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# THE HD 40307 PLANETARY SYSTEM: SUPER-EARTHS OR MINI-NEPTUNES?

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## ABSTRACT

Three planets with minimum masses less than 10 $M_\oplus$ orbit the star HD 40307, suggesting these planets may be rocky. However, with only radial velocity data, it is impossible to determine if these planets are rocky or gaseous. Here we exploit various dynamical features of the system in order to assess the physical properties of the planets. Observations allow for circular orbits, but a numerical integration shows that the eccentricities must be at least $10^{-4}$. Also, planets b and c are so close to the star that tidal effects are significant. If planet b has tidal parameters similar to the terrestrial planets in the solar system and a remnant eccentricity larger than $10^{-3}$, then, going back in time, the system would have been unstable within the lifetime of the star (which we estimate to be $6.1 \pm 1.6$ Gyr). Moreover, if the eccentricities are that large and the inner planet is rocky, then its tidal heating may be an order of magnitude greater than extremely volcanic Io, on a per unit surface area basis. If planet b is not terrestrial, e.g., Neptune-like, these physical constraints would not apply. This analysis suggests the planets are not terrestrial-like, and are more like our giant planets. In either case, we find that the planets probably formed at larger radii and migrated early-on (via disk interactions) into their current orbits. This study demonstrates how the orbital and dynamical properties of exoplanet systems may be used to constrain the planets' physical properties.

*Key words:* methods: *N*-body simulations – planetary systems – stars: individual (HD 40307)

## 1. INTRODUCTION

Mayor et al. (2009) recently announced the discovery of a system of three planets, b, c, and d, orbiting the K dwarf HD 40307. This system is unique because it is the first detected system in which all three companions have minimum masses less than 10 $M_\oplus$. Moreover, the innermost planet, b at 4.2 $M_\oplus$, has the lowest minimum mass yet detected by radial velocity methods. In addition to relatively low masses, the system is striking in that the planets appear to lie close to a Laplace-like resonance: very small eccentricities ($\lesssim 0.01$) and period ratios near 4:2:1. However, as noted by Mayor et al. (2009), the observations rule out such a resonance chain with high confidence (greater than $10\sigma$).

If, as is most probable, the actual masses are similar to the minimum value, it is natural to wonder whether these bodies are larger versions of the rocky planets in the solar system ("super-Earths"), or smaller versions of our gaseous planets ("mini-Neptunes"). The only currently available method to make a direct assessment of these two possibilities requires transit data, but none has been reported, so we must rely on indirect means. One possibility is to consider the theoretical modeling of terrestrial and gaseous planet formation. However, that approach leads to uncertainty. For example, core-accretion models predict that a solid core requires 2–10 $M_\oplus$ in order to accrete a hydrogen envelope (Pollack et al. 1996; Bodenheimer et al. 2000; Ikoma et al. 2001; Hubickyj et al. 2005). Therefore, planet formation models cannot yet constrain the physical nature of the 4–10 $M_\oplus$ planets in this system.

Here we exploit another method for constraining the properties of exoplanets: the orbital history since formation. In our solar system, the rocky and gaseous planets' responses to tides are very different; solid, rocky bodies dissipate tidal energy more effectively (smaller $Q$ values) than their gaseous counterparts. Tides result in orbital migration at rates that can be orders of magnitude different depending on whether the planet is rocky or gaseous (Jackson et al. 2008b, 2008c). Also, the effectiveness of tides falls off rapidly with distance such that in multiple planet systems with close-in planets, the innermost planet has usually experienced tidal migration, while the others have undergone little. By modeling the past tidal evolution of a system, the inner planets' properties may be constrained by forbidding past events, e.g., mean motion resonance crossing or crossing orbits, which would have led to orbits inconsistent with the current system. For example, Barnes et al. (2008) considered the GJ 581 system (Udry et al. 2007) and showed that planet c ($\gtrsim 5\, M_\oplus$) could be terrestrial, but cannot have the same tidal parameters as the present-day Earth. Jackson et al. (2008c) considered the GJ 876 system (Rivera et al. 2005) and showed that planet d ($\gtrsim 7.5\, M_\oplus$) cannot be terrestrial because, considering tides, $e$ would have been $\approx 1$ less than $\sim 30$ Myr ago, with internal heating rates up to $10^5$ times that of Io.

