Kepler-9 revisited
60% the mass with six times more data

Stefan Dreizler and 1 Aviv Ofir 1,2

1 Institut für Astrophysik, Georg-August-Universität, Friedrich-Hund-Platz 1, 37077 Göttingen, Germany
2 Kepler Participating Scientist
e-mail: dreizler@astro.physik.uni-gottingen.de

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ABSTRACT

Aims. Kepler-9 was the first case where transit timing variations have been used to confirm the planets in this system. Following predictions of dramatic TTVs - larger than a week - we re-analyse the system based on the full Kepler data set.

Methods. We re-processed all available data for Kepler-9 removing short and long term trends, measured the times of mid-transit and used those for dynamical analysis of the system.

Results. The newly determined masses and radii of Kepler-9b and -9c change the nature of these planets relative to the one described in Holman et al. 2010 (hereafter H10) with very low, but relatively well characterised (to better than 7%), bulk densities of 0.18 and 0.14 g cm\(^{-3}\) (about 1/3 of the H10 value). We constrain the masses (45.1 and 31.0 M\(_{\oplus}\), for Kepler-9b and -9c respectively) from photometry alone, allowing us to see possible indications for an outer non-transiting planet in the radial velocity data. At 2R\(_{\oplus}\) Kepler-9d is determined to be larger than suggested before - suggesting that it is a low-mass low-density planet.

Conclusions. The comparison between the H10 analysis and our new analysis suggests that small formal error in the TTV inversion may be misleading if the data does not cover a significant fraction of the interaction time scale.

Key words. Planets and satellites: detection, dynamical evolution and stability, fundamental parameters, individual: Kepler-9b, Kepler-9c

1. Introduction

Transit timing variations (TTVs) are deviations from strict periodicity in extra solar planetary transits, caused by non-Keplerian forces – usually the interaction with other planets in the system. These TTVs are particularly important in multi-transiting systems since they can allow learning about dynamics in the system, which in turn can confirm the exoplanetary origin of the transit signals with no further observations [e.g. Holman et al. 2010, H10 hereafter, or Xie et al. 2013], and sometimes even allow deriving the planets’ mass from photometry alone (Kepler-87, Ofir et al. 2014). For these reasons TTVs had attracted a lot of attention since they were first predicted by Holman & Murray (2005) and Agol et al (2005), and especially since they where first observed by H10 in the prototypical Kepler-9 system.

Kepler-9 is prototypical not just because it was the first object detected with TTVs, but also since it is a textbook-like example of TTVs: exhibiting very large TTVs on very deep transits, making the effect abundantly clear. The first study of the Kepler-9 system also included a prediction for the expected TTVs during the following few years (their Figure S4) which included dramatic TTV spanning up to about +3.5d relative to the nominal ephemeris, accumulated over long interaction times scales (e.g. ~1000d from first maximum to first minimum TTV excursion of Kepler-9c).

These very large TTVs are easy to compare to the observed ones in later Kepler data. Indeed by the time we re-analysed this object much more data were available, revealing that the actual TTVs, while still large, were much less extreme than initially predicted. We observed TTV spans of about +0.5d for the same features as above, and TTV time scale about half as long as predicted. These prompted us to re-visit the analysis of Kepler-9.

This paper is therefore divided in the following way: in sections 2 and 3 we describe the input data and TTV analysis procedures we used. In 4 we made sure we are able to recover the H10 results when using only the data that was available at the time, showing consistent analysis, which then allowed us to perform a full analysis using the full data set in 5 before discussing the updated analysis in 6.

