On the track of very low-mass planets with HARPS

In only one and a half years of operation HARPS has discovered eight new extra-solar planet candidates. Many more discoveries are expected with the increase of the duration of the survey. What makes HARPS unique compared with other instruments is its unprecedented precision and its ability to discover planets with very low mass. In fact, all the planets discovered with HARPS lie in the low-mass tail of the planetary companion mass distribution. This distribution, which is known to be highly sensitive in its low mass end to the detection threshold, can be explored with HARPS in a comprehensive way. The exploration of the very low-mass end of giant planets may bring new constraints on planet formation and evolution scenarios.

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HARPS, the High-Accuracy Radial-velocity Planet Searcher on the 3.6-m ESO telescope, became operational in October 2003. Since then, the HARPS Consortium has been carrying out a comprehensive planet-search programme on the assigned Guarantee Time Observations (GTO). The first results, which were obtained during the first GTO period and published in early 2004 (Pepe et al., 2004), announced the discovery of a Saturn-mass planet with an orbital period of seven days around the star HD 330075. Besides unveiling a new extra-solar planet, these measurements clearly demonstrated the detection efficiency and the amazing radial-velocity precision of this instrument (see The Messenger Nr. 114, 2003, page 20, for a full description): First, asteroseismology observations measured a short-time precision (during the night) of about 20 cms^{-1}. Indeed the stellar p-mode oscillations were clearly and directly identified in the time series of observations of a few stars. Second, the low residuals around the orbital solution of the discovered planet showed that the radial-velocity accuracy over several months was better than 2 ms^{-1}. This achievement is even more compelling considering that the instrument suffered several modifications during the first months of its life.

Intense sequences carried out during asteroseismology observations also made it clear that HARPS' capability for planet search was not limited by its performance but rather by the star itself. Indeed, stellar p-mode oscillations on a short-time scale and stellar jitter on a long-time scale introduce extra radial-velocity noise that cannot be neglected at the accuracy level of HARPS. For instance, even a very "quiet" G or K dwarf shows oscillation modes of several 10 cms^{-1} which might add up to radial-velocity amplitudes as large as several ms^{-1}. Moreover, any exposure with integration time shorter than the oscillation period of the star might fall arbitrarily on any phase of the pulsation cycle leading to additional radial-velocity noise. This phenomenon may seriously compromise our ability of detecting very low-mass planets around solar-type stars by radial-velocity measurements.

In June 2004 a European group of astronomers (see ESO Press Release 22/04) proved that p-mode radial velocity variability was not an issue for detecting planets. During asteroseismology measurement campaigns on the star μ Ara they measured its p-oscillation modes, but in addition, they also observed an unexpected coherent night-to-night variation of very small semi-amplitude of 4.1 ms^{-1} that was later confirmed to be the signature of a planetary companion of $m_2 \sin i$ = 14 $M_\oplus$ with an orbital period of P = 9.5 days. This discovery demonstrated that oscillation noise could be averaged out sufficiently to unveil a small radial velocity signature of a Neptune-mass planet companion.

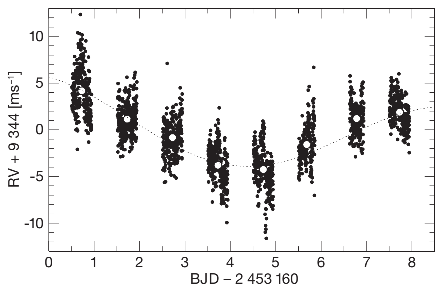

Figure 1: Asteroseismology observations of μ Ara. Although the dispersion of the radial velocity caused by stellar oscillations can be 10 ms^{-1}, one easily sees the "low-frequency" variation induced by the planetary companion on the daily radial-velocity average.

Since the discovery of the very low-mass companion of μ Ara, other very low-mass candidates have been discovered (Butler et al. 2004, McArthur et al. 2004) . These planetary companions start to populate the lower end of the secondary-mass distribution, a region so far affected by detection incompleteness (see Figure 2).