For the HD 40307 system, we can exploit the proximity of mean motion resonances to constrain the tidal evolution of the innermost planet, b. We focus on two end-member cases for HD 40307 b: rocky or gaseous, but allow for other possibilities. To exploit dynamical constraints, we also use what we know about the system's age, as well as how it may have formed. As we show in the following sections, the possibility that the planets are terrestrial in character (i.e., "super-Earths") seems unlikely, but cannot be ruled out. However, the gaseous case (i.e., "mini-Neptunes") is less constrained. Nor can we rule out an intermediate case, which is tidal parameters in between those of the terrestrial and gaseous planets in our solar system. In Section 2, we describe our dynamical and tidal models. In Section 3, we present our results for this system. In Section 4 we infer the character of these planets, and identify likely formation scenarios. In the Appendix we estimate the age of the star, and, by extension, the system.

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## 2. METHODS

### 2.1. Planet–Planet Interactions

We will consider the oscillations of the planets' orbits with the $N$-body code `HNBody`,[5] which includes general relativistic effects. For these integrations, we require numerically induced energy changes to be less than one part in $10^4$, which is adequate precision to produce reliable results (Barnes & Quinn 2004).

### 2.2. Tidal Evolution Models

For our tidal model we use conventional equations assembled by Goldreich & Soter (1966; see also Jackson et al. 2008b; Barnes et al. 2008; Ferraz-Mello et al. 2008). The evolution of semimajor axis $a$ and eccentricity $e$ (to second order in $e$) can be modeled as

$$\frac{da}{dt} = -\left(\frac{63}{2}\frac{\sqrt{GM_*^3}R_p^5}{m_p Q'_p}e^2 + \frac{9}{2}\frac{\sqrt{G/M_*}R_*^5 m_p}{Q'_*}\right. \times \left.\left[1+\frac{57}{4}e^2\right]\right) a^{-11/2} \quad (1)$$

$$\frac{de}{dt} = -\left(\frac{63}{4}\frac{\sqrt{GM_*^3}R_p^5}{m_p Q'_p} + \frac{225}{16}\frac{\sqrt{G/M_*}R_*^5 m_p}{Q'_*}\right) a^{-13/2}e, \quad (2)$$

where $G$ is Newton's gravitational constant, $M_*$ is the stellar mass, $R_p$ is the radius of the planet, $m_p$ is the planet mass, $Q'_p$ and $Q'_*$ are the planet's and star's tidal dissipation function divided by two-thirds its Love number, and $R_*$ is the stellar radius. In Equations (1) and (2) the first terms represent the tide raised on the planet by the star, and the second terms the tide raised on the star by the planet. This model assumes that the tidal components maintain a constant phase lag from the line connecting the centers of mass of the two bodies, and is consistent with observations of the Galilean satellites of our solar system (Aksnes & Franklin 2001). See Jackson et al. (2008b) or Barnes et al. (2008) for more discussion of this model, but note that other plausible models, also consistent with observations in the solar system, also exist (see, e.g., Hut 1981; Néron de Surgy & Laskar 1997; Eggleton et al. 1998; Mardling & Lin 2002; Efroimsky & Lainey 2007; Dobrovolskis 2007; Ferraz-Mello et al. 2008).

