The Astrophysical Journal Letters, 709:L95–L98, 2010 February 1 doi:10.1088/2041-8205/709/2/L95

CoRoT-7b: SUPER-EARTH OR SUPER-Io?

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Received 2009 August 28; accepted 2009 November 25; published 2010 January 11

ABSTRACT

CoRoT-7b, a planet about 70% larger than the Earth orbiting a Sun-like star, is the first-discovered rocky exoplanet, and hence has been dubbed a "super-Earth." Some initial studies suggested that since the planet is so close to its host star, it receives enough insolation to partially melt its surface. However, these past studies failed to take into consideration the role that tides may play in this system. Even if the planet's eccentricity has always been zero, we show that tidal decay of the semimajor axis could have been large enough that the planet formed on a wider orbit which received less insolation. Moreover, CoRoT-7b could be tidally heated at a rate that dominates its geophysics and drives extreme volcanism. In this case, CoRoT-7b is a "super-Io" that, like Jupiter's volcanic moon, is dominated by volcanism and rapid resurfacing. Such heating could occur with an eccentricity of just 10^{-5}. This small value could be driven by CoRoT-7c if its own eccentricity is larger than $\sim 10^{-4}$. CoRoT-7b may be the first of a class of planetary super-Ios likely to be revealed by the *CoRoT* and *Kepler* spacecraft.

Key words: celestial mechanics – planets and satellites: individual (CoRoT-7b)

1. INTRODUCTION

The discovery of CoRoT-7b (Léger et al. 2009; hereafter LRS09) heralds a new era in the study of exoplanets. The detection of rocky exoplanets has been a prime objective of exoplanet surveys as they are the most likely environments to support life. With a radius of $R_p \sim 1.7\, R_\oplus$ (LRS09), and a mass of $4.8\, M_\oplus$ (Queloz et al. 2009), this planet is likely rocky (Valencia et al. 2007; Fortney et al. 2007; Sotin et al. 2007; Seager et al. 2007). CoRoT-7b is clearly not habitable, being only 0.017 AU from its host star, but understanding its origin and properties can inform future interpretations of rocky exoplanets with the potential to be habitable.

Considerable research has already explored the plausible properties of close-in "super-Earths," rocky planets with masses $\lesssim 10\, M_\oplus$, and semimajor axes $a \lesssim 0.1$ AU (see Gaidos et al. 2007 for a review). Such planets probably formed at larger distances and migrated in, although there exist several other formation mechanisms (Raymond et al. 2008). At very close distances ($\lesssim 0.03$ AU), planets orbiting $\sim 1\, M_\odot$ stars may experience enough insolation to partially melt the surface, producing a silicate vapor atmosphere (Schaefer & Fegley 2009). CoRoT-7b may be such a world with a surface temperature of order 2000 K (LRS09, Valencia et al. 2009).

These previous studies assumed that the planet remains at a constant distance from the star. However, CoRoT-7b is so close to its star that its life expectancy is very short as tides cause the orbit to decay quickly, assuming a conventional value for the stellar tidal parameter Q'_* (Jackson et al. 2009). On that basis, LRS09 inferred that the value of Q'_* is unexpectedly large. Alternatively, CoRoT-7b could be on the verge of spiraling down to the star, out of a large population of planets (in many systems), many of which have already been destroyed, as discussed by Jackson et al. (2009). It therefore remains uncertain whether the radiative heating has been intense enough, long enough to melt the surface. Here, we assess the possible orbital history and its implications.

Tides may also contribute to, and even dominate, the heating of the planet. If the planet's orbit is at all eccentric (even if the eccentricity e_b is <0.03 so as to be extremely difficult to measure via radial velocity data (Butler et al. 2006)), the planet's figure is flexed by the time-varying gravitational potential of the star. These tides on the planet transform orbital energy into internal heat, affecting its geophysics as well as contributing to orbital decay. If the orbit of CoRoT-7b is sufficiently eccentric, then the planet could be substantially affected by tidal heating. Tidal heat alone could be adequate to make it a "super-Io," with a surface heat flux far exceeding that of Jupiter's extremely volcanic moon (Barnes et al. 2009b). This Letter identifies the orbital circumstances, histories, and physical properties that lead to Io-like volcanism (a super-Io) and those that do not (a super-Earth).