2. Photometry and light curve modeling

We processed quarters 1 through 16 of Kepler-9 long cadence photometry which spans 1426d, more than six times longer than the original study of H10. We processed it similarly to the processing of Kepler-87 (Ofir et al. 2014), fitting for Kepler-9b and Kepler-9c’s individual times of mid-transit, and fitting Kepler-9d using linear ephemeris since we detected no TTVs for it. In short, this processing used a light curve that was corrected for short-term systematic effects using the SARS algorithm (Ofir et al. 2010, Ofir & Dreizler 2013), which was then iteratively: fitted for long-term trends, modeled for its transit signals, and corrected for the model by dividing it out – till convergence.
Table 1. All fitted parameters from the light curve modeling of the Kepler-9 system. Note a few non-fitted parameters are also given for convenience: the linear periods of Kepler-9b and Kepler-9c, which exhibit TTVs, are computed from the individual times of mid-transit, and the different semi-major axes $a$ are actually a single parameter common to all planets scaled using Kepler's laws. All times ($T_{mid}$ parameters) are measured relative to BJD-2454933.0.

| param  | BestFit | $\sigma$ range | 50%      | 1σ range |
|--------|---------|----------------|----------|----------|
| Linear $P_b$ | 19.2471658 | 19.2471669 | +0.1340 | 0.000036 |
| a/R_\star | 25.00 | 24.95 | +0.15 | +0.00036 |
| r_b/R_\star | 0.208243 | 0.082515 | +0.00009 | +0.000009 |
| Linear $P_c$ | 38.944030 | 38.944011 | +0.000102 | +0.000093 |
| a_c/R_\star | 40.00 | 39.91 | +0.27 | +0.000000 |
| r_c/R_\star | 0.07963 | 0.0764 | +0.27 | +0.000019 |
| b_c/R_\star | 0.8619 | 0.8624 | +0.082483 | +0.082515 |
| P_b/2 | 1.59295922 | 1.59295878 | +0.000009 | +0.000000 |
| Linear $T_{mid,3}$ | 800.15785 | 800.15795 | +0.000020 | +0.000000 |
| a_d/R_\star | 4.748 | 4.738 | +0.32 | +0.000000 |
| r_d/R_\star | 0.01508 | 0.01517 | +0.00013 | +0.000000 |
| b_d/R_\star | 0.6955 | 0.6951 | +0.064 | +0.000000 |

| param | BestFit | $\sigma$ range | 50%      | 1σ range |
|--------|---------|----------------|----------|----------|
| Tmid,b | 44.24962 | 44.24968 | +0.000000 | +0.000000 |
| Tmid,b | 63.48423 | 63.48436 | +0.000000 | +0.000000 |
| Tmid,d | 101.95597 | 101.95545 | +0.000000 | +0.000000 |
| Tmid,d | 121.19173 | 121.19124 | +0.000000 | +0.000000 |
| Tmid,d | 140.43520 | 140.43504 | +0.000000 | +0.000000 |
| Tmid,d | 178.92599 | 178.92624 | +0.000000 | +0.000000 |
| Tmid,d | 198.17235 | 198.17249 | +0.000000 | +0.000000 |
| Tmid,b | 217.42998 | 217.42953 | +0.000000 | +0.000000 |
| Tmid,b | 236.68239 | 236.68220 | +0.000000 | +0.000000 |
| Tmid,c | 255.94584 | 255.94603 | +0.000000 | +0.000000 |
| Tmid,b | 275.20392 | 275.20414 | +0.000000 | +0.000000 |
| Tmid,b | 294.47506 | 294.47509 | +0.000000 | +0.000000 |
| Tmid,d | 313.73752 | 313.73698 | +0.000000 | +0.000000 |
| Tmid,d | 333.01416 | 333.01480 | +0.000000 | +0.000000 |
| Tmid,b | 352.28282 | 352.28264 | +0.000000 | +0.000000 |
| Tmid,b | 371.56419 | 371.56349 | +0.000000 | +0.000000 |
| Tmid,b | 390.85365 | 390.83622 | +0.000000 | +0.000000 |
| Tmid,b | 410.11896 | 410.11837 | +0.000000 | +0.000000 |
| Tmid,d | 429.39832 | 429.39413 | +0.000000 | +0.000000 |
| Tmid,b | 448.67952 | 448.68016 | +0.000000 | +0.000000 |
| Tmid,b | 467.95695 | 467.95682 | +0.000000 | +0.000000 |
| Tmid,b | 487.24089 | 487.24071 | +0.000000 | +0.000000 |
| Tmid,b | 506.5199 | 506.5196 | +0.000000 | +0.000000 |
| Tmid,b | 525.80356 | 525.80302 | +0.000000 | +0.000000 |
| Tmid,b | 545.07889 | 545.07896 | +0.000000 | +0.000000 |
| Tmid,b | 564.36033 | 564.36037 | +0.000000 | +0.000000 |
| Tmid,b | 583.65369 | 583.65378 | +0.000000 | +0.000000 |
| Tmid,b | 602.90982 | 602.90991 | +0.000000 | +0.000000 |
| Tmid,b | 641.45176 | 641.45165 | +0.000000 | +0.000000 |
| Tmid,b | 660.7231 | 660.7215 | +0.000000 | +0.000000 |
| Tmid,b | 679.98214 | 679.98182 | +0.000000 | +0.000000 |
| Tmid,b | 699.24308 | 699.24380 | +0.000000 | +0.000000 |
| Tmid,b | 718.49797 | 718.48967 | +0.000000 | +0.000000 |
| Tmid,b | 737.75264 | 737.75284 | +0.000000 | +0.000000 |
| Tmid,b | 757.00132 | 757.00190 | +0.000000 | +0.000000 |
| Tmid,b | 776.24954 | 776.24997 | +0.000000 | +0.000000 |
| Tmid,b | 795.49196 | 795.49128 | +0.000000 | +0.000000 |
| Tmid,b | 814.73192 | 814.73155 | +0.000000 | +0.000000 |
| Tmid,b | 833.96754 | 833.96814 | +0.000000 | +0.000000 |
| Tmid,b | 853.20484 | 853.20451 | +0.000000 | +0.000000 |
| Tmid,b | 872.43257 | 872.43290 | +0.000000 | +0.000000 |
| Tmid,b | 891.66331 | 891.66329 | +0.000000 | +0.000000 |
| Tmid,b | 910.88965 | 910.88962 | +0.000000 | +0.000000 |
| Tmid,b | 930.11432 | 930.11491 | +0.000000 | +0.000000 |
| Tmid,b | 949.33775 | 949.33794 | +0.000000 | +0.000000 |
| Tmid,b | 968.56094 | 968.56129 | +0.000000 | +0.000000 |
The resultant photometric model parameters are given in Table 1.

