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THE KEPLER-10 PLANETARY SYSTEM REVISITED BY HARPS-N: A HOT ROCKY WORLD AND A SOLID NEPTUNE-MASS PLANET∗

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ABSTRACT

Kepler-10b was the first rocky planet detected by the Kepler satellite and confirmed with radial velocity follow-up observations from Keck-HIRES. The mass of the planet was measured with a precision of around 30%, which was insufficient to constrain models of its internal structure and composition in detail. In addition to Kepler-10b, a second planet transiting the same star with a period of 45 days was statistically validated, but the radial velocities were only good enough to set an upper limit of 20 M⊕ for the mass of Kepler-10c. To improve the precision on the mass for planet b, the HARPS-N Collaboration decided to observe Kepler-10 intensively with the HARPS-N spectrograph on the Telescopio Nazionale Galileo on La Palma. In total, 148 high-quality radial-velocity measurements were obtained over two observing seasons. These new data allow us to improve the precision of the mass determination for Kepler-10b to 15%. With a mass of 3.33 ± 0.49 M⊕ and an updated radius of 1.47+0.03−0.02 R⊕, Kepler-10b has a density of 5.8 ± 0.8 g cm−3, very close to the value predicted by models with the same internal structure and composition as the Earth. We were also able to determine a mass for the 45-day period planet Kepler-10c, with an even better precision of 11%. With a mass of 17.2 ± 1.9 M⊕ and radius of 2.35+0.09−0.04 R⊕, Kepler-10c has a density of 7.1 ± 1.0 g cm−3. Kepler-10c appears to be one of the class of more massive solid planets with longer orbital periods.

Key words: planetary systems – stars: individual (Kepler-10 KOI-072 KIC 11904151) – stars: statistics – techniques: photometric – techniques: spectroscopic

Online-only material: color figures, machine-readable table

1. INTRODUCTION

Transiting planets enable a rich variety of opportunities to explore planetary astrophysics, ranging from the determination of bulk densities to studies of system architectures and atmospheric compositions, and even climate and weather. However, for most of these studies, a critical first step is the determination of a dynamical mass that confirms and characterizes the planetary nature of the candidate. This mass, together with the size of the planet determined from the light curve, yields the bulk density of the planet.

The importance of determining dynamical masses for small planets, either by Doppler spectroscopy or transit-time variations (TTVs) or a photo-dynamical analysis, was brought into focus by the results for the five small inner planets transiting Kepler-11, ranging in size from 1.8 to 4.2 times the diameter of the Earth (Lissauer et al. 2011). The masses derived from TTVs eventually led to densities ranging from 1.7 down to 0.58 g cm−3 (Lissauer et al. 2013), much less than the Earth’s bulk density of 5.5 g cm−3, presumably due to extended atmospheres of hydrogen and helium. It became clear that a better understanding of the occurrence rate for planets similar to the Earth would require determinations for a significant population of small planets.

Based on observations made with the Italian Telescopio Nazionale Galileo (TNG) operated on the island of La Palma by the Fundacini Galileo Galilei of the INAF (Istituto Nazionale di Astrofisica) at the Spanish Observatorio del Roque de Los Muchachos of the Instituto de Astrofisica de Canarias. 16 Swiss National Science Foundation Fellow.
CoRoT-7b was the first small planet that looked like it might be dense enough to be rocky (Queloz et al. 2009; Léger et al. 2009). However, determining its dynamical mass was quite challenging, because strong stellar activity was perturbing the radial velocities (RVs) of the host star. This inspired work on ways to reduce the impact of activity-induced RV signals: pre-whitening by the rotation period and harmonics (Dumusque et al. 2012; Boisse et al. 2011; Queloz et al. 2009), correlation with activity indicators (Boisse et al. 2009), velocity differences using multiple observations during the same night (Hatzes et al. 2010), correlation with photometric variations (Aigrain et al. 2012), and treating stellar activity as correlated noise (Feroz & Hobson 2013; R. D. Haywood et al., in preparation). This work is finally leading to a consensus that CoRoT-7b has a density consistent with a rocky planet. Moreover, learning how to correct the CoRoT photometry and RV measurements for stellar activity is now paying off for other cases (e.g., Pepe et al. 2013; Howard et al. 2013; Dumusque et al. 2012).

Kepler-10b is in many ways a twin of CoRoT-7b, in terms of size and orbital period, but has the advantage of transiting an old quiet star. Still, the mass reported in the discovery paper, 4.56 ± 1.3 $M_\oplus$, has a precision not much better than three sigma (Batalha et al. 2011), which is well short of the accuracy needed to distinguish a rocky planet from a water world, nominally 10%, as we argue below. The discovery paper (Batalha et al. 2011) also reported the detection of a second transiting planet candidate with a period of 45 days and radius of 2.23 $R_\oplus$. However, no orbital motion at this period was detected in the observed RVs, and only an upper limit of 20 $M_\oplus$ could be placed on the mass. With more Kepler data and simultaneous Spitzer Space Telescope photometry, Fressin et al. (2011) reanalyzed the Kepler-10 system and statistically validated the planetary nature of Kepler-10c with BLENDER (Torres et al. 2011). This result was not a surprise, because planet candidates in multi-transit systems are much less likely to verify that they are planets because of the strong constraints provided by the photometric ephemerides. As a population, many of them are likely to be rocky, but the results are not good enough to characterize any individual planet in detail.

At the start of HARPS-N science operations in 2012 August, Kepler-10b looked like the best target for pursuing this goal. It had already been confirmed as a rocky planet, with a mass of 4.56 $M_\oplus$, a radius of 1.42 $R_\oplus$, and a density of 8.8 g cm$^{-3}$ (Batalha et al. 2011). In addition, the stellar parameters of Kepler-10 are well constrained by asteroseismology (Foggmann-Schulz et al. 2014), which gives us an unprecedented precision on the radius of Kepler-10b. The mass determination was based on 40 precise RV measurements obtained with Keck-HIRES, and the uncertainty in the density of nearly 30% was dominated by the uncertainty in the mass. Over the 2012 and 2013 observing seasons, we accumulated nearly four times as many RVs for Kepler-10 (with similar precision, see Pepe et al. 2013; Howard et al. 2013). In this paper, we present the analysis of these new data, which allow us to improve the uncertainty of the mass for Kepler-10b by about a factor of two, and to determine precisely the mass of Kepler-10c for the first time.

