The Densities of Planets and Masses of Host Stars

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Abstract.
Studies of transiting extra-solar planets are of key importance for understanding the nature of planets outside our Solar System, because their densities can be determined, constraining of what the planets are made of. Using the data obtained by the CoRoT space telescope we study the relation between the density of planets, their mass, and the mass of their host stars. Although planets of the same mass can have different densities, we still find some trends. Planets with more than 1000 $M_{\text{Earth}}$ (\(\sim 3 M_{\text{Jup}}\)) have densities larger than 6 g cm$^{-3}$, and are preferentially found in stars that are more massive than the Sun. All known planets in the mass-range between 15 and 600 $M_{\text{Earth}}$ (\(\sim 0.05 M_{\text{Jup}}\)) have densities of less than 3 g cm$^{-3}$. When going further down in the mass of the planets, the density increases steadily, and there is no sudden transition from gaseous to rocky planets. Based on the current sample, we do not find any difference for planets at different galactocentric distances.

Keywords. stars: planetary systems

1. Introduction
Studies of transiting extra-solar planets are of key importance for understanding the nature of planets outside our Solar System, because their mass, diameter, and hence their bulk density can be derived. The density is a key parameter, because it gives us information on the structure and composition of the planets. Space-telescopes like CoRoT and Kepler are particularly suitable for such studies, because they allow us to study large and small planets orbiting different types of stars.

In our Solar System we have basically two species of planets: gas or ice giants which have masses larger than 15 $M_{\text{Earth}}$ (\(\sim 0.05 M_{\text{Jup}}\)) and densities between 0.7 to 1.6 g cm$^{-3}$, and rocky planets (Mercury, Venus, Earth and Mars) which have densities from 3.7 to 5.5 g cm$^{-3}$. It is thus natural to expect that planets outside the Solar System should have the same properties: Planets with more than 15 $M_{\text{Earth}}$ should have a low density, and planets with the mass of the Earth should have a high density. The transition between these two types of planets is expected to be somewhere between 1 and 15 $M_{\text{Earth}}$. In here we compare the results obtained with CoRoT with expectations that small planets should have a high density, an large planets a small density. We also discuss whether there is a relation between the properties of planets and the masses and galactocentric distances of their host stars.

2. The CoRoT mission
CoRoT (COnvection ROtation & planetary Transits) is a space mission that is especially designed to monitor the brightness changes of stars. The objectives of the mission are the study of stellar oscillations and the detection of extrasolar planets. The satellite
was launched on December 27 2006. In the exoplanet part of the mission, CoRoT monitors typically 6000 to 12000 in per field. Up to now 24 fields have been observed. The fields are located in two opposite directions in the sky: The so-called "galactic center eye" (galactic longitude: $\sim 213 \pm 5^\circ$), and the so-called "galactic anti-center eye" (galactic longitude: $\sim 33 \pm 5^\circ$). Given that CoRoT observes stars between 11 and 16 mag, the F and G-stars that CoRoT observes have galactocentric distances between 7 to 9 kpc which corresponds to the galactic habitable zone (Lineweaver et al. 2004).

CoRoT has detected a transiting planet with a relative transit depth of $3.35 \times 10^{-4}$ orbiting a star of 11.7 mag (Leger et al. 2009). Thus, CoRoT is sensitive enough to detect planets with less than two Earth-radii for solar-like stars, and Jupiter-sized planets of B4V-stars. From the CoRoT-data, we obtain a frequency of transiting hot Jupiters orbiting solar-like stars of $0.05^{+0.02}_{-0.01}\%$. This corresponds to a frequency of hot Jupiters of $0.4^{+0.2}_{-0.1}\%$, which agrees well to the rate found in radial-velocity surveys (Cumming et al. 2008; Naef et al. 2005). This means that CoRoT has detected all transiting hot Jupiters in the fields observed.

