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Characterization of small planets with *Kepler* and HARPS-N

A. S. Bonomo[1a], A. Sozzetti[1], C. Lovis[2], L. Malavolta[3,4], K. Rice[5], X. Dumusque[6], A. C. Cameron[7], D. W. Latham[6], E. Molinari[8,9], F. Pepe[2], S. Udry[2], and the HARPS-N team

[1] INAF - Osservatorio Astrofisico di Torino, via Osservatorio 20, 10025 Pino Torinese, Italy
[2] Observatoire Astronomique de l'Université de Genève, 51 ch. des Maillettes, 1290 Versoix, Switzerland
[3] Dipartimento di Fisica e Astronomia "Galileo Galilei", Università di Padova, Vicolo dell'Osservatorio 3, 35122 Padova, Italy
[4] INAF - Osservatorio Astronomico di Padova, Vicolo dell'Osservatorio 5, 35122 Padova, Italy
[5] SUPA, Institute for Astronomy, Royal Observatory, University of Edinburgh, Blackford Hill, Edinburgh EH93HJ, UK
[6] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, Massachusetts 02138, USA
[7] SUPA, School of Physics & Astronomy, University of St. Andrews, North Haugh, St. Andrews Fife, KY16 9SS, UK
[8] INAF - Fundación Galileo Galilei, Rambla Jos Ana Fernandez Prez 7, 38712 Brea Baja, Spain
[9] INAF - IASF Milano, via Bassini 15, 20133, Milano, Italy

Abstract. The high-accuracy and high-precision HARPS-N spectrograph has been installed at the italian Telescopio Nazionale Galileo in La Palma approximately two years and a half ago. Eighty nights per year of Guaranteed Time of Observation are mostly dedicated to the radial-velocity (RV) follow up of *Kepler* small-size planetary candidates to establish their nature and to determine accurately their masses. We report on recent results of this ongoing RV campaign, including the recent characterization of the planetary system Kepler-101.

1 Introduction

The high-precision and high-resolution ($R \sim 120\,000$) HARPS-N spectrograph has been installed during Spring 2012 at the 3.6-m Telescopio Nazionale Galileo at La Palma island. The HARPS-N consortium, which is the builder and owner of the instrument, is a transnational collaboration between Italy, Switzerland, UK, and the US, and has 80 nights per year of Guaranteed Time of Observation for 5 years. One of the most important goals of this consortium is the characterization of *Kepler* small planets by yielding precise and accurate measurements of their mass. In particular, we aim to i) characterize an Earth twin in the habitable zone of a G5V star or later, with a precision of 30% in mass; ii) characterize the structural properties of super-Earths of 2-5 $M_\oplus$ in various orbits with enough precision to distinguish between water-rich and dry planets; and iii) study the transition between super-Earths and Neptunes near 10-20 $M_\oplus$.

[a] e-mail: bonomo@oato.inaf.it

2 First results

2.1 Characterization of the infernal Earth Kepler-78b

We could derive the mass of the infernal Earth Kepler-78b which has a radius $R_{\rm p} = 1.16\ {\rm R}_\oplus$, orbital period of 8.6 hours, and equilibrium temperature $T_{\rm eq} > 2300$ K (Sanchis-Ojeda et al., 2013) thanks to 109 HARPS-N RV observations. We found a mass of $1.86^{+0.38}_{-0.25}\ {\rm M}_\oplus$ and a density ($\rho_{\rm p}$) of 5.6^{+3}_{-1} g cm^{-3} (Pepe et al., 2013), which implies a composition of iron and rocks, similar to the Earth (see Fig. 1). However, because of the very high $T_{\rm eq}$, the planetary surface is likely covered by lava oceans (Léger et al., 2011).

