests that this kind of objects are rather common. Moreover, at larger separations (2–3 AU), the microlensing technique is finding similar mass objects (the lightest with a mass of 5.5 $M_\oplus$, [1]) showing that smaller mass planets can be found over a large range of separations. This is in complete agreement with the latest Monte Carlo simulations of planet formation, that furthermore predict a large population of still lighter Earth-like planets [11].

3 HARPS High-Precision Program

The global histogram of the observed RV dispersions for the stars in the HARPS high-precision GTO program (G- and K-dwarf targets) presents a mode at 1.4 $\mathrm{m\,s^{-1}}$ (Fig. 1, right). The velocities have been obtained over several seasons from 2003 to 2007. Part of the observed rms in the tail of the distribution, at the level of 2 to 3 $\mathrm{m\,s^{-1}}$, can be explained by stars with still some chromospheric activity. Also, several multi-planetary systems have been detected with a global RV rms at the level of 3–4 $\mathrm{m\,s^{-1}}$ (before fitting the orbital solution).

A good example of the latter case is provided by the "Trio of Neptunes" (HD 69830; [6]). The rough 4 $\mathrm{m\,s^{-1}}$ rms of the observed velocities drop to residuals of 0.6 $\mathrm{m\,s^{-1}}$ around the 3-planet Keplerian solution, and even down to 0.2 $\mathrm{m\,s^{-1}}$ around the 6-months 3rd planet (removing the contributions of the 2 shorter-period

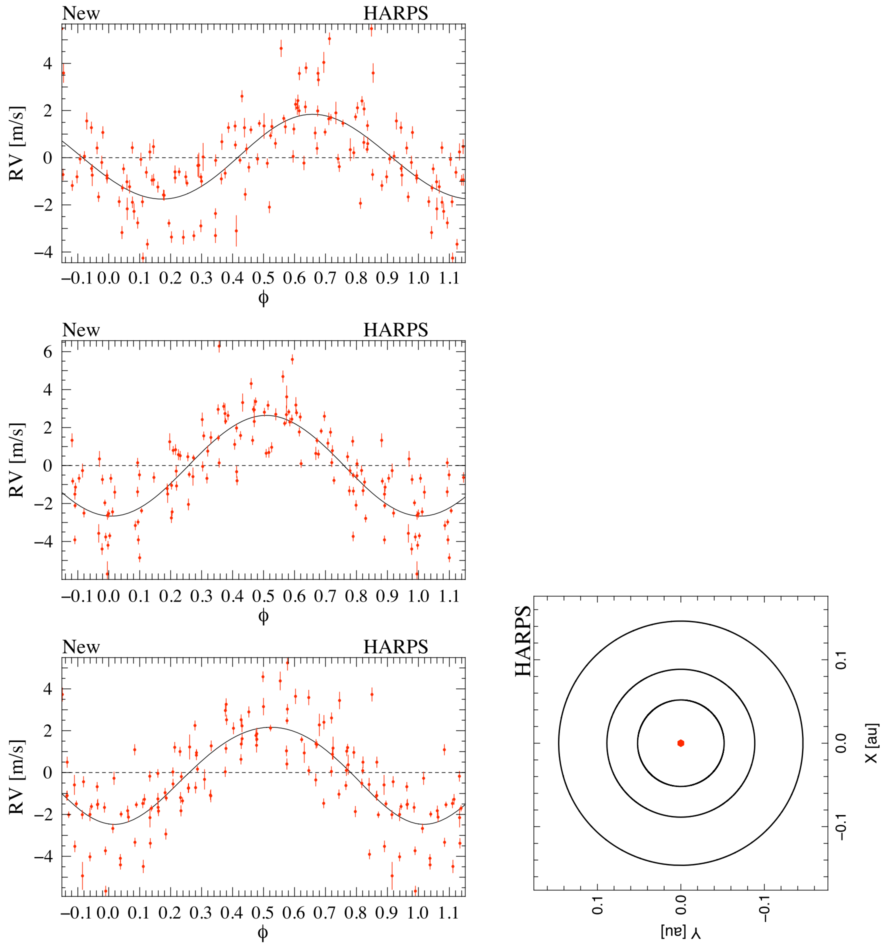

Fig. 2 Phase-folded orbital solutions (*left*) and top view (*right*) of the 3 planets orbiting the next HARPS planetary system to be announced (Mayor et al., in prep.; Table 1). Planet masses are between 3.6 and 8 $M_{\oplus}$. A colour version of this figure is available at dx.doi.org/10.1007/978-1-4020-9190-2_26

