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III.3

CoRoT's planets: A family portrait

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1. Introduction

While the tens of exoplanets discovered by CoRoT now seem like a drop in the ocean of thousands of exoplanets known, each discovery has helped to push our understanding at a time when much fewer objects were known. Still now, owing both to the quality of the photometry from the spacecraft and the great amount of follow-up work, the ensemble of CoRoT planets remain among the ones which are best characterized, i.e., for which we have precise determination of planetary radius and mass. They also form a homogeneous ensemble which is relatively complete, at least for the planets orbiting stars up to magnitude ∼14.

We take this look back at the ensemble of the CoRoT confirmed planets in terms of their properties, internal structure and evolution. This chapter is based in part on the review by Moutou et al. (2013), which we update when necessary. We also show the result of a homogeneous analysis limited to the giant planets of the family.

2. The gallery of CoRoT giant planets

Figure III.3.1 shows an ensemble of 23 giant planets detected by CoRoT. In order to have a homogeneous approach, we have omitted from this gallery the super-Earth CoRoT-7b, brown dwarfs, as well as planets for which no radial-velocity signal was detected. A few planets are still to be announced – these have not been included.

In spite of this selection, the variety of conditions is still large: masses range from 0.2 to 11 M_{Jup}, densities between 0.2 g cm^{-3} (CoRoT-5 b, Rauer et al. (2009)) and 12.6 g cm^{-3} (CoRoT-10 b, Bonomo et al. (2010)), equilibrium temperature (inversely related to orbital distance) between 410 K (CoRoT-9 b, Deeg et al. (2010)) and 1950 K (CoRoT-14 b, Tingley et al. (2011)), and radii from 0.59 (CoRoT-8 b, Bordé et al. (2010)) to 1.49 (CoRoT-1 b, Barge et al. (2008)) Jupiter radius.

The planetary radius and age in Fig. III.3.1 were obtained using the ensemble of published parameters for the planets and are compared to planetary evolution models calculated with the CEPAM code using a homogeneous approach (e.g., Guillot & Havel 2011; Havel et al. 2011).

The planets in this ensemble can be put into three categories: (i) Planets which are smaller than "standard" theoretical evolution models for pure solar-composition gaseous planets and thus require added heavy elements to match their size; (ii) Planets which are larger than these "standard" evolution models but which can be explained by advocating that a small fraction (∼1%) of the incoming stellar energy is dissipated in the planet's interior; (iii) planets that are even larger and would require even higher energy dissipation rates to explain their size.

We show in the next section that the first two sets of planets can be explained with the same hypotheses, i.e. the downward transport of kinetic energy in these planets and a variable mass of heavy elements. How to explain the third ensemble is still unclear but we provide a tentative explanation in Sect. 4.

3. The inflation problem & the compositions of giant planets

As seen in Fig. III.3.1, a fraction of the giant planets of the CoRoT sample are significantly larger than would be expected from the evolution of a hydrogen-helium planet. This is a classical problem (e.g., Bodenheimer et al. 2001; Guillot & Showman 2002) which is quantified by calculating the *radius anomaly*, defined as the difference between the measured radius and that calculated for a solar-composition planet with no core of the same mass, age and equilibrium temperature (Guillot et al. 2006). 8/23 planets (CoRoT-1b, 2b, 5b, 6b, 11b, 12b, 18b, 19b) have positive radius anomalies, indicating that the inflation mechanism is widespread, in line with what found for the ensemble of giant exoplanets (e.g., Guillot 2008; Laughlin et al. 2011). Generally, the problem can be solved for all of these planets by invoking that a non-radiative process leads to the conversion of a small fraction of the stellar absorbed irradiation (of order 1%) to kinetic energy and its dissipation at later depths (e.g., Guillot & Showman 2002; Batygin & Stevenson 2010, plus many other more recent works).