Our model does not include the effects of secular interactions between the planets (see, e.g., Mardling 2007). Such effects could potentially play a role, but we will show that our conclusions regarding the HD 40307 b system are probably not impacted by the neglect of this effect. If it were included, the timescale for eccentricity evolution would likely be slower, and the tidal evolution of the innermost planet would change the eccentricities of other planets in the system (exterior planets modify the eccentricity of the inner planet, as tidal evolution damps it). Equations (1) and (2) allow a reasonable description of the tidal evolution of the system.

We may also determine the amount of heat generated in a body due to tidal friction:

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

(Jackson et al. 2008c). $H$ represents the internal heating rate, but for geophysical considerations it is useful to express the heat as a surface flux $h = H/4\pi^2 R_p^2$. For reference the heat flux on the Earth (due to radiogenic processes) is 0.08 W m$^{-2}$ (Davies 1999), Io's is 2–3 W m$^{-2}$ (Peale et al. 1979; McEwen et al. 2004), and Europa's, scaling from Io's, could be ~0.2 W m$^{-2}$ (O'Brien et al. 2002).

A key parameter is $Q'_p$, which parameterizes the planet's tidal response to the star. In principle $Q'_p$ may take any value, but in our solar system rocky and gaseous bodies tend to cluster around two $Q'_p$ values separated by several orders of magnitude. For terrestrial bodies $Q'_p \sim 500$ (Dickey et al. 1994; Mardling & Lin 2004; Lambeck 1977; Yoder 1995). For gaseous bodies it is common to adopt $Q'_p \sim 10^5$ (Banfield & Murray 1992; Aksnes & Franklin 2001; Zhang & Hamilton 2007, 2008), although it could be much larger (Greenberg et al. 2008). The stellar value $Q'_*$ is not very important in the case of HD 40307 because the planet masses and radii are relatively small (see Equations (1) and (2)); we assume it is $3 \times 10^6$ (Jackson et al. 2008b).

We must also estimate stellar and planetary radii. We assume that the star's radius follows the empirical relationship found by Gorda & Svechnikov (1999). For terrestrial cases we scale $R_p$ as $m_p^{0.27}$ (Fortney et al. 2007). For gaseous cases, $R_p$ is calculated by assuming the planet has the same mean density as Neptune: $r_b = (m_b/M_{\rm Nep})^{1/3}R_{\rm Nep}$, where $M_{\rm Nep}$ and $R_{\rm Nep}$ are the mass and radius of Neptune, respectively. Note that this assumption is consistent with observations of the transiting planet GJ 436 b (Deming et al. 2007; Gillon et al. 2007; Jackson et al. 2008b). Furthermore, our analysis depends on the age of this system, which we estimate as $6.1 \pm 1.6$ Gyr old (see the Appendix).

**Table 1**
Masses and Orbits for the HD 40307 Planets

| Planet | $m$ ($M_\oplus$) | $P$ (d) | $a$ (AU) | $e$ | $T_p$ (JD) |
|---|---|---|---|---|---|
| b | 4.2 | 4.3115 | 0.047 | $0.008 \pm 0.065$ | 2454562.77 |
| c | 6.8 | 9.62 | 0.081 | $0.033 \pm 0.052$ | 2454551.53 |
| d | 9.2 | 20.46 | 0.134 | $0.037 \pm 0.052$ | 2454532.42 |

**Note.**
[a] Set to zero by Mayor et al. (2009).

## 3. RESULTS

Table 1 lists a set of values for the masses and orbits of the planets in HD 40307 computed by Mayor et al. (2009) with all eccentricities treated as free parameters. $P$ is the orbital period and $T_p$ is the time of periastron passage. As $e$ values $\lesssim 10^{-2}$ are not currently measurable in radial velocity data (the uncertainty is larger than the nominal values; Butler et al. 2006), Mayor et al. 2009 preferred a solution in which all eccentricities are set to zero (and longitudes of periastron $\varpi$ are therefore undefined). In this case the residuals dropped slightly, but the other parameters remained the same (with $T_p$ now the time of passage through longitude zero). Here, we consider two possibilities for this system, one in which the eccentricities have the reported nonzero values listed in Table 1 and one in which the eccentricities are all zero.