3. The density of planets and the mass of the host star

An important discovery made by CoRoT was CoRoT-7b, a planet with a mass of $M_p = 7.42 \pm 1.21 M_{\text{Earth}}$, and a density of $\rho = 10.4 \pm 1.8$ g cm$^{-3}$ (detection: Léger et al. 2009; new mass determination: Hatzes et al. 2011). This planet thus was the first rocky planet found outside the solar-system. Kepler-10b is another object like this. It has a mass of $M_p = 4.56^{+1.37}_{-1.29} M_{\text{Earth}}$, and a density of $\rho = 8.8^{+2.1}_{-2.9}$ g cm$^{-3}$ (Batalha et al. 2011). These two planets thus can be nicknamed "super-Earths", planets more massive than the Earth but with a density that is consistent with an Earth-
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Figure 2. Mass-density diagram for the planets discovered by CoRoT (red) and Kepler (black) compared to objects in the solar-system (blue). Note that $13 (\text{or } 25) \ M_{\text{Jup}}$ corresponding to $\log(M_{\text{Earth}}) = 3.6(3.9)$ are usually referred as the boarder line between planets and brown dwarfs (Schneider et al. 2011).

like composition (Valencia et al. [2010]). The only other known low-mass planets ($M_p \leq 10 M_{\text{Earth}}$) with densities larger than $4 \ \text{g cm}^{-3}$ are Kepler-18b ($M_p = 6.9 \pm 3.4 M_{\text{Earth}}, \ \rho = 4.9 \pm 2.4 \ \text{g cm}^{-3}$), Kepler-20b ($M_p = 8.7^{+2.1}_{-2.2} M_{\text{Earth}}, \ \rho = 6.5^{+2.0}_{-2.7} \ \text{g cm}^{-3}$), and Kepler-36b ($M_p = 4.45^{+0.33}_{-0.27} M_{\text{Earth}}, \ \rho = 7.46^{+0.07}_{-0.05} \ \text{g cm}^{-3}$). All other low-mass planets have densities lower than $4 \ \text{g cm}^{-3}$.

Fig. 1 shows the mass-density diagram for the 25 CoRoT-planets. Planets orbiting stars with masses between 0.9 and 1.1 $M_\odot$ are marked with red dots in Fig. 1. Planets orbiting stars of higher mass are marked as black dots, and planets orbiting stars of lower mass as blue dots. The figure shows that planets of the same mass can have quite different densities.

Another interesting aspect is that not only low-mass planets, like CoRoT-7b, can have a high density but also planets of several $M_{\text{Jup}}$. Particularly interesting is CoRoT-20b, a planet with a density of $8.87 \pm 1.10 \ \text{g cm}^{-3}$, and a mass of $4.24 \pm 0.23 \ M_{\text{Jup}}$ (1348 $\pm$ 73 $M_{\text{Earth}}$). This high density implies that the core amounts to between 50 to 75% of the total mass of this planet (Deleuil et al. [2011]). Another object like this is CoRoT-14b, which has a density of $7.3 \pm 1.5 \ \text{g cm}^{-3}$, and a mass of $7.6 \pm 0.6 \ M_{\text{Jup}}$ (2420 $\pm 190 \ M_{\text{Earth}}$)(Tingley et al. [2011]). Interestingly, both planets are the most massive planets found by CoRoT. Is this just a coincidence, or do all massive planets have such high densities? Fig. 2 shows the same diagram as in Fig. 1 but also including the 34 planets discovered by Kepler with measured densities, and the planets of our solar-system. The Kepler results agree very well with the CoRoT results. Also the planets with more than 1000 $M_{\text{Earth}}$ found by Kepler have densities larger than 6 g cm$^{-3}$. It thus seems that...
massive planets in general have a high density. Contrary to this, no planets with a density higher than 3 g cm\(^{-3}\) has been found in the whole mass-range between 15 and 600 M\(_{\text{Earth}}\).

4. The mass of the planets and the mass of the host star

Another interesting aspect is that the two most massive planets that CoRoT has found are orbiting stars that are more massive than the Sun. Since the two brown dwarf companions found by CoRoT, CoRoT-3b (Deleuil 2008) and CoRoT-15b (Bouchy 2011), are also orbiting stars more massive than the Sun, there seems to be a trend that massive planets and brown dwarfs are preferentially found in higher mass stars. Does this mean that there is a close relation between the mass or density of a planet and the mass of its host star? Fig. 3 shows the relation between the density of planets and the masses of the host stars. Planets of different mass-intervals are marked with different colours. Apart from the fact that massive substellar companions are preferentially found in more massive stars, there is no further connection between the mass, or density of planets and the masses of host stars (see also Fig. 5).