planets and considering run-averaged velocities). For the global HARPS high-precision sample, we can thus reasonably suspect that part of the observed RV scatter is really the result of undetected, low-amplitude, multi-planetary systems. Actually, a close analysis of these data provides hints for the existence of many more very low-mass planetary candidates. Among them, an exciting 3-planet system to be published soon, with masses between 3.6 and 8 $M_{\oplus}$, is presented for illustration in Fig. 2 (orbital parameters are given in Table 1).

4 Limitations for Precise Radial-Velocity Measurements

The planetary mass estimated from the Doppler measurements is directly proportional to the amplitude of the reflex motion of the primary star. The measure of very precise RVs requires that all steps along the light path, from the star to the detector, are well understood. The main aspects are discussed e.g. in [13], we just recall here a few important points.

Assuming that the target spectrum is not contaminated by external sources (e.g. stellar neighbors), the interstellar medium, or the Earth atmosphere, the main limitations are basically divided in 3 categories:

(1) **The stellar noise** groups error sources which are produced at the *emission* of the light, i.e. by the observed source itself: stellar pulsations, surface granulation and activity-related jitter. The cross-correlation technique is so efficient that, for most of the stars in the HARPS high-precision sample, the photon noise is at the level of 0.5 $\mathrm{m\,s^{-1}}$ after an exposure time smaller than the typical periods of stellar acoustic modes. Long integrations (15 minutes) are sufficient to damp these RV variations below 0.2 $\mathrm{m\,s^{-1}}$ (rms). At longer variation time scales, Kjeldsen et al. [5] suggest that granulation can induce RV variability larger than (or comparable to) 1 $\mathrm{m\,s^{-1}}$ for solar-type stars. To damp the granulation noise several measurements spanning a few hours could be required. Test observations with HARPS are ongoing to better characterize this point. Finally, any anisotropies of the stellar atmosphere will also induce RV variations with time scales comparable to the stellar rotation period. The amplitude of this RV *jitter* is correlated with stellar chromospheric activity. The reemission in the core of the calcium lines is an efficient indicator to select a sample of “non-active” stars.

(2) **Instrumental errors** are those related to the detection process. They include the whole light path starting at the telescope and ending on the detector. Among these instrumental effects we can distinguish two main contributions: errors affecting the measurements (stability or repeatability) supposing a perfect wavelength reference, and calibration errors (i.e. errors on the wavelength scale). Lovis and Pepe [7] have considerably improved the precision of the wavelength of thorium lines as well as the number of lines to be used for the calibration of the spectrograph. The performances demonstrated by HARPS have excited the imagination of astronomers. New ultra-stable spectrographs are now studied for large telescopes, with the aim of reaching long-term RV precisions down to 10 $\mathrm{cm\,s^{-1}}$ (ESPRESSO/VLT; Pasquini et al., this volume) or even at the level of a few $\mathrm{cm\,s^{-1}}$ (CODEX/E-ELT).

(3) **Photon noise** finally sets the fundamental limit for the attainable precision as the latter scales with the signal-to-noise of the spectra. To get to ultra-high precisions, a huge number of photons is needed. HARPS@3.6-m ESO telescope belongs to the most efficient RV spectrographs; it reaches a precision of about 1 $\mathrm{m\,s^{-1}}$ in less than one minute, on a late G dwarf of $m_v = 7.5$. Reaching 1 $\mathrm{cm^{-1}}$ would then require an exposure time of 10′000 minutes. This makes evident that larger telescopes are urgently needed. To achieve a 10 $\mathrm{cm^{-1}}$ precision on a $m_v = 8$ star, a 10-m class telescope is required. The situation becomes even more dramatic if we consider that typical transit candidates delivered by space-based surveys (COROT, Kepler), carry

magnitudes typically above $m_v = 12$. If 10 cm^{-1} precision had to be achieved in a single exposure, a 50-m telescope would then be ideally needed.