If CoRoT-7b orbited in isolation, then tides would quickly damp any primordial eccentricity (LRS09), and we might expect minimal tidal heating today. However, even small eccentricities (those typically considered negligible) could yield considerable tidal heating and have profound consequences for the geophysical state of this planet. We show here that if the planet is similar to the rocky bodies in our Solar System and has an eccentricity even as small as $\sim 10^{-5}$, tides may generate more heat per unit surface area than on Io. Such an eccentricity can be maintained by perturbations from planet c, the $8.4\, M_\oplus$ planet that orbits at 0.046 AU, but only if its own eccentricity is large enough. In many plausible cases, the tidal heating may be orders of magnitude larger. In Section 2, we discuss tidal theory, the two models for the surface temperature presented in LRS09, and our *N*-body model. In Section 3, we show the possible orbital and thermal histories of planet b. Finally, in Section 4 we discuss the plausible range of physical properties that this planet has in the context of tidal evolution and tidal heating, and suggest that CoRoT-7b could be the first of many super-Ios that will be discovered by *CoRoT* and *Kepler*.

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2. METHODS

Previous investigations have considered the possible range of surface temperatures of CoRoT-7b (LRS09; Schaefer & Fegley 2009; Valencia et al. 2009). Here we review the two models of LRS09: one in which the energy is uniformly distributed over the surface,

$$T_u = (1 - A)^{1/4} g \left(\frac{R_*}{2a}\right)^{1/2} T_*, \tag{1}$$

and one in which there is no surface heat transport to the back side,

$$T_s = (1 - A)^{1/4} g \left(\frac{R_*}{a}\right)^{1/2} T_*. \tag{2}$$

Here, A is the albedo, g quantifies the effectiveness of heat transport, and T_* is the effective temperature of the star (5275 K for CoRoT-7). We assumed $A = 0$ and $g = 1$ (no albedo and no greenhouse effect (LRS09)). In the next section, we will couple these models, Equations (1) and (2), to the tidal evolution of b's orbit in order to estimate its surface temperature history.

Tidal theory is a notoriously complicated and uncertain field. With few examples of tidal evolution in the solar system as well as the long timescales associated with this phenomenon, firm observational constraints are rare (see Lainey et al. 2009 for a recent example). For more complete reviews of tidal models, consult Ferraz-Mello et al. (2008) or Heller et al. (2009). Here we employ a standard model that was developed to study orbital evolution of satellites in our solar system (Goldreich & Soter 1966; see also Jackson et al. 2008c; Barnes et al. 2009a, 2009b; Greenberg 2009). In this model, a planet on a circular orbit migrates (a evolves) at a rate

$$\frac{da}{dt} = -\frac{9}{2} \frac{\sqrt{G/M_*} R_*^5 m_p}{Q'_*} a^{-11/2}, \tag{3}$$

where G is the gravitational constant, R_p is the planetary radius, R_* is the stellar radius, and Q'_* is the star's "tidal dissipation function" which encapsulates the physical response of the body to tides, including the Love number. In order to constrain a planet's orbital history, we integrate Equation (3) backward in time by flipping the sign. We use a time step of 1000 yr which convergence tests demonstrated resolves the evolution. We will use this equation to consider the past evolution of planet b's orbit.

We will also consider the possibility that the planet has a nonzero eccentricity today in order to assess tidal heating, which is parameterized as

$$H = \frac{63}{4} \frac{(GM_*)^{3/2} M_* R_p^5}{Q'_p} a^{-15/2} e^2, \tag{4}$$

where Q'_p is the planet's tidal dissipation function and M_* is the stellar mass (Peale et al. 1979; Jackson et al. 2008b). Note that if the planet has a nonzero eccentricity, Equation (3) will have an additional term, but for the small values we consider below, this change is negligible.

In order to assess the surface effects of tidal heating, we can compare our results with the processes and characteristics observed on planetary bodies in our own solar system. For comparison, heating rates must be scaled to account for the differences in sizes among bodies. Because we are comparing effects at the surface, we consider the heating rate per unit surface area (see, e.g., Williams et al. 1997; Jackson et al. 2008a, 2008b), i.e., the heat flux, $h = H/4\pi R_p^2$, through the planetary surface. On Io, $h = 2$ W m^{-2} (from tidal heating) (McEwen et al. 2004), resulting in intense global volcanism and a lithosphere recycling timescale of 142 to 3.6×10^5 yr (Blaney et al. 1995; McEwen et al. 2004). On Earth, the heating comes from the radioactive decay of U and K and produces a heat flux of 0.08 W m^{-2} (Davies 1999), which is adequate for plate tectonics and some volcanism, which is modest relative to Io. The radiogenic heat flux of CoRoT-7b is of order 0.4 W m^{-2} (A. Léger 2009, private communication). The actual scaling of geophysical processes among various sized planets is much more complex than can be represented by the single parameter h. The internal effects will depend on, and modify, composition and structure. Qualitative differences in heat transport, such as the roles of convection versus conduction, will make for complex diversity. Many of these differences may scale as the heating rate per unit mass, for example. However, modeling these details would require complicated internal geophysical simulations which are beyond the scope of this investigation. Here we assume that the surface heat flux h gives an adequate first-order qualitative representation of surface effects. Thus, we call planets "super-Ios" if their flux exceeds Io's value ($h > 2$ W m^{-2}). Otherwise they can be considered as "super-Earths" (Jackson et al. 2008a; Barnes et al. 2009a, 2009b). We use Equation (4) to make these distinctions in the following section.