2.2 Revisiting the very old Kepler-10 planetary system

148 high-precision RVs obtained with HARPS-N (Dumusque et al., 2014) allowed us to i) determine more precisely and accurately the mass of the hot rocky world Kepler-10b ($P = 0.84$ d; $R_{\rm p} = 1.47 \pm 0.03\ {\rm R}_\oplus$, $M_{\rm p} = 3.3 \pm 0.5\ {\rm M}_\oplus$, $\rho_{\rm p} = 5.8 \pm 0.8$ g cm^{-3}) and ii) derive for the first time the mass, hence the density, of the outer planetary companion Kepler-10c ($P = 45.29$ d; $R_{\rm p} = 2.35^{+0.09}_{-0.04}\ {\rm R}_\oplus$, $M_{\rm p} = 17.2 \pm 1.9\ {\rm M}_\oplus$, $\rho_{\rm p} = 7.1 \pm 1.0$ g cm^{-3}). The latter turned out to be a solid Neptune-mass planet with a bulk composition dominated by rocks and a significant amount of water in the form of solid high-pressure ice (from 5 to 20 wt.%; see Fig. 1). It might be the first firm example of a population of solid planets with masses above 10 ${\rm M}_\oplus$.

2.3 Characterization of the planetary system Kepler-101

The planetary system Kepler-101 is formed by a hot super-Neptune (Kepler-101b) and an outer Earth-sized planet (Kepler-101c), which orbit a sub-giant and metal-rich G-type star in 3.49 and 6.03 days. Thanks to forty HARPS-N RVs (see Fig. 2), we could measure the mass of Kepler-101b and put an upper limit on that of Kepler-101c (Bonomo et al., 2014). With mass, radius, and density of $M_{\rm p} = 51.1^{+5.1}_{-4.7}\ {\rm M}_\oplus$, $R_{\rm p} = 5.77^{+0.85}_{-0.79}\ {\rm R}_\oplus$, and $\rho_{\rm p} = 1.45^{+0.83}_{-0.48}$ g cm^{-3}, Kepler-101b is the first fully characterized super-Neptune. It lies in a region of the $R_{\rm p} - M_{\rm p}$ diagram which is not populated by any other transiting planet (Fig. 1) and its density suggests that heavy elements make up a significant fraction of its interior; more than 60% of its total masss. Kepler-101c has a radius of $1.25^{+0.19}_{-0.17}\ {\rm R}_\oplus$, which implies the absence of any H/He envelope, and the upper limit on its mass, i.e. $< 3.8\ {\rm M}_\oplus$ at 1σ, excludes a pure iron composition with a probability of 68.3%. The architecture of this planetary system - containing a close-in giant planet and an outer Earth-sized planet with a period ratio larger than the 3:2 resonance - is certainly of interest for scenarios of planet formation and evolution (Bonomo et al., 2014). This system does not follow the trend reported by Ciardi et al. (2013), that the larger planet has the longer period in the majority of *Kepler* systems of planet pairs with at least one Neptune-sized or larger planet.

3 Conclusions

The RV follow up of *Kepler* small planets with HARPS-N is permitting us to determine their masses with unprecedented accuracy and precision. With other new coming results, this will prove to be of fundamental importance to investigate the diversity of the internal structures of small planets and to improve to a greater extent their mass-radius relation (e.g., Weiss & Marcy, 2014).