Over timescales much shorter than tidal evolution, interactions among the planets cause periodic variations in orbital elements. Figure 1 shows the variations of the eccentricities, produced by our $N$-body models. In the top panel we model the oscillation of the orbits using the reported, nonzero eccentricities. In the bottom panel, we show the evolution assuming all eccentricities are initially zero. For these cases we set $\varpi_b = \varpi_d = 0$ and $\varpi_c = 180°$ (different choices of the $\varpi$'s

[5] Publicly available at http://www.astro.umd.edu/~rauch/HNBody.

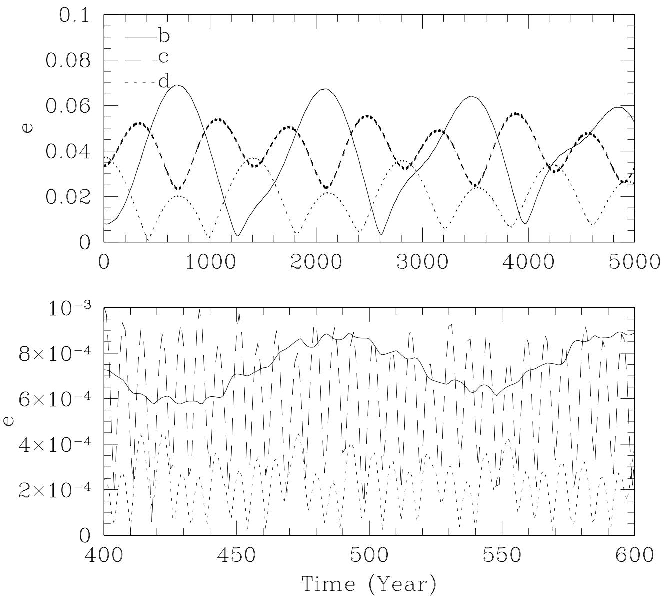


**Figure 1.** Top: eccentricity evolution of HD 40307 b, c, and d assuming nominal parameters from Table 1. Bottom: eccentricity evolution assuming all $e$ values are initially zero (the timescale here is shorter than above because the oscillation period is much shorter and was chosen to illustrate the maximum values of $e_b$).

