Planetary Science and Exoplanets in the Era of JWST
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Detecting and characterising exoplanets with HARPS-N

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Abstract. Exoplanet follow-up with JWST requires precise masses and radii. HARPS-N is a high-resolution spectrograph on the Telescopio Nazionale Galileo (TNG), predominantly used to detect and characterize exoplanets using the radial velocity (RV) method. The HARPS-N Collaboration has been characterising exoplanets with HARPS-N for over a decade. In this short paper we highlight the contributions that the HARPS-N Collaboration has made to the characterisation of small exoplanets.

Keywords. Exoplanets, Radial velocities, Transits, Exoplanet characterisation

1. Introduction

The High Accuracy Radial Velocity Planet Searcher for the Northern hemisphere (HARPS-N) is a high-precision radial-velocity spectrometer located on the Telescopio Nazionale Galileo (TNG) on La Palma. It has a spectral resolution of $R = 115000$, covers the wavelength range from 378 nm to 691 nm (Cosentino et al. 2012) and is a close copy of the HARPS instrument on the 3.6-m ESO telescope at La Silla, Chile (e.g., Mayor et al. 2003).

The HARPS-N Project was initially a collaboration between the Department of Astrophysics of the University of Geneva, Center for Astrophysics – Harvard & Smithsonian, University of St-Andrews, University of Edinburgh, Queen's University Belfast, and the Fundación Galileo Galilei - Instituto Nazionale di Astrofisica, but is now also open to researchers from other institutions. This collaboration, often referred to as the GTO Collaboration, still contributes to maintenance of the instrument and development of the data reduction pipeline.

The HARPS-N Collaboration has three broad scientific goals:†

- to characterize "super-Earths" in various orbits with enough precision to distinguish between volatile-rich and predominantly iron-silicate planets;
- to measure accurate masses to a precision of 10%, or better, for planets near the transition between super-Earths and Ice Giants (i.e., ∼10 $M_\oplus$);
- to confirm an Earth-twin planet in the habitable zone of a G5V star or later, with a precision of 30% in mass.

The HARPS-N Collaboration also has a secondary scientific goal of detecting Earth-like planets around nearby stars. Referred to as the Rocky Planet Search (RPS), this involves observing a sample of the brightest, least active K-dwarfs in the Northern hemisphere.

HARPS-N started making observations in late 2012. In this short paper, we highlight some of the successes of just over a decade of work by the HARPS-N Collaboration and also the impact that HARPS-N has had on the detection and characterisation of exoplanets, in particular presenting precise masses and radii of exoplanets that will be key targets for JWST. We focus mostly on the work done by the Collaboration, but should stress that HARPS-N has also been very successfully used by other groups (e.g., Covino et al. 2013; Luque et al. 2023).

2. Synergy with *Kepler*

One of the motivations for HARPS-N was to follow-up targets first detected by NASA's *Kepler* mission (Borucki et al. 2010). The *Kepler* satellite launched in March 2009 and initially monitored a single field in Cygnus/Lyra, identifying more than 2300 transiting exoplanets.

The HARPS-N Collaboration published mass estimates for a number of these *Kepler* targets, the first being Kepler-78 b, an Earth-sized planet with an Earth-like density (Pepe et al. 2013). Even for this relatively faint K-star ($m_\mathrm{V} = 11.75$) the mass was determined with a precision of 20% ($m_p = 1.86^{+0.38}_{-0.28}$ $M_\oplus$), helped by the planet having an orbital period of only 8.5 hours. This was followed by intensive observations of Kepler-10, which hosts Kepler-10 b, the first rocky planet detected by *Kepler*, and Kepler-10 c (Batalha et al. 2011). The discovery paper presented a 3σ mass estimate for Kepler-10 b, and an upper limit for Kepler-10 c. Our HARPS-N campaign allowed us recover a mass precision of 15% for Kepler-10 b (3.33 ± 0.49 $M_\oplus$), and determine a mass for Kepler-10 c with a precision of 11% (17.2 ± 1.9 $M_\oplus$) (Dumusque et al. 2014). Given the interest in this system, the HARPS-N Collaboration is continuing to observe this system (Bonomo et al. 2024 in prep.).

Other Kepler systems characterised by the HARPS-N Collaboration include Kepler-101 (Bonomo et al. 2014), Kepler-93 (Dressing et al. 2015), Kepler-454 (Gettel et al. 2016), Kepler-20 (Buchhave et al. 2016), Kepler-21 (López-Morales et al. 2016), and Kepler-19 (Malavolta et al. 2017). In many of these systems, we were able to determine the masses of the small exoplanets with precisions of 20%, or better. We were also able to confirm the low densities of the planets in the Kepler-9 system (Borsato et al. 2019).