It is quite difficult to correctly estimate the real amplitude of the different sources of noise intrinsic to the star or due to the instrument. The final precision will depend on which of these factors actually dominates the error budget. However, we can set an upper limit for the quadratic sum of these noises (for non-active stars) at less than 1 $\mathrm{m\,s^{-1}}$. This limit is estimated from the O–C around the orbital solutions of planets detected with HARPS (Table 1) or from the lowest RV dispersion of HARPS measurements (Fig. 1, right).

5 Searching for Earth-Type Planets in the Habitable Zone

Is it possible to detect terrestrial planets in the Habitable Zone (HZ) of neighboring stars? For planets orbiting M dwarfs this is already feasible. The detection of two low mass planets (5.1 $M_{\oplus}$ and 8 $M_{\oplus}$) at both edges of the HZ of the M4V star GJ 581 [17] is a good example of that possibility.

For Earth-type planets orbiting solar-type stars, the situation is obviously more challenging. About an order of magnitude in the precision of the measured RVs has to be gained. We have seen that perspectives for such an improvement are good. In particular, the ESPRESSO@VLT project presently studied to be implemented at the incoherent combined focus of the VLT's, and later CODEX@E-ELT, will provide the required efficient and ultra-stable instrumentation to reach this challenging goal.

The unambiguous identification of the signature of an Earth-like planet from Doppler measurements will require a large number of observations (to beat activity-related effects), and the set up of an adequate observing strategy (to diminish the influence of acoustic modes and granulation). A search for Earth-like planets around a sample of a couple of tens of stars will then be possible but will be expensive in term of telescope time.

6 Concluding Remarks

The future detection of very low mass planets and possibly Earth twins requires precision at the cm^{-1}-level. Opposite to what was thought 3 to 6 years ago, HARPS has been able to demonstrate that sub-$\mathrm{m\,s^{-1}}$ precision can be reached. Although stellar noise may be one of the limiting factors, there seem to be many stars that allow us to reach even 20 to 30 cm^{-1} rms on short-term. How quiet the most stable stars are, and over which time scales, needs to be investigated in more detail. On the instrumental side, many progresses have been made. In particular, from the HARPS experience, we have not identified any show stopper until date, and we think that a final precision of better than 5–10 cm^{-1} on the most stable stars is within reach. The development of extremely stable spectrographs on large telescopes will provide us with high instrumental precision and high efficiency. Despite the different

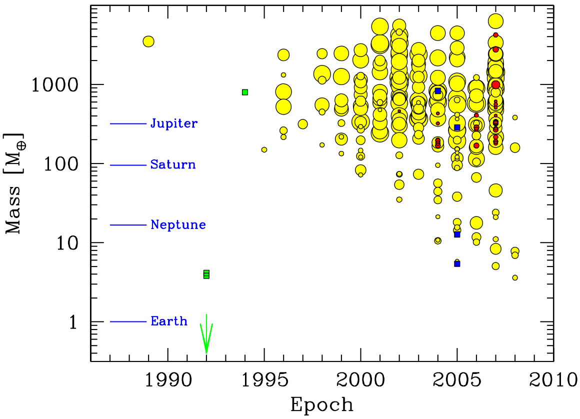

Fig. 3 Masses of detected exoplanets as a function of the year of discovery. The planets orbiting a neutron star (1992) or detected by microlensing (∼ 2005) are represented by *squares*, transiting planets and the most numerous exoplanets discovered by Doppler spectroscopy by *circles* having radii proportional to their orbital eccentricities. The lower envelope illustrates the continuous progresses of the spectrograph sensitivity. Since a few years we have entered the era of super-Earth detections, rushing towards Earth masses. A colour version of this figure is available at dx.doi.org/10.1007/978-1-4020-9190-2_26

sources of noise, we are confident that Doppler spectroscopy will be able to detect rocky planets in the Habitable Zone of solar-type stars well before the launch of DARWIN- or TPF-type space satellites, and thus provide the prerequisite targets for these enthusiastic missions.

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