2. OBSERVATIONS AND DATA REDUCTION

We monitored the RV variation of Kepler-10 with the HARPS-N spectrograph installed on the 3.57-m Telescopio Nazionale Galileo at the Spanish Observatorio del Roque de los Muchachos, La Palma Island, Spain (Cosentino et al. 2012). This instrument is an updated version of the original HARPS planet hunter installed on the 3.6-m telescope at the European Southern Observatory on La Silla, Chile (Mayor et al. 2003). Just like its older brother, the HARPS-N instrument is an ultra-stable fiber-fed high-resolution ($R = 115,000$) optical echelle spectrograph optimized for the measurement of very precise RVs. The use of a more modern monolithic 4k×4k CCD enclosed in a more temperature stable cryostat, and the use of octagonal fibers for a better scrambling of the incoming light fed into the spectrograph should improve the precision of the instrument compared to HARPS. By observing standard stars of known constant RV during the first year of operation, we estimated the RV precision to be of at least 1 m s$^{-1}$ when not limited by photon noise. When observing fainter stars, we expect a RV precision of 1.2 m s$^{-1}$ to be achieved in a 1-h exposure on a slowly rotating late-G or K-type dwarf with $m_V = 12$.

Scientific operations began at HARPS-N in 2012 August. Over the first two observing seasons, we obtained 157 RV measurements of Kepler-10. Four observations that were obtained during bad weather conditions had very low signal to noise ($S/N, <10$) and were rejected. During the first year of operation, in 2012, half of the CCD stopped working and the stellar spectra were only recorded on half of the echelle orders. With only a subset of the lines used to derive the RV using the cross correlation technique, it is not clear if the data taken with half of the chip can be used or not. We therefore decided to reject those five points that were taken before the CCD was replaced. This paper...
therefore presents 148 RV observations of Kepler-10, which are listed in Table 1.

Kepler-10 has a *Kepler* magnitude *K* = 10.96 (*m* = 11.16), so exposure times of 30 minutes were required to reach a S/N adequate for high RV precision. Scaling from the expected precision for faint stars given in the first paragraph of this section, 30 minutes of exposure on the slowly rotating G-type dwarf Kepler-10 should yield a precision of 1.12 m s$^{-1}$. Looking at the data, the best precision we could get on a single measurement for an S/N of 80 at 550 nm. However, due to not always optimal conditions, the average error on the entire RV set is 1.63 m s$^{-1}$ for an average S/N of 59 at 550 nm. This precision is two times smaller than the RV semi-amplitude of Kepler-10b (Batalha et al. 2011), and was expected to be roughly the same as the semi-amplitude of Kepler-10c, assuming that planet has the same mass as the similar-sized planet Kepler-69b (2.31 $R_\oplus$, 8.3 $M_\oplus$; Gilliland et al. 2013).

The data exhibit a small RV offset between the measurements taken with the old and the new CCD mainly because of the different charge transfer efficiency of the detectors. This offset will be considered as a free parameter when fitting the RVs.

### 3. STELLAR PROPERTIES

Stellar parameters for Kepler-10 have been determined using a combined spectrum with S/N of 750 at 550 nm, resulting from the co-addition of all the individual spectra with S/N $\geq$ 30, after dividing by the blaze function and correcting for the barycentric velocity.

Equivalent widths (EWs) were measured using a modification of the ARES code (Sousa et al. 2007), which provides an estimate of the error in the continuum determination and the root mean square of the residuals of the Gaussian fit. These values, together with the FWHM of each line, were used to reject lines with poorly measured EWs. Weak lines with EWs $\leq$ 5 m Å were excluded from the analysis because of sensitivity to continuum determination. In addition, lines with EW $\geq$ 110 m Å were also not considered because those lines depart from Gaussian shape.

Atmospheric parameters were determined using the 2013 version of the local thermodynamic equilibrium code MOOG (Sneden 1973) and the Kurucz model atmosphere grid calculated with the new opacity distribution function (ODFNEW; Castelli & Kurucz 2004; Kurucz 1992). Atmospheric models were interpolated with a software developed by A. McWilliam and I. Evans and provided by C. Sneden.

We adopted the line list from Sousa et al. (2011), but the oscillator strength values log $gf$ were re-determined by inverse analysis of their solar EWs using an Iron abundance of log $\epsilon$(Fe) = 7.52 (and the other photospheric parameters unchanged), to be consistent with the solar value used in the calculation of the model atmosphere grid and by MOOG in the abundance computation.

Table 1

<table>
<thead>
<tr>
<th>HARPS-N RV Measurements</th>
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<tbody>
<tr>
<td><strong>BJD - 24000000</strong></td>
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<tr>
<td>56072.704768</td>
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<td>56103.661644</td>
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(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)
Projected rotation, Color index (Effective temperature, $T_{\text{eff}}$) (see Section 4.2.2). The error bars represent a 1 σ uncertainty on the parameters.

The center-of-mass velocity of Kepler-10 relative to the solar system barycenter is $-98.7 \pm 16 \text{ km s}^{-1}$. This is an unusually large RV that was already noticed in Batalha et al. (2011). Given this barycentric RV, the proper motion of 38 mas yr$^{-1}$ (Zacharias et al. 2009), and the estimated distance of 173 pc (Fressin et al. 2011), the probability of the star being a member of the thick disk is 96% (Soubiran & Girard 2005). This is consistent with the old age of the star, i.e., 10.6$^{+3}_{-1.3}$ Gyr. Stars of the thick disc are normally more metal poor than Kepler-10, like for example WASP-21 (Bouchy et al. 2010) with $[\text{Fe/H}] = -0.46$. However the separation in metallicity is not such a clear-cut argument (Adibekyan et al. 2013, and references therein).

### 4. ANALYSIS OF THE RADIAL VELOCITY DATA

This section is dedicated to the detection of the orbital motion induced by Kepler-10b and c in the HARPS-N RV data, and the best estimation of their masses. We first discuss the activity of the star and its rotational period, as these parameters can give us important information for the selection of the best model to use when fitting the data. Indeed, significant stellar activity will induce RV variations, and in this case, a suitable model should be considered.