A particularly interesting system is Kepler-107, which hosts 4 sub-Neptune sized planets (Rowe et al. 2014) the inner two of which have very similar radii. Using HARPS-N, we were able to show that although these two planets have almost the same radii, they have very different masses, with the outer (Kepler-107 c) being almost twice as dense as the inner (Kepler-107 b) (Bonomo et al. 2019). The most likely scenario is that the outer part of Kepler-107 c's silicate mantle was stripped off by a giant impact.

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† https://plone.unige.ch/HARPS-N/science-with-harps-n

2.1. *K2 mission*

When the second of four reaction wheels failed in May 2013, the primary *Kepler* mission came to an end. However, by pointing along the ecliptic and balancing the spacecraft against radiation pressure, it was possible to extend the mission. This mission extension was referred to as K2. The HARPS-N Collaboration then focussed on following up K2 targets, which were typically brighter than *Kepler* targets.

Some early examples were HIP 116454 (Vanderburg et al. 2015), which hosted the first planet discovered by the K2 mission, and K2-141 (Malavolta et al. 2018). K2-141 b still has the most precise mass of all small planets and, until recently, was the shortest period ultra short period (USP) planet known. Other examples are K2-3 (Damasso et al. 2018), a system that likely hosts 3 sub-Neptunes, HD 80653/K2-312 (Frustagli et al. 2020), a system with a short-period rocky Earth, and K2-111 (Mortier et al. 2020), the first time that detailed stellar, planetary and orbital characteristics were used to infer the internal structure of a transiting planet around a star with a chemical composition different to that of the Sun. This latter analysis confirmed a link between stellar composition and planet composition.

The HARPS-N Collaboration also used HARPS-N RVs to further constrain the properties of the GJ 9827 system (Rice et al. 2019), a 3 planet systems with planets on either side of the radius gap (Fulton et al. 2017) that separates rocky super-Earths from those that probably still retain substantial volatile atmospheres. Recent observations have indicated the presence of water in the atmosphere of GJ 9827 d (Roy et al. 2023).

2.2. *Combining almost 10 years of HARPS-N observations*

Given that the HARPS-N Collaboration has been observing since 2012, we eventually had a very large sample of radial velocities (RVs) for numerous *Kepler* and K2 targets. This allowed us to carry out a homogeneous analysis of 38 *Kepler* and K2 small planet systems (Bonomo et al. 2023). This resulted in improved physical and orbital parameters for 64 *Kepler* and K2 small planets, but also allowed us to search for the presence of cold Jupiters, exoplanets with semimajor axes of $a \sim 1-10$ AU and masses of $m_p = 0.5-13$ $\mathrm{M_{Jup}}$.

We found 5 cold Jupiters in 3 of the systems, including a highly eccentric one in HD 80653/K2-312, and linear trends compatible with an outer planet in 2 others. Overall, we inferred a cold Jupiter occurrence rate of $9.3^{+7.7}_{-2.9}\%$. This is lower than some earlier estimates and does not confirm previous claims of an excess of cold Jupiters in systems with small inner planets (e.g., Bryan et al. 2019).

3. Synergy with TESS and CHEOPS

With the launch of NASA's Transiting Exoplanet Survey Satellite (TESS - Ricker et al. 2015), the HARPS-N Collaboration started to contribute to the follow-up of TESS targets. Of particular interest was the origin of the radius valley (e.g., Fulton et al. 2017), especially around M-dwarfs (Cloutier and Menou 2020). The HARPS-N Collaboration published a number of analyses of *keystone* "super-Earths". These are planets that lie in a region of radius-orbital period space where their properties can help to constrain the different formation pathways, such as radius evolution through thermally-driven mass loss, direct formation in a gas-poor environment, and formation in a gas-depleted environment. Examples are TOI-1235 b (Cloutier et al. 2020) and TOI-1634 b (Cloutier et al. 2021). Although thermally-driven mass loss is a favoured mechanism around stars with $T_{\rm eff} > 4700$ K, the results in these papers suggest that around cooler M-dwarfs, close-in "super-Earths" might preferentially form in a gas depleted environment.