3. TTV modeling

We did not include Kepler-9d in the TTV modeling since it is dynamically decoupled from the outer two planets (see also Section 5). For the modeling of the TTVs we use the mercury6 code (Chambers & Mignard, 1993, Chambers, 1999). The integration of the planetary orbits is done using the Bulirsch-Stoer integrator implemented in mercury6 starting from a set of initial values for the orbital elements for the planetary system. For integration of orbits in the Kepler-9 system, we use a time step of 0.5 days, i.e. about one 40th of the orbital period of planet b. The duration of the integration is limited to the duration of the Kepler mission. From the osculating orbital elements at each time step we calculate the next transit time. The final transit times are then calculated from spline interpolations. These calculated and the observed mid transit times are used to run a Levenberg-Marquardt optimization resulting in an optimized parameter set for the planetary system.

Since the fit may depend on the choice of the initial values, we use the best fit parameters as well as the formal fit errors from the covariance matrix for a second extended fit. Within the 3-σ limit we randomly vary the start parameters, however obeying parameter limits, e.g. positive eccentricity, if required. This procedure probes the χ²-landscape around the initial best fit value, it typically finds a better best fit and we use the distribution of parameters as an estimate of the error bars.

As a final check, we also integrate the best fit orbital solution over 5 Gyr using the hybrid-symplectic integrator of mercury6 at a time step of 0.8 days. Only a long-term stable solution is accepted.

4. Recovery of previous results

In a first step, we use the TTV data from H10 in order to demonstrate that we can recover their solution. Given the rather low number of TTV measurements, we restrict the orbits to coplanar orbits, given the low dispersion in measured inclinations that seems not to be a restrictive constraint. The free parameters therefore are the orbital period, eccentricity, argument of periastron, and mean anomaly at the beginning of the integration for each of the two planets. We take the mass of the central star as input with a distribution according to Havel et al. (Havel et al., 2011). During each fit, the stellar mass is fixed. Instead of using the planetary masses as parameters, the mass of planet b is given relative to the stellar mass, the mass of planet c relative to that of planet b. We use 2500 random starting values for the Levenberg-Marquardt optimization as described in Sect. 5. As also discussed by H10, the planetary masses can only be weakly constrained from the partial TTV data set. We therefore also included the radial velocity (RV) measurements from H10 in our fit for the partial data set.