#### 4.1. Kepler-10 Stellar Activity and Induced Radial Velocity Variations

Kepler-10 is a very old main sequence star, estimated to be 10.6 Gyr old, which should imply a low activity level. When measuring the Ca II HK chromospheric activity index (hereafter calcium activity index) of Kepler-10 (Noyes et al. 1984), which is the best activity proxy for solar type stars, we find an average value of $\log(R'_{\text{HK}})$ equal to $-4.96$, with a standard error of 0.04 dex (see Figure 1). This average is near the lower end of

$$T_{\text{eff}} = 5695 \pm 50 \text{ K}, \ [\text{Fe/H}] = -0.16 \pm 0.08, \text{ and } v \sin i = 0.6 \pm 0.5 \text{ km s}^{-1}.$$

These results are consistent with the preceding analysis, which provides confidence in the derived atmospheric parameters.

The adopted $T_{\text{eff}}$ and $[\text{Fe/H}]$ are the averages of the values obtained independently with the two aforementioned methods, i.e., $T_{\text{eff}} = 5708 \pm 28 \text{ K}$ and $[\text{Fe/H}] = -0.15 \pm 0.04$. The mass, radius, surface gravity, and age of Kepler-10 (see Table 2) were afterward determined by comparing the asteroseismic stellar density $\rho_*$ as measured by Fogtmann-Schulz et al. (2014), the $T_{\text{eff}}$, and $[\text{Fe/H}]$ with the Yonsei-Yale evolutionary tracks (Torres et al. 2012; Sozzetti et al. 2007; Demarque et al. 2004) and by performing the same chi-square minimization as in Santerne et al. (2011). Uncertainties on stellar parameters were estimated through 5000 Monte Carlo simulations by assuming independent Gaussian errors on $\rho_*$, $T_{\text{eff}}$, and $[\text{Fe/H}]$. Stellar parameters and their 1σ errors are listed in Table 2 and are practically identical to those derived by Fogtmann-Schulz et al. (2014), as expected, because our effective temperature and stellar metallicity are consistent within 1σ with the values found by these authors. No more iterations to re-determine the atmospheric parameters were required because the derived stellar surface gravity, i.e., $\log g_* = 4.344 \pm 0.004$, is equal to the previously fixed value.

![Figure 1](image)

Figure 1. Left: calcium activity index of Kepler-10 as a function of time. The activity level is very low, with an average in $\log(R'_{\text{HK}})$ equal to $-4.96$, and a standard error of 0.04 dex. Right: periodogram of the calcium activity index. No clear variation in the activity index is detected as no peaks exhibit a FAP lower than 10%.

(A color version of this figure is available in the online journal.)
the solar value, which varies between $-5$ and $-4.8$ along its activity cycle. It is possible that we just observed the star during its minimum activity phase, which represents $\sim 30\%$ of the solar cycle. However, during the four years of Kepler photometry, we do not see any strong variation similar to that induced by typical solar active regions when the Sun is active (see last following paragraph). The study of the activity index points to a star quieter than the Sun, which is compatible with its old age. With this low activity level, we do not expect the RVs to be significantly affected (Dumusque et al. 2011a).

To estimate the RV variations induced by activity for Kepler-10, we compared the amplitude of the variations seen in the Kepler photometry with that expected from active region simulations. Excluding quarters 4 and 17 because they were not detrended by the PDCMAP reduction pipeline (Smith et al. 2012), and quarter 9 because of instrumental systematics, the maximum peak-to-peak variation in the photometry is less than 500 ppm. Assuming that this variation is due to activity and not to instrumental systematics, and assuming a star with no limb darkening, a 500 ppm variation in photometry would be induced by a dark spot with a filling factor of 0.05%. According to Boisse et al. (2012), a 1% dark spot would induce a RV semi-amplitude of 35 m s$^{-1}$ for a $v \sin i$ of 3 km s$^{-1}$. Scaling from this value, this spot would induce a 1.75 m s$^{-1}$ semi-amplitude. Considering a more sophisticated model that includes quadratic limb-darkening, convective blueshift suppression in active regions, and a more realistic $v \sin i$ of 2 km s$^{-1}$ (see Table 2), this spot would have a filling factor of 0.09%, and would induce a peak-to-peak RV variation of 1.1 m s$^{-1}$ (X. Dumusque et al., in preparation). If instead we assume that a plage is inducing this 500 ppm photometric variation, its size would be much larger, 1.4%, and it would induce a RV peak-to-peak variation of 5 m s$^{-1}$. However a plage would also strongly affect the FWHM of the cross correlation function by a peak-to-peak variation of 20 m s$^{-1}$ (X. Dumusque et al., in preparation). If we assume that the plage is dominating the activity signal, which is consistent with the low activity index of log($R'_{HK}$) = $-4.96$ that is measured for the star.

4.2. Kepler-10 Rotational Period

In this section, we estimate the rotational period of Kepler-10 using several different techniques: activity and stellar age estimations, projected rotational velocity, and the Kepler photometry.

4.2.1. Kepler-10 Rotational Period Estimation with Activity Index and Stellar Age

The activity level and rotational period are strongly correlated for main sequence stars. Indeed, stellar activity is generated through the stellar magnetic dynamo, the strength of which appears to scale with rotation velocity (Montesinos et al. 2001; Noyes et al. 1984). Both stellar activity and rotation are observed to decay with age (Mamajek & Hillenbrand 2008; Barnes 2007; Pace & Pasquini 2004; Soderblom et al. 1991; Wilson 1963). In the course of their evolution, solar-type stars lose angular momentum via magnetic braking due to coupling with their stellar wind (Mestel 1968; Weber & Davis 1967; Schatzman 1962).

With an age of 10.6 Gyr, Kepler-10 is a very old main sequence star, which should imply a rotational period longer than the Sun, and therefore a lower activity level. We saw in the preceding section that the activity level of Kepler-10 is very low, with an average value of log($R'_{HK}$) = $-4.96$. With this average activity value and a color index ($B - V$) = 0.622 (Everett et al. 2012), we can estimate a rotational period of 21.9 $\pm$ 3.0 days using the empirical relation of Mamajek & Hillenbrand (2008). The age of 3.7 Gyr given by this empirical relation is much younger than the value derived with asteroseismology. However gyrochronology relations are not well constrained for old main-sequence stars. Given this inconsistency, we can only conclude that the star should be rotating more slowly than a period of 22 days.

Stellar rotation can also be studied by analyzing the periodicity of the variation of the Ca ii HK chromospheric activity index. Active regions coming in and out of view will induce a semi-periodic signal in the activity index and the RVs (Dumusque et al. 2011a). When looking at a generalized Lomb–Scargle periodogram (GLS; Zechmeister & Kürster 2009) of the calcium activity index derived with HARPS-N spectra in Figure 1, signals with periods greater than 30 days can be found. However these signals all have a false alarm probability (FAP) greater than 10% implying that there is no significant variation in the activity level, which is generally the case for slow rotators that exhibit a low activity level.