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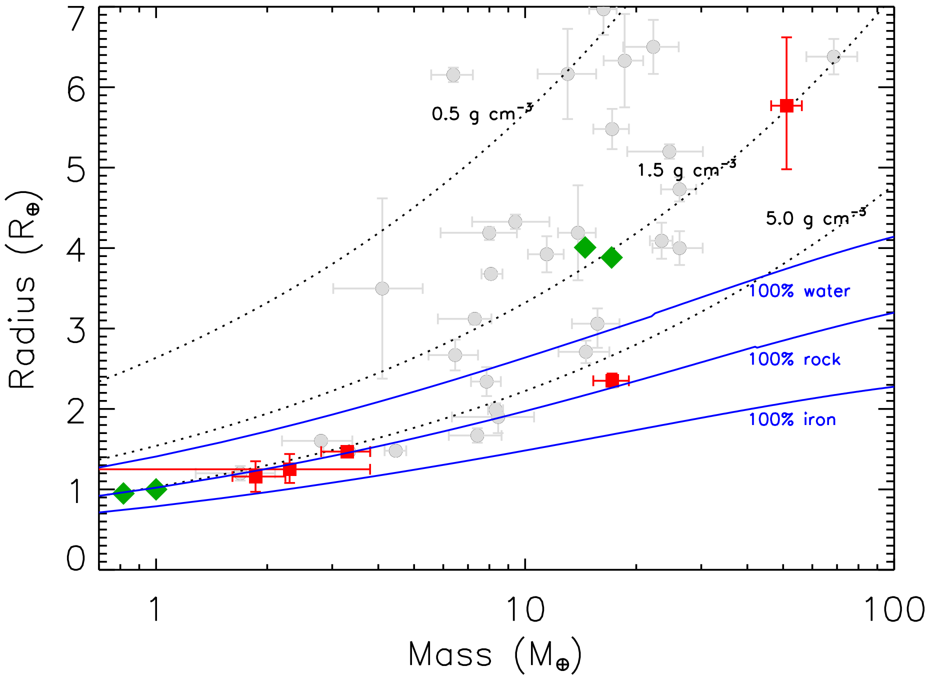

Fig. 1. Mass-radius diagram of the known transiting planets with radius $R_p \leq 7$ R$_\oplus$, mass $M_p \leq 100$ M$_\oplus$, and precision on the mass better than 30%. Green diamonds indicate Neptune, Uranus, the Earth, and Venus (from right to left). The three dotted lines indicate isodensity curves of 0.5, 1.5, and 5 g cm^{-3}, and the blue solid lines show the mass and radius of planets consisting of pure water, 100% rocks, and 100% iron Seager et al. (2007). The positions of the *Kepler* planets characterized with HARPS-N to date are shown with red squares.

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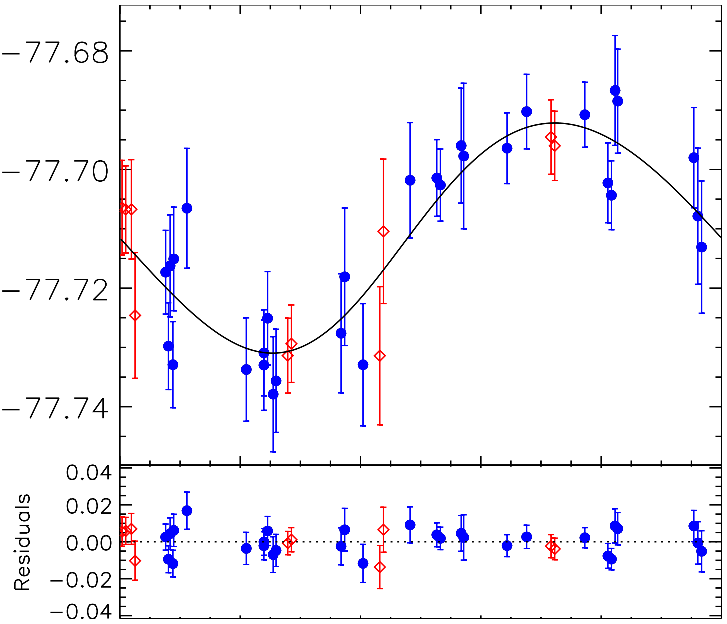

Fig. 2. HARPS-N RVs of Kepler-101 phase-folded with the ephemeris of the inner super-Neptune and, superimposed, the Keplerian model (black solid line). Red and blue circles show the HARPS-N data obtained with the original and replaced CCD, respectively. From Bonomo et al. (2014).