We also consider the perturbations from planet c which can maintain b's eccentricity in a manner similar to the mutual perturbations of the planets in the HD 40307 system (Barnes et al. 2009b). We model the interactions with the N-body code HNBody,[7] which includes general relativity precession. We assume the orbits are coplanar, with planet c's mass, $m_c = 8.93\,M_\oplus$ (Queloz et al. 2009). For the remaining orbital parameters, we used the nominal values from Queloz et al. (2009), except that the eccentricity of planet c was chosen from the possible range $3 \times 10^{-5} < e_c < 10^{-3}$. We integrated the orbital motion for 10^5 yr. Then, for each case, using the average astrocentric eccentricity of b, we computed the tidal heat flux of planet b, h_b. We calculate the average heating flux because the mantle (if such a layer exists) of CoRoT-7b probably cannot respond to heating variations with timescales of thousands of years. We have not tested system stability numerically, but note that the above parameter space is Hill stable (Marchal & Bozis 1982; Gladman 1993), which implies Lagrange stability as well (Barnes & Greenberg 2006).

3. RESULTS

3.1. Surface Temperature Evolution

Here, we consider the past evolution of this planet in order to estimate how the surface temperature has changed. We consider a range of Q'_* values from 10^5 to 10^7 (Mathieu 1994; Lin et al. 1996; Ogilvie & Lin 2004; Jackson et al. 2009) and integrate back in time over the past 2.5 Gyr in order to cover the full age of the system, 1.2–2.3 Gyr (LRS09). Here, we assume that e_b has always been small enough that tides raised on the planet have not affected the orbital evolution (note that this assumption assumes the least amount of migration). The evolution of the semimajor axis of planet b's orbit is shown in the top panel of Figure 2. For low Q'_*, the planet could have begun nearly twice as far out, whereas if $Q'_* = 10^7$ or greater, there has been little change. The actual value of Q'_* remains uncertain.

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[7] http://janus.astro.umd.edu/HNBody/

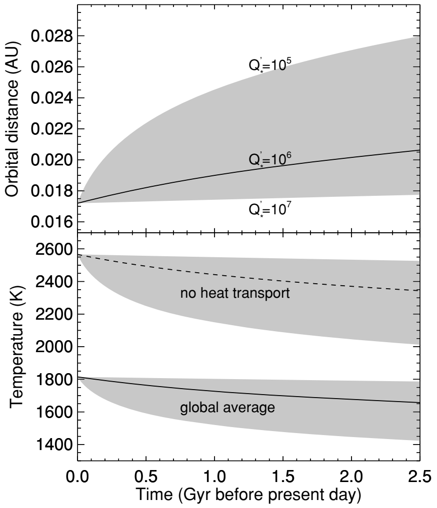

Figure 1. History of CoRoT-7b's semimajor axis (top) and surface temperature (bottom). Note that the present time is at the left. The top panel shows a range of possible semimajor axes due to tidal evolution for a range of Q'_* values. The solid curve represents $Q'_* = 10^6$, and the gray region shows all values in the range $10^5 \leqslant Q'_* \leqslant 10^7$. The bottom panel shows the surface temperature evolution for the same range of Q'_*, assuming uniform redistribution of stellar heat over the entire globe (Equation (1); "global average" strip) and no redistribution (Equation (2); "no heat transport" strip). In this panel, the top of the gray strips corresponds to $Q'_* = 10^7$ and the bottom to $Q'_* = 10^5$.

This evolution has important consequences for the surface temperature, as given by Equations (1) and (2). Figure 1 shows the possible histories of this quantity. For $Q'_* = 10^5$ (the lowest extent of the gray strips), the planet has only recently reached the extreme temperature it has today (the global average was 150 K cooler 10^8 years ago). Only if $Q'_* \geqslant 10^7$ has the temperature been as great over the past billion years as it is now.