4.2.2. Kepler-10 Rotational Period Estimation with Projected Rotational Velocity

Another way of estimating the rotational period of the star is using the projected rotational velocity $v \sin i$ measured on the stellar spectra, as rotation will broaden spectral lines. As we can see in Table 2, the value of 0.6 km s$^{-1}$ derived for fitting HARPS-N spectra with synthetic spectra is extremely low (using the SPC code). This value is consistent with the one derived in the discovery paper using the SME code (Valenti & Piskunov 1996). These techniques are not sensitive below $\sim 2$ km s$^{-1}$ because of the limited instrumental resolution. Another way of estimating the $v \sin i$ is to look at the FWHM of the cross correlation function used to derive the RVs (Boisse et al. 2010; Santos et al. 2002). In this case, the instrumental FWHM is 5.9 $\pm$ 0.2 km s$^{-1}$ at ($B - V$) = 0.7, and Kepler-10 has a FWHM of 6.41 km s$^{-1}$. Using the numerical factor of 1.23 from Hirano et al. (2010) valid for slow rotators, we arrive to $v \sin i = \sqrt{FWHM^2 - FWHM_{inst}^2}/1.23 = 2.04 \pm 0.34$ km s$^{-1}$. Assuming that the star is seen equator on, which is probably given that we have a multi-planet transiting system (Hirano et al. 2014), and assuming a radius of 1.065 $R_\odot$, our two $v \sin i$ estimates point to slow rotational periods of 90 and 26 days, respectively.

4.2.3. Kepler-10 Rotational Period Estimation Using the Kepler Photometry

Finally, rotation can also be studied with Kepler light curves by searching for flux variations induced by active regions coming in and out of view. As these active regions rotate with the star, a signal with a period similar to the rotation of the star is expected. Depending on the coverage and evolution of active regions, the amplitude of the activity signal can strongly vary from one rotational period to the next because these regions only live for a short amount of time. On the Sun, the lifetime of active regions is about a few rotational periods (e.g., Howard 2000).
Kepler light curves over time spans of dozens of days are strongly affected by instrumental systematics. As clearly stated in the Kepler Data Release 21 Notes, the detrended light curves (PDCSAP) should not be used to look for stellar rotational periods greater than 20 days, as the pipeline removes all signals on longer timescales. Because all the rotation indicators discussed in the preceding sections agree on a rotational period greater than 20 days, we did not attempt to derive the rotational period of Kepler-10 using the Kepler photometry.

We used different indicators to infer the rotational period of Kepler-10. None of these indicators can give us a precise value, but they all agree that the star rotates with a period longer than 20 days.

4.3. Kepler-10b

Kepler-10b has an orbital period of 0.84 days, and therefore several measurements per night were obtained to sample efficiently the planetary signal. The other signal expected in the RVs of Kepler-10 is the one coming from Kepler-10c with a 45 day period, if detectable. Considering these signals, the RV variation expected over two days is dominated by Kepler-10b, with the RV offset corrected every two nights to filter out the signal of Kepler-10b, with the RV offset corrected every two nights to filter out the signal of Kepler-10c. The signal of this planet, if detectable, is not well constrained, but it has the same phase from one year to the next, are strong arguments in favor of the planetary nature of the signal.

4.4. Kepler-10c

In the preceding section, we analyzed the data without considering Kepler-10c. The signal of this planet, if detectable, was filtered out by adjusting the RV offset every two nights. In this section, we do not utilize this filtering and instead search for significant signals in the GLS (Zechmeister & Kürster 2009) of the raw RVs.

When looking at the GLS periodogram (see Figure 3, left), it is clear that a signal at 45 days emerges from the noise, even when the signal of Kepler-10b is not removed. To push the analysis further and check that this 45-day signal corresponds to Kepler-10c and not stellar activity, we removed the signal of Kepler-10b by fitting a circular orbit, fixing the period and the transit time to the published values (Batalha et al. 2011), and leaving the amplitude as a free parameter. We then compared the GLS periodogram of the RV residuals for the measurements obtained in 2012, the ones obtained in 2013, and for the entire data set. As we can see in Figure 3, right, the 45-day signal can be seen in each individual subset. The period of this signal is not well constrained, but it has the same phase from one subset to the other, which is expected for a planetary signal. The semi-amplitudes found, fitting a circular orbit with the published photometric ephemeris of Kepler-10c (Fressin et al. 2011), are $3.38 \pm 0.62$, $3.74 \pm 0.44$, and $3.11 \pm 0.35$ m s$^{-1}$ for the measurements obtained in 2012, the ones obtained in 2013, and for the entire data set, respectively. The good agreement between these amplitudes, in addition to the fact that the signal keeps the same phase from one year to the next, are strong arguments in favor of the planetary nature of the signal.

4.5. MCMC Analysis of the RVs Assuming Gaussian Noise with Priors from Kepler Photometry

The preceding section showed that the signal of Kepler-10c is present in the RV data. The next step is to obtain reliable parameters for the mass of this planet. The Kepler photometry exhibits 1124 transits of Kepler-10b and 24 transits of Kepler-10c, which gives us a very-high precision on the period and the transit epoch for both planets. The RV measurements sample ~350 periods of Kepler-10b and ~7 periods of Kepler-10c, with a much sparser sampling. From those numbers, it is clear that

The orbital inclination of Kepler-10c is $89.7^\circ$ (Fressin et al. 2011), therefore the minimum mass of the planet is equal to the real mass.

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**Figure 2.** Radial velocity fit of Kepler-10b using a circular orbit model plus RV offsets every two nights. Left: contour plot of the $\chi^2$ surface around the ephemeris for the period and epoch of transit given by the published Kepler photometric solution (origin of the axis). The minimum $\chi^2$ fit obtained with the RV measurements matches the photometric solution. Right: phase-folded radial velocity signal of Kepler-10b. The gray points corresponds to all the RV measurements obtained for Kepler-10, the big red dots represent the same data binned in phase with a window of 0.2, and the black dotted line our best fit for Kepler-10b.