Our best fit parameters for the partial data set are summarized in Table 2 and compared to previous results. Our error bars are taken from the distribution of parameters as shown in Figures 1 and 2. The best fit model compared to the RV data is shown in Figs. 3. The comparison with Fig. (3) of H10 shows an nearly identical situation: The observed RV variations can be matched reasonably well, however, the deviation between the model and observation is up to 8 m/s and larger then expected given the error bars. Like in H10, we also conclude that more RV observations would be necessary to check for the influence of additional planets or stellar activity jitter. In Fig. 4 we show the TTV data together with our best fit of the partial data set and in Fig. 5 we show the residuals to that fit. The reduced χ² of 2.4 is dominated by the deviations from the RV measurements while the TTV measurements can be matched within their error bars.

Table 2. Parameters of the planetary system of Kepler-9 derived from the TTV analysis using the partial data set of H10. The stellar mass is an input parameter with a distribution according to Havel et al. (2011). The osculating orbital elements are given at a reference time BJD=2454900.0. For comparison, we list the literature value for the stellar mass (Havel et al., 2011) and those of the the planetary parameters from H10.

| Parameter | this work | Holman et al. |
|-----------|-----------|---------------|
| m_1 [M_⊙] | 1.05±0.03 | 1.05 ± 0.03   |
| m_2 [M_⊙] | 0.14 ± 0.02 | 0.13 ± 0.04   |
| m_3 [M_⊙] | 0.08 ± 0.01 | 0.13 ± 0.04   |
| P_b [days] | 19.2159 ± 0.0008 | 19.2372 ± 0.0007 |
| P_c [days] | 39.084 ± 0.003 | 38.992 ± 0.005 |
| a_b [AU] | 0.143 ± 0.001 | 0.140 ± 0.001 |
| a_c [AU] | 0.229 ± 0.002 | 0.225 ± 0.001 |
| e_b | 0.10 ± 0.02 | 0.15 ± 0.04 |
| e_c | 0.08 ± 0.02 | 0.13 ± 0.04 |
| ω_b [°] | 357.5 ± 21.0 | 18.6 ± 1.2 |
| ω_c [°] | 101.5 ± 4.0 | 101.3 ± 9.6 |

Fig. 1. Distribution of derived mass of planet b (black solid line) derived using the partial data set. The Gauss fit to this distribution is shown as black dotted line. The best fit as well as the 1σ error range is indicated as red dotted line. The median of the distribution is indicated as black dashed line. The planetary mass and its uncertainty derived by H10 is indicated as green dashed-dotted line.
Fig. 2. Distribution of derived mass of planet c (black solid line) derived using the partial data set. The Gauss fit to this distribution is shown as black dotted line. The best fit as well as the 1σ error range is indicated as red dotted line. The median of the distribution is indicated as black dashed line. The planetary mass and its uncertainty derived by H10 is indicated as green dashed-dotted line.

Fig. 3. Radial velocity measurements from H10 compared to those predicted by our best fit for the partial data set. The time is given as BJD - 2454933.0.

Fig. 4. Transit timing variation measurement, i.e. the difference between the observed transit times and a linear ephemeris, of planet b (top) and planet c (bottom). Data by H10 (large circles) compared to our best fit (red squares) obtained using only these early TTV measurements. Error bars are smaller than the symbols. The small circles indicate the following transit times variations against the same linear ephemeris as later observed by Kepler. The time is given as BJD - 2454933.0.

Fig. 5. Deviation between the measured transit timing variations of planet b (top) and planet c (bottom) planet by H10 and our best fit. The time is given as BJD - 2454933.0.