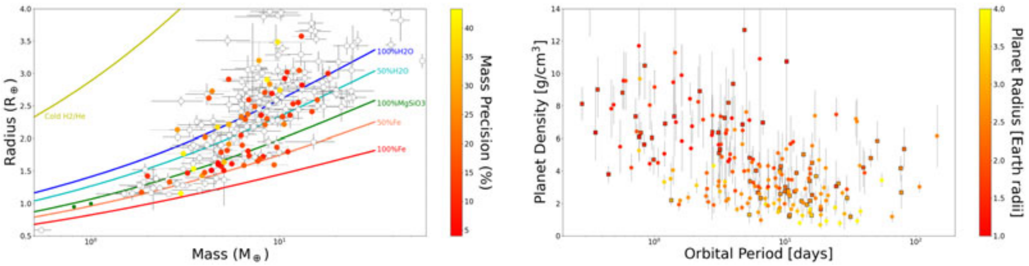

Figure 1. Mass-radius (left-hand panel) and density-orbital period (right-hand panel) plots for all planets with sizes below 4 Earth radii and with mass and radius precisions better than 3σ, taken from the Encyclopedia of Exoplanetary Systems. In the left-hand panel, the coloured symbols are those characterised by the HARPS-N Collaboration, while these planets are indicated by squares in the right-hand panel. The colours also indicate the mass precision.

The HARPS-N Collaboration also started taking advantage of the CHaracterising ExOPlanet Satellite (CHEOPS - Benz et al. 2021) to further constrain the properties of the systems being studied. CHEOPS is an ESA mission with one of its main scientific goals being to refine the radii of known exoplanets. This was especially useful when trying to determine the properties of the TOI-561 system. It was initially presented as a system with 3 planets, the outer of which transited twice. This interpretation was supported by the analysis in Weiss et al. (2021).

The HARPS-N Collaboration's analysis, however, concluded that TOI-561 actually had 4 planets, with the outer 2 only transiting once each (Lacedelli et al. 2021). CHEOPS played a crucial role in resolving this discrepancy. CHEOPS observed numerous transits of the inner two planets and one transit of an outer planet at a time consistent with this being a 4-planet system, but not a 3-planet system (Lacedelli et al. 2022). This analysis also indicated that the innermost planet was the lowest density ultra-short period planet detected to date. The low metallicity of the host star makes this consistent with the general bulk density-stellar metallicity trend initially highlighted in our analysis of K2-111 (Mortier et al. 2020).

The HARPS-N Collaboration also successfully combined HARPS-N RVs with TESS and CHEOPS photometry in the analysis of HD 77946 (TOI-1778), which hosts a planetary-mass object that lies in a region of mass-radius space where there is compositional confusion. This analysis suggests that HD 77946 b is probably a sub-Neptune with a low-mass H/He atmosphere that makes up a significant fraction of its radius, but can't entirely rule out a water world (Palethorpe et al. 2024).

4. Rocky Planet Search

As mentioned earlier, the HARPS-N Collaboration have also been observing 52 of the brightest, least active K-dwarfs in the Northern hemisphere to detect an Earth-like planet around a nearby star. The first result from this survey was the detection of a 4-planet system around HD 219134, the inner planet of which is a transiting rocky planet (Motalebi et al. 2015). The second innermost planet has since also been shown to transit and is also rocky (Gillon et al. 2017). This is still the closest known transiting system.

This dataset has since been used to review the planetary systems around HD 99492, HD 147379 and HD 190007 (Stalport et al. 2023), to show that it is possible to detect RV signals with amplitudes below 1 m/s (John et al. 2023), and to present a trio of super-Earths around HD 48948, one of which is in its star's habitable zone (Dalal et al. 2024).

5. Overall impact of HARPS-N Collaboration

Figure 1 illustrates the overall impact of the HARPS-N Collaboration on the characterisation of small, transiting exoplanets. The left-hand panel shows a mass-radius diagram of all known exoplanets with radii below 4 Earth radii, with RV mass estimates, and with mass and radius precisions better than 3σ. The right-hand panel is the same planet sample, but showing density plotted against orbital period.

In the left-hand panel, the coloured symbols are all systems characterised by the HARPS-N Collaboration, while in the right-hand panel these systems are represented by squares. The colours also indicate the mass precision. To-date, the HARPS-N Collaboration has characterised 25% of $R_p < 4$ R$_\oplus$ planets with mass precisions better than 30% and 25% of those with mass precisions better than 10%. For planets with $R_p < 2$ R$_\oplus$, the HARPS-N Collaboration has characterised one-third of those with mass precisions better than 30% and 40% of those with mass precisions better than 10%.

6. Summary

Exoplanet follow-up observations with JWST require precise mass and radius estimates, with detailed atmospheric characterisation requiring mass precision of 20%, or better (Batalha et al. 2019). The HARPS-N Collaboration has been collecting RVs with HARPS-N since late 2012. The Collaboration has made substantial contributions to our understanding of the composition of small exoplanets, the origin of the radius gap, the frequency of cold Jupiters, and the presence of rocky planets around nearby bright stars. It has also characterised a significant fraction of the small exoplanets with mass and radius estimates that are precise enough for them to be key targets for JWST.

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