(A color version of this figure is available in the online journal.)
the period and the transit time are constrained by the photometry itself and that RV measurements will not help to improve the determination of these parameters. We therefore decided to fit the RV data only, using the strong priors on the planetary periods and times of transit given by the photometry. These parameters were estimated by fitting, on all the available Kepler short-cadence simple-aperture-photometry data \(^{19}\) (up to quarter Q17, with a 5\(\sigma\) outlier rejection), a model for each transit (Giménez 2006), and a straight line to the individual transit times. The ephemeris values are reported in Table 3 and are consistent within 1\(\sigma\) with those previously derived by Batalha et al. (2011) and later on by Fogtmann-Schulz et al. (2014).

The model that is fitted to the RV data includes two Keplerian signals, one for each planet, plus a RV offset \(RV_0\) to account for a possible offset between the data taken with the old and the new HARPS-N CCD:

\[
\Delta RV(t_i) = \gamma + RV_0(t_i) + \sum_{j=1}^{2} K_j \cos(\theta(t_i, T_{0,j}, P_j, e_j) + \omega_j) + \epsilon_j \cos(\omega_j),
\]

(1)

In this formula, \(\gamma\) is the systemic velocity of Kepler-10, and \(RV_0(t_i) = 0\) for \(t_i < \text{BJD}=2456185\) and a constant for \(t_i > \text{BJD}=2456185\). Each planet \(j\) is characterized by its semi-amplitude \(K_j\), period \(P_j\), time of periastron \(T_{0,j}\), eccentricity \(e_j\) and argument of periastron \(\omega_j\). The function \(\theta(t_i, T_{0,j}, P_j, e_j)\) is the true anomaly of the planet at time \(t_i\). In addition to this model, we also consider that Gaussian noise of stellar origin could affect the RVs. The choice of a Gaussian noise term was made because Kepler-10 does not show any significant sign of activity. Therefore, correlation between measurements due to active regions drifting on the stellar surface is not expected. However, granulation phenomena induced by stellar convection are known to induce correlated noise in the RVs (Dumusque et al. 2011b). With an effective temperature similar to the Sun, super granulation, which is the most important phenomenon of granulation, should induce a RV rms smaller than 1 m s\(^{-1}\) on the timescale of a day. This should perturb the RV signal of Kepler-10b only slightly because the RV semi-amplitude of this planet is three times bigger. In addition, the strategy of observing the target twice per night, over more than 70 nights, allows us to average out this correlated noise. Regarding Kepler-10c, we do not expect any perturbation as the timescale of super granulation and the planetary period are totally different. We concluded that no significant correlated noise should affect the RV measurements of Kepler-10, and we decided to only consider Gaussian noise when fitting the data.

Before starting any fitting procedure on the data, the \(T_{0,j}\) values for both planets were shifted close to the average date of the HARPS-N observations to limit error propagation when fitting the periods \(P_j\) and epochs \(T_{0,j}\). In addition, we used \(C^j = \sqrt{\sigma^j / \cos(\omega_j)}\) and \(S^j = \sqrt{\sigma^j / \sin(\omega_j)}\) as free parameters of the fit instead of \(e_j\) and \(\omega_j\). This modification allows a more efficient exploration of the parameter space in the case of small eccentricities (Ford 2006), which is the case for Kepler-10b and c (Fogtmann-Schulz et al. 2014). The model is then fitted to the data using a Markov Chain Monte Carlo (MCMC) algorithm that is similar to the one recently applied to the CoRoT-7 system (see R. D. Haywood et al., in preparation). The stellar signal contribution is modeled as a constant jitter term \(\sigma_j\) in addition to the RV instrumental noise \(\sigma_i\) returned by the HARPS-N pipeline. The following likelihood:

\[
\mathcal{L} = \frac{1}{\sqrt{2\pi(\sigma^2_i + \sigma^2_j)}} \exp \left[ -\frac{(RV(t_i) - \Delta RV(t_i))^2}{2(\sigma^2_i + \sigma^2_j)} \right]
\]

(2)

is used for the MCMC. Uniform priors were set on all the parameters with the constrain that the RV jitter and semi-amplitudes of both Kepler-10b and c must be greater or equal than zero. Gaussian priors for the period and the transit epoch of both planets were imposed based on our previous photometric ephemeris determination (see Table 3).

Although Fogtmann-Schulz et al. (2014) find very low eccentricities for both planets, we decided to test a model with free

---

19 http://keplergo.arc.nasa.gov/PyKEprimerLCs.shtml (Jenkins et al. 2010)
orbital eccentricities (13 parameters) as well as one with eccentricities fixed to zero (9 parameters). In order to assess which model is best, we calculated the marginal likelihood of each model according to the method of Chib & Jeliazkov (2001) (see the Appendix in R. D. Haywood et al., in preparation), which uses the posterior distributions of the MCMC chain. We obtained a Bayes factor of 10 in favor of the model with fixed zero eccentricities. While this does not constitute strong evidence, according to Jeffreys (1961), in favor of circular orbits, it implies that the penalty induced by the extra parameters needed to allow free eccentricities outweighs the increase in likelihood brought by the improvements to the fit. Indeed, when the eccentricities are free to vary, we obtain $0 < e_b < 0.12$ and $0 < e_c < 0.14$ which suggests that both orbits are compatible with circular orbits. The outcome of the circular orbit fit is shown in Table 3, where the modes of the marginal posteriors with their errors are shown. The phase-folded RVs with the best fit model for Kepler-10b and c can be found in Figure 4, and the posteriors for all the parameters with their mutual correlation can be found in Figure 5.