3.2. *Current Tidal Heating*

In this subsection, we explore a range of orbital configurations permitted by the observations in order to determine which cases predict CoRoT-7b is a super-Io and which predict a super-Earth. We begin by applying Equation (4) to find h_b as a function of e_b. We consider a plausible range of physical and orbital properties listed in LRS09 (their Tables 5 and 6), with radii from 1.41 to 1.95 $R_\oplus$ and Q'_p values from 20 to 1000, consistent with observations in our solar system (Yoder 1995; Dickey et al. 1994; Mardling & Lin 2002; Lainey et al. 2009). The solid line in Figure 2 shows the possible values of h_b as a function of its current eccentricity e_b, assuming the nominal system parameters and $Q'_p = 500$. The dotted lines show a range of possible values given the uncertainties in Q'_p and R_p. For reference, the current heat fluxes for the Earth and Io are also shown (also note that the stellar energy flux at the planet is $\sim 2.5 \times 10^6$ W m^{-2}).

Figure 2 shows that, if $e_b > 10^{-4}$ and assuming nominal radius and Q'_p values, the planet is experiencing at least as much tidal heating (in terms of surface flux) as Io. For other plausible parameters, the critical value of e_b could be as low as 10^{-5}. Based on the example of our solar system, which has much larger e values, one would expect that b is indeed a super-Io. However, without an external perturber, tides could have damped even a very large primordial e below these values in only 10^8 yr. (Even the effects of stellar oblateness, passing stars, and the galactic tide could not keep $e_b > 10^{-4}$ as tidal damping occurs.)

The most likely mechanism, therefore, for e_b to be $\geqslant 10^{-4}$ is through gravitational interactions with other planets in the system. So far only one other planet is known, so we consider its effects on planet b. The magnitude of e_b will depend on the current values of e_c and m_c, both of which are poorly constrained. We assume the orbit of planet c is inclined 20° to the line of sight (coplanar with b (LRS09)), with a mass of 8.93 $M_\oplus$. Figure 3 shows the average heating flux $\langle h_b \rangle$, based on the average value of e_b over the 10^5 yr integration, as a function of e_c. If $e_c \gtrsim 10^{-4}$, then $\langle h_b \rangle$ exceeds the threshold for planet b to be a super-Io.

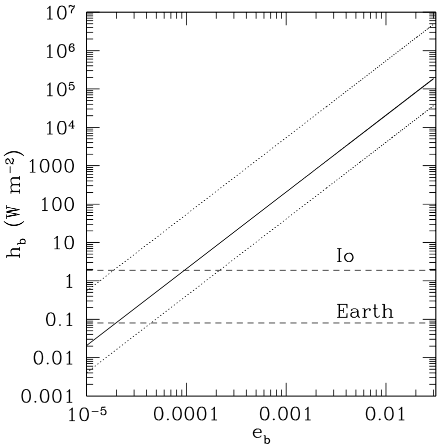

Figure 2. Tidal heating of CoRoT-7b as a function of its current eccentricity. The solid line shows the heating flux assuming nominal system parameters. The dotted lines represent a reasonable range of uncertainties: the upper line corresponds to $R_p = 1.95\, R_\oplus$ and $Q'_p = 20$, the lower to $R_p = 1.41\, R_\oplus$ and $Q'_p = 1000$. For reference, the tidal heating flux of Io and the radiogenic heating flux of the Earth are also shown.

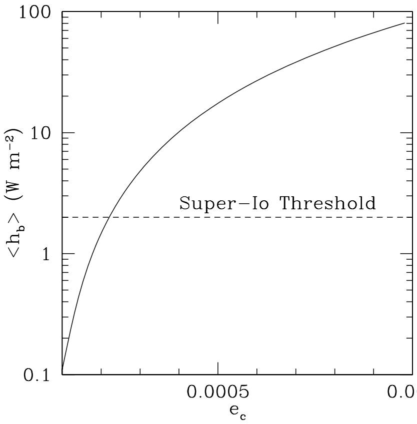

Figure 3. Tidal heating of planet b resulting from perturbations due to planet c assuming its orbit is coplanar with b (its mass is then 8.93 $M_\oplus$). If $e_c \gtrsim 2 \times 10^{-4}$, planet b is heated at least as much as Io.