5. TTV analysis using the full data set

We repeated the analysis using the full data set in the same way as described in the previous section, except that we now allow for non coplanar orbits and increased the number of random starting values to 3000 (see Figures 6 and 7). The full data set also allows to constrain the planetary masses without including the RV data in the fit. As expected from the poor agreement between the extrapolated solution from the partial data set, the planetary parameters changed. The main change is a significant reduction of the planetary masses in our new fit, while the mass ratio agrees within the error range. In Table 3 we compare the new parameters to those we obtained from the partial
Table 3. Fitted parameters (upper block) of the planetary system of Kepler-9 derived from the TTV analysis using the full Kepler data set. The oscillating orbital elements are given at a reference time BJD=2454933.0. The stellar mass is an input parameter with a distribution according to Havel et al. (2011), i.e. our errors take the uncertainties in the stellar mass into account. For comparison, we list our best fit parameters based on the TTV measurements from H10 (see Table 2). Note that those orbital elements are given at a reference time BJD=2454900.0. We also list derived quantities (lower block) for the stellar radius, the planetary masses, radii, orbital periods, and densities using the fitted parameters $a/R_*$ and $r/R_*$ from Table 1.

| Parameter this work | full data set without RV | this work partial data set with RV best fit $\sigma$ best fit $\sigma$ |
|---------------------|--------------------------|--------------------------|
| $m_*$ [M$_{\odot}$] | 1.05 0.03 | 1.05 0.03 |
| $m_0/m_*$ [M$_{\odot}$/M$_{\odot}$] | 43.0 0.7 | 75.4 3.3 |
| $m_0/m_b$ | 0.6875 0.0003 0.69 0.004 |
| $P_0$ [days] | 19.22418 0.00007 19.2159 0.0008 |
| $P_0$ [days] | 39.03106 0.0002 39.084 0.003 |
| $e_0$ | 0.0626 0.001 0.10 0.02 |
| $e_0$ | 0.0084 0.0002 0.08 0.02 |
| $i_0$ [°] | 87.1 0.7 | not fitted |
| $i_0$ [°] | 87.2 0.7 | not fitted |
| $\omega_0$ [°] | 356.9 0.5 | 357.5 21.0 |
| $\omega_0$ [°] | 169.3 0.2 | 101.5 4.0 |
| $M_0$ [°] | 337.4 0.6 | 105.3 23.1 |
| $M_0$ [°] | 313.5 0.1 | 36.6 20.6 |
| $r_*$ [R$_*$] | 1.23 0.01 |
| $m_0$ [M$_{\odot}$] | 45.1 1.5 | 79.6 3.6 |
| $m_0$ [M$_{\odot}$] | 31.0 1.0 | 54.8 2.6 |
| $r_0$ [R$_*$] | 11.1 0.1 |
| $r_0$ [R$_*$] | 10.7 0.1 |
| $a_0$ [AU] | 0.143 0.001 0.143 0.001 |
| $a_0$ [AU] | 0.229 0.002 0.229 0.002 |
| $a_0$ [AU] | 0.0271 0.0001 |
| $p_0$ [g cm$^{-3}$] | 0.18 0.01 |
| $p_0$ [g cm$^{-3}$] | 0.14 0.01 |

The discrepancy of the observed and calculated RV variations as well as possible slight systematic residuals in the TTVs of planet c raised the question whether or not we can find evidence for a forth, possibly non-transiting planet in the system. We therefore first searched for additional transiting planets in the system in the photometric model’s residuals using Optimal BLS (Ofir 2014) but found none. We also repeated the dynamical analysis adding an outer, co-planar, plane to the system. Since the parameter range for an outer planet is huge, we restricted our search to orbits of the test planet in 3:2, 2:1, 5:2, and 3:1 mean motion resonances to planet c. No solution with a better reduced $\chi^2$ could be found. We note that the short time span of the RV data – less than one orbit of Kepler-9c – severely limit the orbits that one can hope to fit to such a test outer planet.