The RV semi-amplitudes found for Kepler-10b and c are in agreement with our preceding analyses within 1σ (see

<table>
<thead>
<tr>
<th>Stellar Parameters</th>
<th>RV Only</th>
<th>RV and Photometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Limb-darkening coefficient $\alpha_d$</td>
<td>...</td>
<td>0.40 ± 0.07</td>
</tr>
<tr>
<td>Limb-darkening coefficient $\beta_d$</td>
<td>...</td>
<td>0.27 ± 0.10</td>
</tr>
<tr>
<td>Systemic velocity $v$ (m s$^{-1}$)</td>
<td>$-98739.90 ± 0.42$</td>
<td>$-98739.89 ± 0.43$</td>
</tr>
<tr>
<td>RV offset $v_0$ (m s$^{-1}$)</td>
<td>1.83 ± 0.45</td>
<td>1.78 ± 0.32</td>
</tr>
<tr>
<td>Radial-velocity jitter (m s$^{-1}$)</td>
<td>$2.45^{+0.23}_{-0.21}$</td>
<td>2.47 ± 0.23</td>
</tr>
</tbody>
</table>

**Table 3**

Kepler-10 Planetary System Parameters

<table>
<thead>
<tr>
<th>Transit and orbital parameters</th>
<th>RV Only</th>
<th>RV and Photometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbital period $P$ (days)</td>
<td>0.8374907 ± 0.0000002</td>
<td>0.8374907 ± 0.0000002</td>
</tr>
<tr>
<td>Transit epoch $T_0$(BJD$_{TDB}$ − 2454900)</td>
<td>134.08687 ± 0.00018</td>
<td>134.08687 ± 0.00018</td>
</tr>
<tr>
<td>Transit duration $T_{14}$ (hr)</td>
<td>...</td>
<td>1.8110$^{+0.0064}_{-0.0036}$</td>
</tr>
<tr>
<td>Radius ratio $R_p/R_*$</td>
<td>...</td>
<td>0.01261$^{+0.00026}_{-0.00013}$</td>
</tr>
<tr>
<td>Inclination $i$ (deg)</td>
<td>...</td>
<td>84.9$^{+1.9}_{-3.9}$</td>
</tr>
<tr>
<td>$a/R_*$</td>
<td>...</td>
<td>3.46$^{+0.14}_{-0.28}$</td>
</tr>
<tr>
<td>Impact parameter $b$</td>
<td>...</td>
<td>0.31 ± 0.19</td>
</tr>
<tr>
<td>Orbital eccentricity $e$</td>
<td>0 (fixed)</td>
<td>0 (fixed)</td>
</tr>
<tr>
<td>Radial-velocity semi-amplitude $K$ (m s$^{-1}$)</td>
<td>2.38 ± 0.34</td>
<td>2.38 ± 0.35</td>
</tr>
</tbody>
</table>

**Planetary parameters**

| Planet mass $M_p(M_\oplus)$ | ... | 3.33 ± 0.49 |
| Planet radius $R_p(R_\oplus)$ | ... | 1.47$^{+0.03}_{-0.02}$ |
| Planet density $\rho_p$ (g cm$^{-3}$) | ... | 5.8 ± 0.8 |
| Planet surface gravity log $g_p$ (cgs) | ... | 3.18$^{+0.06}_{-0.07}$ |
| Orbital semi-major axis $a$ (AU) | ... | 0.01685 ± 0.00013 |
| Equilibrium temperature $T_{eq}$ (K) | ... | 2169$^{+96}_{-44}$ |

**Kepler-10b**

<table>
<thead>
<tr>
<th>Transit and orbital parameters</th>
<th>RV Only</th>
<th>RV and Photometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Orbital period $P$ (days)</td>
<td>45.294301 ± 0.000048</td>
<td>45.294301 ± 0.000048</td>
</tr>
<tr>
<td>Transit epoch $T_0$(BJD$_{TDB}$ − 2454900)</td>
<td>162.26648 ± 0.00081</td>
<td>162.26648 ± 0.00081</td>
</tr>
<tr>
<td>Transit duration $T_{14}$ (hr)</td>
<td>...</td>
<td>6.899$^{+0.058}_{-0.032}$</td>
</tr>
<tr>
<td>Radius ratio $R_p/R_*$</td>
<td>...</td>
<td>0.02014$^{+0.00081}_{-0.00081}$</td>
</tr>
<tr>
<td>Inclination $i$ (deg)</td>
<td>...</td>
<td>89.59$^{+0.25}_{-0.43}$</td>
</tr>
<tr>
<td>$a/R_*$</td>
<td>...</td>
<td>47.9$^{+2.0}_{-2.2}$</td>
</tr>
<tr>
<td>Impact parameter $b$</td>
<td>...</td>
<td>0.36$^{+0.25}_{-0.20}$</td>
</tr>
<tr>
<td>Orbital eccentricity $e$</td>
<td>0 (fixed)</td>
<td>0 (fixed)</td>
</tr>
<tr>
<td>Radial velocity semi-amplitude $K$ (m s$^{-1}$)</td>
<td>3.25 ± 0.36</td>
<td>3.26 ± 0.36</td>
</tr>
</tbody>
</table>

**Kepler-10c**

<table>
<thead>
<tr>
<th>Planetary parameters</th>
<th>RV Only</th>
<th>RV and Photometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>Planet mass $M_p(M_\oplus)$</td>
<td>...</td>
<td>17.2 ± 1.9</td>
</tr>
<tr>
<td>Planet radius $R_p(R_\oplus)$</td>
<td>...</td>
<td>2.35$^{+0.09}_{-0.04}$</td>
</tr>
<tr>
<td>Planet density $\rho_p$ (g cm$^{-3}$)</td>
<td>...</td>
<td>7.1 ± 1.0</td>
</tr>
<tr>
<td>Planet surface gravity log $g_p$ (cgs)</td>
<td>...</td>
<td>3.48$^{+0.05}_{-0.06}$</td>
</tr>
<tr>
<td>Orbital semi-major axis $a$ (AU)</td>
<td>...</td>
<td>0.2410 ± 0.0019</td>
</tr>
<tr>
<td>Equilibrium temperature $T_{eq}$ (K)</td>
<td>...</td>
<td>584$^{+50}_{-17}$</td>
</tr>
</tbody>
</table>

**Notes.** Kepler-10 planetary system parameters for the circular solution using the RV data only (with priors from photometry), and for the circular solution with the combined photometric and RV analysis. The error bars represent a 1σ uncertainty on the parameters.

* Black body equilibrium temperature assuming a zero Bond albedo and uniform heat redistribution to the night-side (Rowe et al. 2006).
These semi-amplitudes are estimated with an uncertainty of 14% and 11%, respectively. Looking at the GLS periodogram of the RV residuals after removing our best fit solution (see the left plot of Figure 6), the highest signal remaining in the data is found at \( \sim 17 \) days, with a FAP of 0.5%. The FAP of this signal is significant enough to try a three-planet model fit. Performing an MCMC with three circular planets converges to a realistic solution. Calculating the Bayes factor between the two and three-planet models results in a highly significant factor of \( e^{14} \) in favor of the more complex model. However, looking at the periodogram for each season of observation (see the right plot of Figure 3), the 17-day signal is only present in the second season. This signal is thus not a coherent signal of constant amplitude spanning both seasons, and therefore cannot be associated to a planet. When removing the RV measurements between BJD = 2456350 and BJD = 2456450 (31 points in total, equal to 20% of all the measurements), the 17-day signal disappear from the residuals (see the right plot of Figure 6). These rejected RV measurements seem affected by small activity variations that can be seen when looking at the calcium activity index variation (see left plot of Figure 1). The periodogram of the calcium activity index (see right plot of Figure 1) shows important, however, not significant variations. Even though Bayes factor favors a more complex model including an extra planet, an in-depth analysis is required to characterize the real nature of this extra signal.