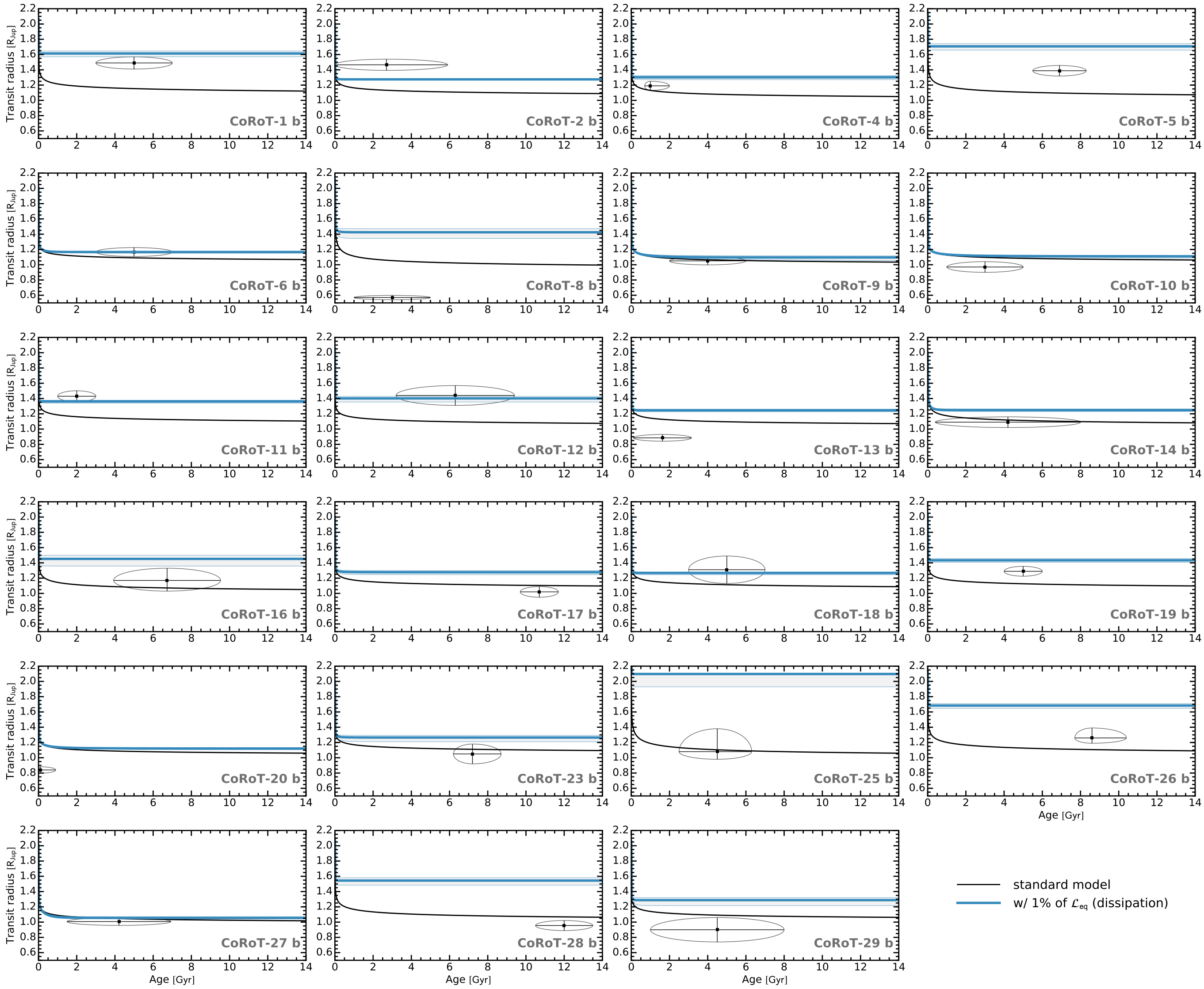

Fig. III.3.1. Gallery of the CoRoT giant planets, showing in each case planetary radius as a function of age. The ellipses indicate solutions obtained from the photometric, radial velocimetry and spectroscopic constraints (see text). The curves show theoretical evolution models for solar composition planets. The black lines correspond to standard models (including irradiation but no extra energy source), the blue lines assume that 1% of the incoming energy is dissipated deep into the planets.

However, one of the CoRoT planets is found to resist standard explanations so-far: CoRoT-2b has a radius that is not amongst the largest so far, but it is massive, and explaining its size thus requires a considerable amount of additional energy (Alonso et al. 2009; Gillon et al. 2010), of about 25% of the absorbed solar luminosity if this is a long-term feature (Guillot & Havel 2011). Interestingly, CoRoT-2 shows all the signs of being young, and the possibility of a recent (10 to 30 Ma) giant impact or circularization from a large eccentricity has been invoked to explain the large planetary radius (Guillot & Havel 2011). We will come back to this case in the next section.

Once a prescription for the missing physics is assumed, the mass of heavy-elements in the giant planets may be calculated (see Guillot et al. 2006): the presence of additional heavy elements either as a central core or inside the envelope generally leads to a shrinking of the planet compared to solar-composition models and naturally explains the negative $\delta_{\rm anomaly}$ values. For simplicity, this is done by assuming that a fraction of the incoming energy is dissipated at the planet's center, and that all the heavy elements are embedded as a central core.