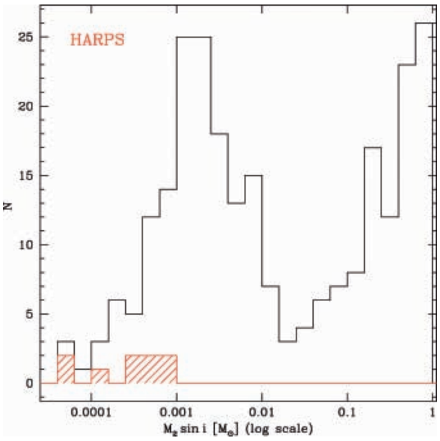

Figure 2: Mass distribution of companions to solar-type stars from 1 $M_\odot$ down to the mass of Neptune (< 5 10^{-5} $M_\odot$). The right-hand slope represents the tail of the stellar companion distribution. The left-hand peak shows the planetary companions. In between, the brown-dwarf "desert" appears clearly. The very high-precision HARPS GTO survey is devoted to explore the shape of that mass function from 1 M_{Jup} (0.001 $M_\odot$) down to the mass of Uranus and Neptune. Note that all newly detected HARPS planets clearly lie in this low-mass range. HARPS is one of the most sensitive and efficient instruments to explore this domain of the mass distribution. It will provide many new inputs for the formation and evolution theories of exoplanets.

The discovery of these very low-mass planets close to the detection threshold of radial-velocity surveys for a limited sample of stars suggests that this kind of object may be rather frequent. But already the simple existence of such planets may produce headaches for the theoretician. Indeed, statistical considerations predict that a planet with a mass between 1 and 0.1 M_{Sat} and with semi-major axis of 0.1 to 1 AU must be rare (Ida and Lin, 2004). At least for the moment, the recent discoveries contradict these predictions. In any case, the continuous detection of planets with increasingly lower mass will set new constraints to possible planetary-system formation and evolution models.

Constraining formation and evolution scenarios

Low-mass giant planets, i.e. planets with a mass in the range 10–100 $M_\oplus$ are of particular importance in order to constrain formation and evolution models. Indeed, and perhaps contrary to intuition, the presence of a large number of planets within this mass range would not be expected by any of the current theoretical formation models. However, because all the currently known low-mass planets are located close to their star, one cannot exclude that these objects were much more massive in the past and lost a significant amount of their mass through evaporation during their lifetime (see for example Baraffe et al. 2004). The situation is therefore a complex one in which formation and subsequent evolution over the system's entire lifetime has to be considered. In what follows we venture into some speculations regarding possible evolutionary scenarios leading to μ Ara type objects.

In the direct collapse scenario planets form through gravitational collapse of patches of the protoplanetary disc (Boss 2002). High-resolution simulations of this process show that planets tend to form on elliptical orbits with semi-major axis of several astronomical units and masses between 1 and 7 M_{Jup}. Even if such a planet would subsequently migrate inwards to 0.1 AU, evaporation will not be able to reduce its mass to the one inferred for μ Ara. After all, several planets of the order of a Jupiter mass are observed to exist at these distances in orbit around similar stars.

In the core accretion scenario (Pollack et al 1996; Alibert et al. 2005), forming planets in this mass range is not trivial either. The main reason is that in the standard scenario once the core mass has reached a critical value, the accretion of the gaseous envelope proceeds in a runaway fashion. Since this critical mass is of order 10–15 $M_\oplus$, planets are expected to form either less or significantly more massive than this value. Ida & Lin (2004) have argued that this mass range should be severely depleted (a planetary desert). If correct, the relatively numerous small-mass objects discovered so far start to pose a real problem. While mass loss from initially more massive objects could possibly account for the planets very close to their star (Baraffe et al. 2004), it is not clear whether μ Ara located at a distance of close to 0.1 AU could actually result from the evaporation of a more massive object.

If this were not, or only partially, the case, the existence of the planetary desert or at least its depth must be questioned. In Ida & Lin (2004), the growth rate of a planet is given by the Kelvin-Helmholtz time which becomes increasingly shorter with increasing mass. On the other hand, in Alibert et al. (2005), the gas accretion rate is actually limited by the disc once the planet has opened a gap (Veras & Armitage 2004). Monte Carlo models are being computed in order to check whether this more realistic approach changes the extent and/or the depth of the planetary desert. From an observational point of view a larger sample especially of objects for which evaporation clearly cannot play a role, i.e. far enough away from the star, would be of paramount importance to constrain these issues.

Finally, given their close location to their star, these small-mass planets are likely to have migrated to their current position from further out in the nebula. The chemical composition of these planets will depend upon the extent of their migration and the thermal history of the nebula and hence the composition of the planetesimals along the accretion path of the planet. The situation is made more complicated by the fact that the ice-line itself is moving as the nebula evolves (see for example Sasselov & Lecar 2000). Detailed models of planetary formation including these effects have yet to be developed.