4.6. Combined MCMC Analysis of the RVs and Kepler Photometry Considering RV Gaussian Noise

In this section, we proceed to a combined RV and photometric fit to determine the orbital and physical parameters of Kepler-10b and c by taking advantage of all the available Kepler data.

To derive the Kepler-10 system parameters, a Bayesian combined analysis of the Kepler short-cadence photometry and HARPS-N RV measurements was performed using a Differential Evolution Markov Chain Monte Carlo method (DE-MCMC; Eastman et al. 2013; Ter Braak 2006). For this purpose, the epochs of the HARPS-N observations were converted from BJD\(_{\text{UTC}}\) into BJD\(_{\text{TDB}}\) (Eastman et al. 2010), which is the time stamp of Kepler data. The light curves of Kepler-10b and 10c were phase-folded with our new ephemeris (see Table 3 and discussion in Section 4.5) and binned in samples of 4 s and 30 s, respectively, to significantly reduce the computation time of our combined analysis.

The HARPS-N RVs and the phase-folded and binned light curves of Kepler-10b and c were simultaneously fitted by considering a two-planet model with two Keplerian orbits and two transit models (Giménez 2006). Circular orbits were adopted for both planets based on the strong constraints from the asteroseismic density determination (Fogtmann-Schulz et al. 2014) and our analysis of HARPS-N RV measurements in Section 4.5. In total, our model has seventeen free parameters: the transit epochs, orbital periods, RV semi-amplitudes, transit durations, orbital inclinations, and planet-to-stellar radius ratios of Kepler-10b and c, the stellar systemic velocity, a RV offset between the HARPS-N measurements obtained with the old and the new CCD, an uncorrelated RV jitter term (e.g., Gregory 2005), and the limb-darkening coefficients which were fitted by using the triangular sampling method as suggested by Kipping (2013): \( q_1 = (u_a + u_b)^2 \) and \( q_2 = 0.5 u_a / (u_a + u_b) \), where \( u_a \) and \( u_b \) are the linear and quadratic coefficients of the limb-darkening quadratic law.

A Gaussian likelihood was maximized in our Bayesian analysis (see Equation (2)). Thirty-four DE-MCMC chains, i.e., twice the number of free parameters, were run simultaneously, after being started at different positions in the parameter space but reasonably close to the system values. The jumps of a given chain in the parameter space were determined from two random chains, according to the prescriptions given by Ter Braak (2006). The Metropolis-Hastings algorithm was used to accept or reject a proposal step for each chain. Uniform priors were set on all parameters with the constraints that the RV jitter and semi-amplitudes of both Kepler-10b and 10c must be greater or equal than zero, and \( q_1 \) and \( q_2 \) are allowed to vary in the interval \([0, 1]\) (Kipping 2013). Gaussian priors were imposed on the transit epochs and orbital periods based on our previous ephemeris determination (see Table 3). Unlike Fogtmann-Schulz et al. (2014), no prior was set on \( a/R \), because this prior strongly
Figure 5. Posterior distributions and correlation between the different MCMC parameters for the model with Gaussian noise and circular orbits. “RV offset” corresponds to the RV offset between the old and the new HARPS-N CCD, while “gamma” is the systemic velocity of Kepler-10.

(A color version of this figure is available in the online journal.)
affects the posterior distributions of transit parameters and yields unrealistic error bars.

The DE-MCMC analysis was stopped after convergence and well mixing of the chains were reached according to the Gelman–Rubin statistics ($\hat{R} < 1.03$ for all parameters; Gelman et al. 2004). Steps belonging to the “burn-in” phase were identified following Knutson et al. (2009) and excluded. Figure 7 shows the phase-folded and binned transits of Kepler-10b and c along with the best-fit models. The linear and quadratic limb-darkening coefficients $u_a = 0.40 \pm 0.07$ and $u_b = 0.27 \pm 0.10$ agree well with values predicted by Kurucz stellar models for the Kepler bandpass (Sing 2010), i.e., $u_a = 0.390 \pm 0.006$ and $u_b = 0.264 \pm 0.004$. We derived a radius of $1.47_{-0.03}^{+0.03} R_\oplus$, a mass of $3.33 \pm 0.49 M_\oplus$, and a density of $5.8 \pm 0.8 g cm^{-3}$ for Kepler-10b and a radius of $2.35_{-0.09}^{+0.09} R_\oplus$, a mass of $17.2 \pm 1.9 M_\oplus$, and a density of $7.1 \pm 1.0 g cm^{-3}$ for Kepler-10c.

5. KEPLER-10C DENSITY

Understanding the transition from rocky planets to planets defined by a hydrogen-dominated envelope is critical to planet formation theory. Kepler-10c stands out in the mass–radius diagram (Figure 8), in direct challenge to theory.

To begin with, it is possible to show that Kepler-10c cannot possess a hydrogen-dominated envelope. At 0.24 AU from a solar-luminosity star of very old age, Kepler-10c is too hot ($T_{eq} = 584 K$) to retain an outgassed hydrogen atmosphere, or an accreted hydrogen–helium mixture, as shown by applying Rogers et al. (2011) calculations for $T_{eq} = 500 K$ and the radius of Kepler-10c (all loss timescales are shorter than 1 Gyr).

Had Kepler-10c accreted a massive hydrogen–helium envelope 10.6 Gyr ago and still kept some of it, its radius would have to be larger than $3 R_\oplus$, similar to Kepler-20c (at $15.7 M_\oplus$ in Figure 8). Therein lies the challenge, as Kepler-10c is significantly above...
the theoretical critical mass of $10^{-12}$ $M_\oplus$ enabling envelope accretion (Ikoma & Hori 2012; Lopez & Fortney 2013), but has none.