5. The frequency of planets and the mass of the host star

So far CoRoT has measured the mass and radii of 25 planets, of which 8 are orbiting F-stars, 13 are orbiting G-stars, 4 are orbiting K-stars. Does this mean that planets are more common in G-type stars than in other types of stars? Certainly not, we have to know how many F, G, and K-stars the sample contains. In order to characterize the sample that CoRoT did observe, we have obtained spectra of 11466 stars in 3 of the 24 CoRoT-fields (Guenther et al. 2012 Sebastian 2012). About 4% of the stars that CoRoT
observes are main sequence B-stars, 16% A-stars, 35% F-stars, 15% G-stars, 5% K-stars. Less than 1% of the stars are M-dwarfs. Taking the frequency of stars in the sample into account, we find that the frequency of close-in massive planets around F-stars is less or equal to that of G-stars. We thus do not find any significant increase of the frequency of close-in planets with the mass of the host star.

6. The radius of planets and their mass

The first parameter that can usually be determined when a planet is discovered in a transit search program is its radius. It would thus be helpful if there were a relation between the radius of the planet and its mass or density. If there were such a relation, we could immediately focus on the most interesting objects. Fig. 4 shows the relation between the radius and the density for planets. The only feature that can be seen is that planets with 3 to 10 $R_{\text{Earth}}$ have densities below 3 g cm$^{-3}$. Planets with radii larger than 10 $R_{\text{Earth}}$, and planets with radii below 3 $R_{\text{Earth}}$ can have a low, or a high density. Thus, the measurement of the radius of a planet alone does not immediately tell us what it is.

7. Do the properties of the planets change with the galactocentric distance?

CoRoT observes fields in two opposite directions in the sky. F- and G-stars in the so-called galactic center eye (SRc/LRc-fields) have typical galactocentric distances of about 7 kpc, and F and G-stars in the opposite direction (SRa/LRa-fields) about 9 kpc. Fig. 5 shows the relation between the mass of the discovered planets and the mass of the host
stars for the two CoRoT “eyes”. We do not see any significant difference between the planets in the two regions.

8. Summary and conclusions

Based on the currently available statistics we draw the following conclusions:

- Planets of the same mass can have different densities.
- Planets with more than $1000 \, M_{\text{Earth}}$ ($\sim 3 \, M_{\text{Jup}}$) have densities larger than $6 \, \text{g cm}^{-3}$. Such planets are preferentially found around stars that are more massive than the Sun.
- All planets in the mass-range from 15 to $600 \, M_{\text{Earth}}$ ($\sim 0.05$ to $2 \, M_{\text{Jup}}$) have densities below $3 \, \text{g cm}^{-3}$.
- When going further down in mass of the planets, the density increases steadily, there is no sudden transition from gaseous to rocky planets.
- Up to now we do not see any significant difference between the masses, or densities of the planets at different galactocentric distances.
- The frequency of close-in planets of F-stars in not higher than that of G-stars.
- The measurement of the radius of planets alone is not sufficient for characterizing it.

References

Batalha, N.M., Borucki, W.J., Bryson, S.T., et al. 2011, ApJ, 729, 27
Bouchy, F., Deleuil, M., Guillot, T., et al. 2011, A&A, 525, 68
Cumming, A., Butler, R.P., Marcy, G.W., et al. 2011, PASP, 120, 531
Deleuil, M., Deeg, H. J., Alonso, R., et al. 2008, A&A, 491, 889
Deleuil, M., Bonomo, A.S., Ferraz-Mello, S., et al. 2011, A&A, 538, 145
Guenther, E.W., Gandolfi, D., Sebastian, D., et al. 2012, A&A, 543, 125
Hatzes, A.P., Fridlund, M., Nachmani, G., et al. 2011, ApJ, 743, 75
Léger, A., Rouan, D., Schneider, J., et al. 2009, A&A, 506, 287
Lineweaver, C.H., Fenner, Y., & Gibson, B.K. 2004, Science, 303, 59
Naef, D., Mayor, M., Beuzit, J.-L., et al. 2005, Proceedings of the 13th Cambridge Workshop on Cool Stars, Stellar Systems and the Sun, held 5-9 July, 2004 in Hamburg, Germany. Edited by F. Favata, G.A.J. Hussain, and B. Battrick. ESA SP-560, European Space Agency, 2005., p.833
Queloz, D., Bouchy, F., Moutou, C., et al. 2009, A&A, 506, 303
Sebastian, D., Guenther, E.W., Schaffenroth, V., Gandolfi, et al. 2012, A&A, 541, 34
Schneider, J., Dedieu, C., Le Sidaner, P. et al. 2011, A&A, 532, A79
Tingley, B., Endl, M., Gazzano, J.-C., et al. 2011, A&A, 528, 97
Valencia, D., Ikoma, M., Guillot, T., & Nettelmann, N. 2010, A&A, 516, A20