More Neptune-mass planets to come

The semi-amplitude of the radial-velocity wobble of μ Ara-like objects is hardly larger than typical stellar p-mode oscillations. The discovery of Neptune-mass planets may only be feasible by applying an adequate observational strategy that includes an increase of the integration time beyond the typical period of stellar oscillations, i.e. more than 5 minutes, in order to average them out. In practice, the integration time is fixed to 15 minutes independently from the star magnitude, provided that the detector is not saturated. An example of the effect of this strategy is presented in Figure 3, which shows the low residuals of 0.9 ms^{-1} obtained on the radial-velocity curve of the planet-harbouring star HD 102117 (Lovis et al. 2005).

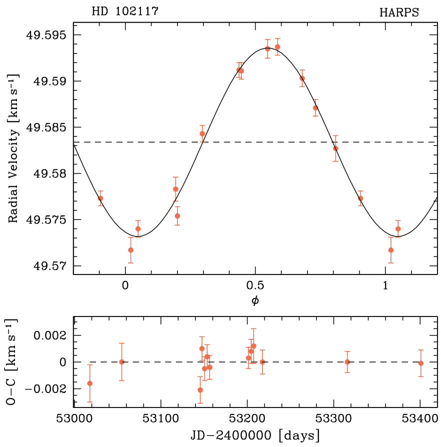

Figure 3: Measured radial velocity of HD 102117 in phase with the orbital period of the planet. The fitted orbital solution is shown as well. The residuals of the data points to this solution are only 0.9 ms^{-1} rms. This value includes photon noise and remaining "stellar noise".

We conduct this strategy on a set of 200 selected stars of the HARPS GTO survey. For this very high-precision survey an accuracy better than 1 ms^{-1} is sought for each individual measurement. So far the results obtained demonstrate that this strategy is successful. The histogram of the radial-velocity dispersion peaks at 2 ms^{-1} and decreases rapidly towards higher values. More than 80 % of these stars show dispersion smaller than 6 ms^{-1}, and more than 30 % have dispersions below 2 ms^{-1}. It must be noted that the dispersion value includes photon noise, stellar oscillations and jitter, and, in particular, it is "polluted" by known extrasolar planets (μ Ara, HD 102117, etc.) or still undetected planetary companions.

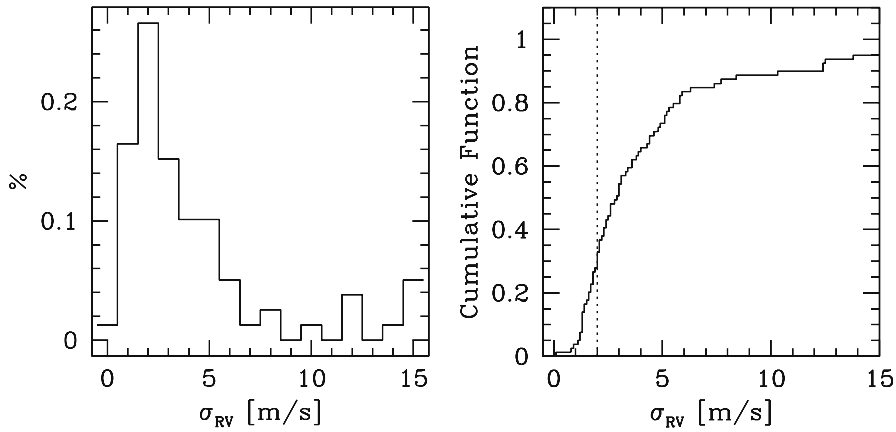

Figure 4: **Left:** Histogram of the radial-velocity scatter for all targets belonging to the very high-precision HARPS planet survey. **Right:** Cumulative distribution of the radial-velocity scatter. The distribution peaks at 2 m/s and is mainly dominated by stellar oscillations and jitter. We must point out here that μ Ara (corrected for the drift due to μ Ara b) and HD 102117, are part of this distribution, and that the orbital motions of their planets alone induce a radial-velocity scatter of 2.5 ms^{-1} and 6 ms^{-1} rms, respectively!

Where is the limit?

The threshold of the lowest-mass planet detectable by radial-velocity survey keeps decreasing. Today with the current achieved precision of about 1 ms^{-1} a Neptune mass planet can be discovered. Nobody has yet explored in detail the domain below the 1 ms^{-1} level. The measurements on μ Ara have demonstrated that it is possible to beat the stellar pulsation noise by investing sufficient observing time. One open issue however remains unsolved: the behaviour of the stars on a longer time scale, where stellar jitter and spots may impact the final achievable accuracy. In this case, an accurate pre-selection of the stars may help focusing on "good" candidates and optimizing the observation time. In addition, bisector analysis and follow-up of activity indicators such as log R'_{HK}, as well as photometric measurements would allow the identification of potential error sources.