Additionally, we have also checked our assumption that planet d has no impact on our results: We included planet d in the dynamical model by fixing its orbital period at the measured value, assuming a co-planar and circular orbit, the latter motivated by the short circularization time scale at the small orbit distance, and determined the mean...
Fig. 8. Transit timing variation measurement, i.e. the difference between the observed transit times and a linear ephemeris, of planet b (top) and planet c (bottom) planet (large circles) compared to our best fit (red squares) obtained using the full Kepler data set. The error bars are smaller than the size of the symbols. The small circles indicate the following transit times variations against the same linear ephemeris. The time is given as BJD - 2454933.0.

Fig. 9. Deviation between the measured transit timing variations of planet b (top) and planet c (bottom) planet and our best fit using the full data set. The time is given as BJD - 2454933.0.

Fig. 10. Radial velocity measurements from H10 compared to those predicted by our best fit using the full data set. We note that we do not include the RV data into our fit procedure but just derive it from the best fit model. The time is given as BJD - 2454933.0.

Fig. 11. Residuals of radial velocity measurements from H10 compared to those predicted by our best fit using the full data set. The time is given as BJD - 2454933.0.

A more extended RV follow-up would be necessary in order to come to a more conclusive result.

6. Discussion and conclusion

6.1. Partial vs. full dataset

We re-analysed the Kepler-9 system using both the partial Kepler data set that was available to H10 and the full data set available today. The comparison between the previous and new results show, that a very good fit to a planetary system in first order mean motion resonance can be misleading if only a fraction of the interaction time scale is covered. Even the much longer currently available Kepler data set might not be sufficiently long for that. We therefore follow H10 and extrapolated our best fit model into the future (Fig. 8 and Table 4). Given the large TTVs, ground based observations even with a marginal detection of the
Table 4. Predicted future transit time for planet b and planet c from our best fit using the full data set. The time is given as BJD - 2454933.0

| planet b          | 1468.30491 1853.2171 2238.0993 2623.31170 |
|-------------------|---------------------------------------------|
| 1487.53311        | 1872.4837 2257.9648 2642.53063             |
| 1506.76023        | 1891.7648 2277.2149 2661.74940             |
| 1525.98749        | 1911.0370 2296.4624 2680.96384             |
| 1545.21757        | 1930.3289 2315.7044 2700.18775             |
| 1564.44709        | 1949.5967 2334.9427 2719.09022             |
| 1583.68102        | 1968.8823 2354.1816 2738.62704             |
| 1602.91356        | 1988.1597 2373.4175 2757.84566             |
| 1622.15229        | 2007.4451 2392.6472 2777.06742             |
| 1641.38867        | 2026.7326 2411.8786 2796.28738             |
| 1660.63310        | 2046.0673 2431.1035 2815.50893             |
| 1679.87441        | 2065.2845 2450.3308 2834.72942             |
| 1699.12498        | 2084.5652 2469.5521 2853.95164             |
| 1718.37136        | 2103.8407 2488.7755 2873.17278             |
| 1737.62904        | 2123.1176 2507.9955 2892.39566             |
| 1756.88121        | 2142.3891 2527.2170 2911.61740             |
| 1776.14570        | 2161.6603 2546.4353 2930.84130             |
| 1795.40378        | 2180.9271 2565.6558 2950.06446             |
| 1814.67463        | 2200.1917 2584.8741 2969.28904             |
| 1833.93085        | 2219.4528 2604.0936 2988.51385             |

| planet c          | 1477.96294 1807.5156 2225.75156 2646.06579 |
|-------------------|---------------------------------------------|
| 1517.01523        | 1906.3267 2294.6907 2685.14079             |
| 1556.55655        | 1945.1225 2333.6613 2724.21523             |
| 1595.07993        | 1983.9135 2372.6605 2736.82891             |
| 1634.98355        | 2024.7038 2411.6835 2802.36177             |
| 1673.06218        | 2061.4967 2450.7255 2841.43735             |
| 1712.01228        | 2100.3014 2488.7812 2880.50445             |
| 1750.93174        | 2139.1240 2528.8462 2919.57315             |
| 1789.82030        | 2177.9703 2567.9170 2958.63851             |
| 1828.67971        | 2216.8452 2606.9903 2997.96945             |

H10 could confirm the Kepler-9b and Kepler-9c as planets from photometry alone, but could only place weak constraints on their masses without using RV data. They therefore included a few RV measurements in their fit, and it comes as no surprise that the RV fit is good since the partial photometry of the time did not have the constraining power to match the RV data. The peak is given as BJD - 2454933.0. We note, however, that the systematic residuals shown in Fig. 10 and especially Fig. 11 cause us to warn of unmodeled phenomena, such as other planets in the system or longer time-scale interaction between the planets or stellar activity.