But could planet c have such a "large" eccentricity given the extreme tidal damping in this system? The orbital circularization rate falls off as $a^{-6.5}$ (Goldreich & Soter 1966), which might seem to suggest that c's orbital eccentricity would be damped relatively slowly. However, planets b and c are coupled through their secular interactions, so that the tidal damping of one may affect the other. Planet c's orbit could be circularized quickly through its interaction with b, i.e., planet b essentially drains away c's excess eccentricity. Therefore planet c alone may not be able to maintain b's eccentricity to the level required for it to be a super-Io.

4. DISCUSSION

We have shown how tides may revise previous interpretations of the physical properties of CoRoT-7b. Consideration of tidal migration has important implications for the planet's surface temperature, and hence the possibility that the surface is (partially) melted (Schaefer & Fegley 2009). Valencia et al. (2009) argue that such a high surface temperature would lead to loss of the volatile inventory within 10^8 yr after formation. However, Figure 1 shows that such a supposition implicitly assumes $Q'_* \gtrsim 10^6$. Although the temperature difference could be only a few hundred degrees or less, we encourage future research into the surface and interior properties of CoRoT-7b (and close-in terrestrial bodies discovered in the future) due to insolation to bear in mind the tidal evolution of the orbit.

Previous interpretations of the surface properties of CoRoT-7b (Léger et al. 2009; Schaefer & Fegley 2009; Valencia et al. 2009) have only considered the radiative properties of the star. We have shown that other stellar properties, specifically its physical response to tides, are at least as important (at least on the dark side of the planet). In this case, the range of plausible Q'_* values permits a wide range of surface temperature histories. This result emphasizes the urgent need to determine Q'_* values more precisely.

Furthermore, we have shown that a slight eccentricity in the orbit of CoRoT-7b can result in enough tidal heating for it to be a super-Io planet (Barnes et al. 2009b), even without taking into account surface melting resulting from stellar radiation. However, tides would quickly circularize the orbit without an external agent. Perturbations from CoRoT-7c are a likely mechanism to drive the requisite eccentricity. Depending on CoRoT-7c's mass and orbit, CoRoT-7b could be tidally heated to be a super-Io or less heated so as to be a super-Earth. Crucially, these distinctions lie below the current detection limit for the orbital eccentricities, so either is possible. However, given their close proximities to the host star, tidal damping may be strong enough to circularize both orbits below the threshold to make b a super-Io. As shown in Figure 2, the uncertainties in e_b are consistent with a tidal heating rate of greater than 10^6 W m^{-2}. Such a large heating rate is unlike anything observed in our solar system and would have dramatic effects on the internal, surface and atmospheric properties.

Regardless of the current eccentricity of CoRoT-7b, most models of planet formation predict that planets form with eccentricities of at least a few percent (Raymond et al. 2004, 2006; O'Brien et al. 2006; Morishima et al. 2008). Therefore, it seems likely that the planet was a super-Io early in its history (assuming it never had a large gaseous envelope), even accounting for tidal migration which implies formation was somewhat farther from the star than the current orbit.

We have assumed that CoRoT-7b has been a terrestrial-like planet throughout its history. Valencia et al. (2009) point out that ablation could strip away many Earth masses of gas within 1 Gyr, but we have showed it used to be further out. We are currently examining mass loss with tidal evolution (B. Jackson et al. 2010, in preparation). If the planet began with a large gaseous envelope, many of the ideas presented here may require revision.

Tides play a crucial role in defining the characteristics of the atmosphere, surface and interior of CoRoT-7b. This planet is the first close-in terrestrial planet discovered, but the *CoRoT* and *Kepler* spacecrafts are likely to find many more. Mayor et al. (2009) find that 30% of solar-mass stars have super-Earth to Neptune mass companions on periods of 50 days or less, Marcy et al. (2005) and Cumming et al. (2008) find that the mass-frequency distribution of exoplanets is a power law with slope −1.1 (low mass planets are more common), and the geometric transit probability of a 10 $M_\oplus$ planet orbiting a 1 $M_\odot$ star is ∼10%. Taken together these results suggest *Kepler*, which is monitoring 10^5 stars, should find at least 100 terrestrial planets with orbital periods less than 10 days. Like CoRoT-7b, these planets can be strongly tidally heated. A significant fraction of the first wave of rocky exoplanets may be super-Ios.

R.B. and S.N.R. acknowledge funding from the NASA Astrobiology Institute's Virtual Planetary Laboratory lead team, supported by NASA under Cooperative Agreement No. NNH05ZDA001C. R.G. acknowledges support from NASA's Planetary Geology and Geophysics program, grant No. NNG05GH65G. B.J. is funded by an NPP administered by ORNL.

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