Nevertheless, the discovery of an extra-solar planet by means of the Doppler technique requires that the radial-velocity signal induced by the planet is significantly higher than the dispersion, or requires alternatively a large number of data points. This is particularly important to rule out artefacts, given the relatively high number of free parameters in the orbital solution and more specifically for multi-planet systems. A large number of measurements could overcome this problem, but would demand an enormous investment of observing time.

The transit survey may provide another interesting route towards the characterisation of the very low-mass planets. If one considers a transit signal with known orbital period it is obvious that measuring its mass is less demanding both on the number and the accuracy of the radial-velocity measurements. For example a 2 $M_{\oplus}$-planet on a 4-day orbit would produce a radial-velocity amplitude of about 80 cms^{-1}. Given the present precision of HARPS which is estimated to about 60 cms^{-1} it may be possible to detect and measure the amplitude of the radial-velocity wobble with just a few radial-velocity measurements if we knew the period of the system.

The CNES-ESA satellite COROT to be launched in late 2006 will conduct a transit search survey in selected fields. It may detect Neptune-sized transiting planet candidates with orbits similar to μ Ara c. The radial-velocity follow-ups of the COROT planetary candidates is within reach of the capabilities of HARPS. It may deliver the precise mass of these objects. When this information is combined with the transit observation parameters one may obtain the mass-radius relation of planets in the domain of Neptune masses. This combined approach is currently carried out for OGLE planetary candidates of about the mass and the size of Jupiter and we refer the reader to the article of Pont et al. in this issue of The Messenger (page 19) for more details. In the COROT context the most exciting aspect is its capability to explore the domain of Neptune-mass planets with short period where one may expect some overlap between rocky planets and giant planets.

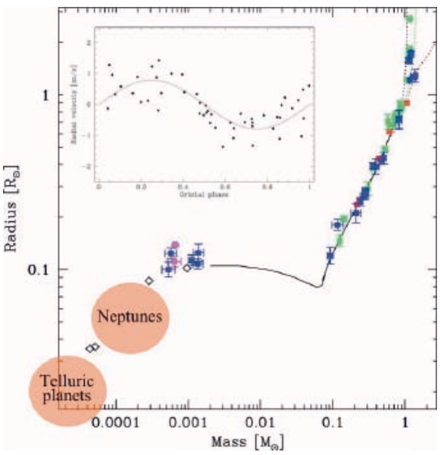

Figure 5: The mass-radius diagram from stars to planets. The low-mass end of the diagram can be investigated by the combination of precise transit search and radial-velocity measurements. With COROT and HARPS the Neptune-mass domain will already be accessible. The inserted diagram on the top left shows a simulation of the radial-velocity variation caused by a two-Earth-mass planet on a 4-day orbit around a solar-type star. With the HARPS precision of about 60 cms^{-1} only 50 measurements are needed to determine the planet mass with an accuracy of 10 %.

The future is still bright for radial velocities

HARPS has demonstrated that radial-velocity measurements with an accuracy better than 1 ms^{-1} can be achieved. This performance makes possible an ambitious and exciting planet search programme. The HARPS GTO Planet Search Programme has led so far to the discovery of eight new low-mass planets. We can easily speculate that many more are likely to be detected in the future to further populate the very low-mass end of the giant planet mass distribution. New inputs on the theory of planetary formation are expected from these discoveries. Follow-up of COROT shallow transit candidates may allow us to push the detection limit to even lower mass.

In parallel to these developments, the possibility to increase even further the radial-velocity measurement precision is being investigated in the frame of the CODEX project (COsmic Differential EXpansion), a visible high-resolution spectrograph to be coupled with ESO's concept of an Extremely Large Telescope, the 100-m diameter OWL now under study. The main scientific driver of CODEX is the direct measurement of the universe's expansion acceleration-deceleration (Monnet G. and D'Odorico S., 2004). A project group headed by ESO and involving several European institutes is investigating the feasibility of such an instrument to reach a radial-velocity measurement precision of 1 cms^{-1} over an extended time span (> 10 years). The combination of the unique collecting power of OWL with the most accurate radial-velocity measurement techniques developed for the extra-solar planet search may make the realization of such an instrument possible. In addition to the determination of the cosmological model with a dynamical measurement at high redshift, this measurement precision will open new possibilities also in the domain of extra-solar planets. First investigations show that Earth-like planets around bright stars could be detected, provided that the total integration time is kept sufficiently long (~ hours) to average out the stellar oscillations. A number of studies have been started to investigate the instrumental aspects. HARPS may serve in this context as a test bench for attaining extremely high radial-velocity precision. Indeed, new instrumental concepts, and new calibration techniques and algorithms are being explored and could partially be verified on HARPS on the 3.6-m telescope in the near future. Nevertheless, any measurement aiming at the cms^{-1} accuracy with HARPS would be limited to very bright objects, due to the limited telescope size. A star with $m_V \sim 4$ would require 125 sequences of 2-minute exposures each leading to a total observing time of 5 hours to obtain a single data point with 1 cms^{-1} photon limited error. An improved version of the HARPS spectrograph at the VLT as a new-generation spectrograph seems more appropriate for this kind of science. In addition, it would represent an ideal intermediate step toward CODEX. With the refinement of HARPS and the possible future with CODEX, the Doppler technique promises us many new exciting discoveries and new knowledge in the domain of extra-solar planets.