When plotted against stellar metallicity, the giant planets in the CoRoT sample appear to have amounts of heavy elements that are correlated with that of their parent star, confirming the trend observed for many planets (Guillot et al. 2006; Burrows et al. 2007; Guillot 2008; Laughlin et al. 2011; Moutou et al. 2013). The correlation coefficient between $10^{\rm [Fe/H]}$ and $M_Z^{\rm b}/M_{\rm p}$ for the CoRoT planets is $r = 0.52$ and a Spearman's test indicate that its statistical significance is 2.3σ. When including other planets, the value of r remains the same, but the significance increases to 3.5σ (Moutou et al. 2013).

However, some of the CoRoT planets have small radii for large masses and require masses of heavy elements in excess of what is usually envisioned by formation models.

This is the case of CoRoT-10b, 13b, 14b, 17b, 20b and 23b which all require core masses in excess of 70 $M_\oplus$ to explain their small size. The large amounts of heavy elements found for these planets was unexpected from planet synthesis models. The relatively high frequency of these superdense planets among the CoRoT sample is also surprising. It appears to be larger than in the general sample, which may be attributed to the fact that these planets are generally smaller and more difficult to detect from the ground. On the theoretical standpoint, for large M_Z values, the assumption that all the heavy elements are in the core and the very high central pressures both probably imply that M_Z is significantly overestimated (see Deleuil et al. 2012; Baraffe et al. 2008). In any case, further work both on the internal structure of these planets and their formation is required.

4. Young planets?

Three CoRoT stars with planets, CoRoT-2, 18 and 20 appear to be younger than 1 Ga. When accounting for the main-sequence lifetime of stars and the age of the Galaxy, this is consistent with a uniform age distribution. Over this effective temperature range, none of the other known transiting planets are that young. This can be explained by two factors: first most of the usual transit surveys are biased towards non-active stars both because of the photometric stability requirement for the transit detection and because of the easier radial-velocity follow-up. Second, the CoRoT systems have been studied more thoroughly than the average exoplanet, with in particular measurements of chromospheric activity, lithium abundance and stellar spin. These measurements are important to detect signs of youth which are generally not accessible from the study of the evolution tracks themselves.

Two CoRoT systems are particularly interesting because of their complex lightcurves revealing that the stars are heavily spotted, the fast stellar spin and presence of a close-in, relatively massive giant planet. This is the case of CoRoT-2 and 18. Interestingly, these two systems are almost twins of each other. The two stars, CoRoT-2 (Alonso et al. 2008) and CoRoT-18 (Hébrard et al. 2011) have comparable effective temperatures (5450 vs. 5440 K), metallicities (0.0 vs. −0.1), spin periods (4.5 vs. 5.4 days) and $v \sin i$ (12 vs. 8.0 km s^{-1}), and they are both active, with peak to peak photometric variabilities of ∼4% and ∼2%, respectively. In addition CoRoT-2 and CoRoT-18 are the fastest-spinning stars with a known planet and an effective temperature below 6000 K.

The two systems show signs of youth: an analysis of the X-ray activity of CoRoT-2 and its fast spin indicate an age of 100 to 300 Ma (Schröter et al. 2011), whereas the spin of CoRoT-18 and its lithium abundance seem to indicate an age between 400 to 600 Ma (Hébrard et al. 2011). The latter is problematic however, as the age obtained from evolution tracks would indicate an age in excess of 1 Ga (or a star on the pre-main sequence, which is very unlikely).

A third young system is CoRoT-20: the star's spin is not as important ($v \sin i = 4.5 \pm 1.0$ km s^{-1}), but it exhibits a clear lithium line, indicative of an age younger of 100^{+800}_{-40} Ma (Deleuil et al. 2012). In this case, stellar evolution tracks only provide upper limits on the star's age (below 5 Ga, within 1σ). Without the lithium measurement, this star would probably have been attributed an older mean age compatible with a star on the main sequence. This examples illustrates how detailed follow-up studies are important in order to fully characterize these exoplanetary systems. Interestingly, this case also share similarities with the two others: the planet is massive (4.24 ± 0.23 $M_{\rm Jup}$), it has a larger orbital period ($P = 9.24285$ days) but a high eccentricity implies that it makes close approaches with the star and last but not least, its inferred size is also problematic. This time, it is too small, as shown by the very low radius anomaly and extremely high M_Z value that is inferred to fit its radius ($M_Z = 1.75$ M_{Jup}!).