6.2. The revised planets

The scaled radii \( \rho \) and \( R \) we determined are slightly larger than the ones obtained by H10 by \( \sim 3\sigma \) and \( \sim 4.5\sigma \) for Kepler-9b and Kepler-9c, respectively. The new values are much more constrained with formal errors 5 to 8 times smaller. Actually, Kepler’s data allows in principle to determine the planets’ mass to 2.8% and the planets’ radii to better than 0.2% – but those are limited by our knowledge of the host star properties. Furthermore, Kepler-9 was measured in short cadence mode (1 minute sampling instead of the regular 30-minute sampling) starting from Quarter 7, which allows for an even better timing precision (and thus mass determination). While we did not use short cadence data, using this data would have had little effect on the global uncertainty which is dominated by stellar parameters errors.

The newly determined masses and radii of Kepler-9b and -9c change the nature of these planets relative to the one described in H10. Both planets are now determined to have sizes similar to Jupiter’s but they are 7 to 10 times less massive than Jupiter, i.e. have densities about 1/3 of the density given in H10. Consequently, both planets have very low derived densities of \( \rho_b \approx 0.18 \text{ g cm}^{-3} \) and \( \rho_c \approx 0.14 \text{ g cm}^{-3} \) – among the lowest known. H10 specifically excluded coreless models for the planets, but the more abundant data we have today forces us to reconsider that Kepler-9b and -9c may not have cores at all. This result is of special interest in the context of the core accretion theory (Pollack et al. 1996): with masses of 30.6 and 44.5 M\(_{\oplus}\) these planets have apparently just started their runaway growth when it stopped at this relatively rare intermediate mass.

Figure 12 shows the masses and radii of lower-mass \( (M < 100 M_{\oplus}) \) planets that have both mass and radius known to better than \( \sim 3\sigma \). It is evident that the new locations of Kepler-9b and -9c put them at the edge of the mass-radius distribution, with very low density and in a mass range that is very poorly sampled, and yet – both planets are now among the best-characterized exoplanets known with bulk densities known to 7% or better. The recent successful launch of the GAIA mission further highlights that last point: the knowledge about both Kepler-9b and -9c in both radius and mass is limited by the knowledge about their host star, GAIA’s observations will fix Kepler-9’s properties to high precision, allowing to use other data (such as the available short cadence data) to further reduce the uncertainty on the physical parameters of Kepler-9b and -9c, and significantly so.

Finally, we note that Kepler-9d is now determined to have a radius of \( 2.00 \pm 0.05 R_{\oplus} \), an increase relative to H10. The increased size, together with the low metal content of its neighboring planets, suggest that Kepler-9d may not be rocky, or at least that it may have a significant volatiles fraction, again unlike the initial suggestion by H10. If this is true, then Kepler-9d is perhaps similar to the new and exciting subgroup of low-mass, low-density planets (e.g. Kepler-87c or GJ 1214b) (Ofir et al. 2014; Charbonneau et al. 2009; Fortney et al. 2013).

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1 Extracted from the NASA Exoplanet Archive (http://exoplanetarchive.ipac.caltech.edu/) on January 21, 2014
Fig. 12. The mass-radius distribution of all well determined planets (both mass and radii determined to better than 3$\sigma$). For each planet the mass- and radius- semi-major axes represent the 1-$\sigma$ error bar, and the transparency is such that better determined planets are more opaque. Contours of constant bulk density are shown in dashed gray lines. The names of some of the better-determined planets are indicated. All planets are shown in shades of blue, but Kepler-9 which is shown in shades of red: larger (and more transparent) symbols for the H10 values, and smaller (and more opaque) symbols for the current study’s values. Solar system planets are shown as letters.

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