Kepler-10c is best characterized as a solid planet, implying that its bulk composition is dominated by rocks (silicates, judging from the star’s composition) and a significant amount of volatile material of high mean molecular weight (i.e., water) of 5 to 20 wt.%. Even if that water is in a separate envelope, which is likely if it is more than 10 to 15 wt.% (Elkins-Tanton 2011), most of it will be in the form of solid high-pressure ices at age 10.6 Gyr (Zeng & Sasselov 2014). The precise amount of water in Kepler-10c cannot be constrained further, given the known compositional degeneracy of the mass–radius diagram (Valencia et al. 2007).

We note in Figure 8 that Kepler-10c is not alone in this region of the mass–radius diagram, as Kepler-131b ($P_{\text{orb}} = 16$ days, $16.1 \pm 3.5$ $M_\oplus$, $2.4 \pm 0.2$ $R_\oplus$; Marcy et al. 2014) lies very close to it. However, the mass determination of Kepler-131b is not as robust as for Kepler-10c and more data are required to assess if this planet is a twin of Kepler-10c.

Regardless of any water, Kepler-10c is a clear outlier, being many sigmas smaller in size than the densest Neptune-mass exoplanet Kepler-20c. Except Kepler-131b for which the density still have to be measured more precisely, the exoplanets that appear closest to Kepler-10c in composition, 55 Cnc e and Kepler-20b, are half its mass. They are also both extremely close to their stars and hot, so it is not entirely clear how much the water they contain would contribute to their radii.

Kepler-10 has a space motion and an age characteristic of the old thick disk population, though with $[\text{Fe}/\text{H}] = -0.15$, it is not as metal poor as the typical thick disk metallicity of about $[\text{Fe}/\text{H}] = -0.6$. This implies caution regarding the Fe/Mg and Fe/Si ratios in the proto-planetary disk from which Kepler-10b and 10c formed. The model composition curves on Figure 8 assume solar ratios (Zeng & Sasselov 2013); the expected variations due to expected enhancements are of 1%–2% in planet radius (Grasset et al. 2009). Kepler-10b and c might differ in their internal structure in the amount of Fe that is differentiated in their core; for the high mass of Kepler-10c full differentiation is questionable, but given its water content, the oxidation state of Fe is unclear (Zeng & Sasselov 2013). These uncertainties and the comparison to Kepler-10b imply that Kepler-10c could also have no bulk water, which remains the best composition for Kepler-10b.

6. CONCLUSION

We revisited the Kepler-10 planetary system using the HARPS-N spectrograph. In total, 148 high-quality RV measurements of the star were obtained, which is nearly four times as many as the Keck-HIRES RV campaign reported in the discovery paper (Batalha et al. 2011). Using an optimized sampling, we were able to recover the signal of both planets, with a precision on the mass$^{20}$ of 15% and 11% for Kepler-10b and c, respectively.

Kepler-10b is a hot rocky world with a mass of $3.33 \pm 0.49$ $M_\oplus$ and a radius of 1.47$^{+0.03}_{-0.02}$ $R_\oplus$, which implies a bulk density of $5.8 \pm 0.8$ g cm$^{-3}$, slightly higher than the Earth, and an internal structure and composition very similar to Earth.

Kepler-10c is a Neptune mass planet with a density higher than the Earth. Our best estimate of its mass is $17.2 \pm 1.9$ $M_\oplus$ for a radius of only $2.35^{+0.09}_{-0.04}$ $R_\oplus$, which yields a density of $7.1 \pm 1.0$ g cm$^{-3}$. With these properties, Kepler-10c is

---

$^{20}$ It is not surprising that the precision on the mass of Kepler-10b is two times better than the previous value (28%; Batalha et al. 2011). With four times as many observations of similar precision (see Pepe et al. 2013; Howard et al. 2013), we expect an improvement of a factor of two, everything else being equal.
best characterized as a solid planet, implying that its bulk composition is dominated by rocks and a significant amount of water, about 5 to 20 wt.%

Kepler-10c might be the first firm example of a population of solid planets with masses above 10 $M_{\oplus}$. From a recent theory of gas accretion at short orbital periods, the critical core mass required to accrete the gas present in the protoplanetary disc onto the planet is $M_{cr} \approx 2.6 M_{\oplus}$ ($\eta/0.3)^{1/2}$ ($P_{orb}/1$ day)$^{5/12}$, where $\eta = M_{crit}/M_{\star}$ is the fractional mass comprised by the atmosphere (Rafikov 2006). If this model is correct, it implies that the core mass limit for gas accretion should increase with orbital period. A recent study from Buchhave et al. (2014), analyzing hundreds of Kepler candidates, seems to agree with this theoretical prediction. With a period of 45.29 days, a radius of 2.35 $R_{\oplus}$, and a density higher than Earth, Kepler-10c would be at the limit of the transition from terrestrial to gaseous planets observed by Buchhave et al. (2014). Kepler-10c might be the first object confirming that longer period terrestrial planets can be more massive than ones with shorter periods. We note that Kepler-131b ($P_{orb} = 16$ days, $16.1 \pm 3.5 M_{\oplus}$, $2.4 \pm 0.2 R_{\oplus}$, Marcy et al. 2014) lies in the same location of the mass–radius diagram as Kepler-10c. However the mass determination of Kepler-131b is not as robust as for Kepler-10c and more data are needed to confirm the high density of this planet. Measuring precisely the mass of several other long-period Kepler candidates orbiting bright stars could test this speculation. This experiment has just been started as a new observational program on HARPS-N.

The mass determination of Kepler-10c with HARPS-N shows once more how ground-based RV spectrophotographs and photometric transit surveys such as Kepler can work together to efficiently measure the densities of small planets. Such observational studies are crucial to constrain theoretical models of internal structure and composition of small-radius planets.

Although Kepler-10c induces a gravitational effect on its host star three times greater than the instrumental precision of HARPS-N, determining its mass to a satisfactory degree of precision required an important RV follow-up campaign; this is because Kepler-10 is a faint star for high-resolution spectroscopy. It is essential that future transit searches focus on bright stars in order to allow high-quality RV follow-up needed to measure planet masses with a 10% precision. The upcoming Kepler K2 mission (Howell et al. 2014) should provide soon a few interesting candidates. Then, in a few years, the TESS satellite (Ricker et al. 2010) should provide hundreds of candidates by performing an all sky survey of short-period transiting planets orbiting stars brighter than $V = 12$. On the longer term, PLATO (Rauer et al. 2013) will look for habitable Earth-like planets around those same bright stars.

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