The fact that these three systems pose particular problems (the large size of CoRoT-2b, the inconsistent age determinations for CoRoT-18 and the small size of CoRoT-20b) seems to indicate that our knowledge of young, rapidly spinning, spotted stars is incomplete.

Indeed, a survey of stars with companions have shed new light on this problem. Poppenhaeger & Wolk (2014) have shown that the main star of the CoRoT-2 system has a K-dwarf companion, CoRoT-2B, and that, unlike CoRoT-2A, it is a very weak X-ray emitter. This implies that CoRoT-2B is at least 5 Ga. Given that companions of multiple systems should have the same age, it appears that CoRoT-2A should in fact be old. What happened? In fact, this is evidence that CoRoT-2A has been spun up by its close-in massive planetary companion. This means that gyrochronology, the set of empirical relation that relate stellar spin to age cannot be used. The same is true for indicators linked to chromospheric activity as it is also directly linked to the star's magnetic field intensity and hence to its spin rate.

As can be seen from the fully set of solutions obtained by Guillot & Havel (2011), when using old instead of young ages, the inferred planetary radius of CoRoT-2b decreases. This allows finding solutions with lower values of the dissipation rate. However, a qualitative estimate using the Guillot & Havel (2011) results indicates that a still high value of the dissipation rate ($\gtrsim 5\%$) may be needed. One possibility to be investigated is whether the spin up of the star by the planetary companion may lead to differential rotation inside the star and alter its internal structure and evolution.

The analysis of the CoRoT data combined with further follow-up observations should shed light on this important issue which bears directly on the problem of the formation of planetary systems.

5. CoRoT-7b: the first transiting super-Earth

Of course, this family portrait would be incomplete without mentioning CoRoT-7b, the first transiting super-Earth known (Léger et al. 2009; Queloz et al. 2009) which heralded many to come discovered by the Kepler mission (e.g., Howard et al. 2012). With a size of 1.585 ± 0.064 $R_\oplus$ (Barros et al. 2014) and a mass of 4.73 ± 0.95 (Haywood et al. 2014), CoRoT-7b has the density expected for a planet of the same composition as our Earth (Valencia et al. 2010; Barros et al. 2014). However, we stress that this solution assumes a relatively young age of 1.32 ± 0.75 Ga for the star, based on gyrochronology. If, based on the experience of CoRoT-2 we choose to leave out the gyrochonology constraint, the preferred age solution then becomes $8.4^{+5.0}_{-3.3}$ Ga yielding a much larger inferred planetary radius, $1.94 \pm 0.1\ R_{\oplus}$ (Barros et al. 2014). It is not clear at the moment why the star would be rotating so fast if it is old: contrary to the massive CoRoT-2b, little CoRoT-7b is incapable of spinning its star up, its angular momentum being too small (e.g., Damiani & Lanza 2015). This would thus require the recent ingestion of a more massive planet, a scenario which is less likely than a relatively young age for the system.

Another important issue with CoRoT-7b and the ensemble of very close-in super-Earths is their origin. Mass-loss is an important part of their evolution, and it is energetically possible that such close-in super-Earths are stripped-off cores of giant planets (Valencia et al. 2010). On the other hand, super-Earths appear to be much more common than giant planets (e.g., Howard et al. 2012), making that possibility less likely.

6. Conclusion

The family of planets detected by CoRoT sheds light on planetary formation and evolution and on the interactions between stars and planets. A large fraction of close-in giant planets are oversized, implying the existence of a yet unidentified mechanism to slow their evolution (or possibly, increase their size). Some giant planets are smaller than expected for solar-composition objects, implying that they must contain significant amounts of heavy elements in their interior (in their core, or throughout their envelope). We see a correlation between the metallicity of the star and that inferred for the planets, requiring the existence of a process leading to an efficient collection of heavy elements by the forming planets. Finally, the study of binary systems shows evidence for massive planets spinning up their parent star – the most striking example being that of the complex CoRoT-2 system.

The success of CoRoT in that respect lied in the combination of great quality photometry and intense, dedicated follow-up for each object. This made possible to efficiently discover even rare systems, characterize them accurately (determination of planetary mass, stellar spin rate, eccentricity when possible, etc.) and model them in detail. It is most important for future space exoplanet missions to fully integrate the analysis of space data to intense follow-up mostly with ground-based telescopes.

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