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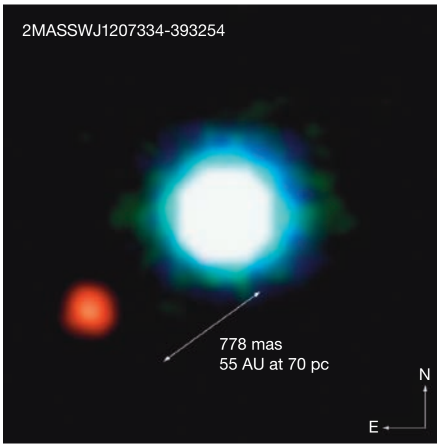
Confirmation of the First Image of an Extra-Solar Planet



2M1207 (centre) and its Planetary Companion (red). The photo is based on three near-infrared exposures (in the H, K and L′ wavebands) with NACO. *ESO PR Photo 14a/05.*

A team of astronomers[1] has confirmed the discovery of a giant planet, approximately five times the mass of Jupiter, that is gravitationally bound to a young brown dwarf, putting an end to a year-long discussion on the nature of this object.

Last year, the team reported a faint red object in the close vicinity of a young brown dwarf (see ESO PR 23/04). The red object, now called 2M1207b, is more than 100 times fainter than the brown dwarf, 2M1207A. The spectrum of 2M1207b contains a strong signature of water molecules, confirming that it must be cold. Based on the infrared colours and the spectral data, evolutionary model calculations led to the conclusion that 2M1207b is a 5-Jupiter-mass planet. Its mass can also be estimated from a different method, which focuses on the strength of its gravitational field; this technique suggests that the mass might be even less than 5 Jupiter masses.

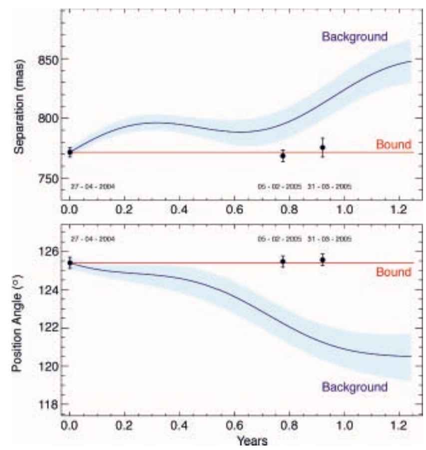
At the time of its discovery in April 2004, it was impossible to prove that the faint source is not an unrelated background object. In February and March of this year, new images were obtained of the young brown dwarf and its giant planet companion with NACO on the VLT. They show with high confidence that the two objects are moving together and hence are gravitationally bound.

The new observations therefore show that this really is a planet, the first planet that has ever been imaged outside of our solar system. The separation between the planet and the brown dwarf is 55 times the separation of the Earth and Sun.

"Given the rather unusual properties of the 2M1207 system, the giant planet most probably did not form like the planets in our solar system," says Gaël Chauvin, the leader of the team. "Instead it must have formed the same way our Sun formed, by a one-step gravitational collapse of a cloud of gas and dust."

Anne-Marie Lagrange, another member of the team from the Grenoble Observatory in France, looks towards the future: "Our discovery represents a first step towards one of the most important goals of modern astrophysics: to characterise the physical structure and chemical composition of giant and, eventually, terrestrial-like planets."

(Based on ESO Press Release 12/05)



Relative position of 2M1207b with respect to 2M1207A at three different epochs (April 2004, February and March 2005). The top panel shows the separation between the two objects in milli-arcseconds, while the lower one represents the relative angle. The blue line shows the predicted change in position if the faint red source were a background object.

[1] The team consists of Gaël Chauvin and Christophe Dumas (ESO), Anne-Marie Lagrange and Jean-Luc Beuzit (LAOG, Grenoble, France), Benjamin Zuckerman and Inseok Song (UCLA, Los Angeles, USA), David Mouillet (LAOMP, Tarbes, France) and Patrick Lowrance (IPAC, Pasadena, USA).