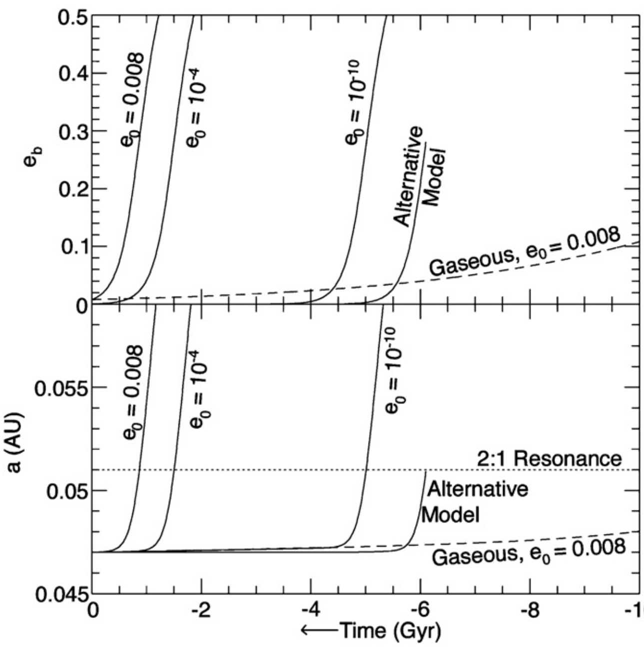


**Figure 2.** Top: history of $e_b$ for different orbital and physical assumptions. Solid curves assume $Q'_b = 500$ (rocky super-Earths), dashed curves assume $Q'_b = 10^5$ (gaseous mini-Neptunes). The assumed value of the initial eccentricity of planet b, $e_0$, is indicated on each curve. The "Alternative Model" curve assumes that planet b formed with $e \approx 0.25$ and $a_b$ just interior to the 2:1 resonance with planet c. The value of $e_b$ in this case damped to its minimum perturbed value and remained there. Bottom: evolution of $a_b$ (solid and dashed lines) for the same cases and in the same sequence as above. For reference the location of the inner 2:1 resonance with planet c (labeled "2:1 Resonance") is shown by the dotted line. Note that we assume that any history prior to the 2:1 crossing is unphysical.

can result in about a factor of 2 difference in the eccentricity oscillation amplitudes, but this difference does not affect our conclusions). If we assume the eccentricities are initially nonzero, then they remain below 0.1, with planet b's eccentricity as large as 0.07. If all the eccentricities are initially zero, then they all quickly grow to nonzero values. Even if eccentricities were fully damped by tides, mutual interactions would keep them greater than 0. The minimum perturbed eccentricity is thus $\sim 5 \times 10^{-4}$.

We have modeled the long-term effect of tides on planet b by integrating Equations (1) and (2) back in time for various assumed values of its current eccentricity ($e_0$) (Figure 2; the "Alternative Model" is explained below). For these three cases, $a_b$ jumps up in values at about the same time as $e_b$ gets large. So, for example, with $e_0 = 0.008$, $a_b$ would have been at the location of the 2:1 resonance with planet c less than 1 Gyr ago (dotted line in the bottom panel of Figure 2). If planet b crossed the resonance, both planets' eccentricities would have been pumped up because it is a divergent crossing (Hamilton 1994; Chiang et al. 2002; Zhang & Hamilton 2007, 2008). Such a crossing would likely have destabilized the system, or at least prevented the system from appearing as packed as it is today. This process would have been similar to models of the 2:1 resonance crossing of Jupiter and Saturn in our solar system (Gomes et al. 2005), which significantly spread out the giant planets. For HD 40307, such a history is unlikely given the current orbital architecture. Thus, if we assume that the resonance crossing could not have happened during this system's history, either (1) tides must have damped $e_0$ to its minimum possible value several billion years ago, (2) the system must be younger than 1 Gyr, or (3) $Q'_b$ must be larger than 500.

While using $e_0 = 5 \times 10^{-4}$ as an initial condition for the tidal evolution gives resonance crossing 2 Gyr ago, a different history is possible. The current value of $e$ for this planet would be $\sim 5 \times 10^{-4}$ even if the system was fully damped by tides much earlier. Thus, we have no way to constrain how long the system has been in this state; the $e_0 = 5 \times 10^{-4}$ curve in Figure 2 could be shifted by any amount to the right and still be a possible model of the system's history. For example, the curve labeled "Alternative Model" was shifted so that the system formed inside the 2:1 resonance 6.1 Gyr ago (its estimated age; see the Appendix), then was fully damped within 2 Gyr, and remained with the minimum perturbed eccentricities ever since (with such small eccentricities, $da/dt \approx 0$ for the intervening 4 Gyr). This scenario avoids a past resonance and permits super-Earths ($Q' \sim 500$) in the HD 40307 planetary system.

Next we calculate the tidal heating of the planets, still assuming terrestrial planet parameters ($Q' = 500$, density of 5 g cm$^{-3}$). For eccentricities of $5 \times 10^{-4}$, the heating is $10^{-2}$ W m$^{-2}$ for planet b and $3 \times 10^{-5}$ W m$^{-2}$ for planet c, assuming radii of $9.4 \times 10^3$ and $1.07 \times 10^4$ km, respectively. On the per-unit-surface-area basis (relevant for surface characteristics), these values are considerably lower than the Earth's radiogenic heating, 0.08 W m$^{-2}$. If the planets have the nonzero eccentricities listed in Table 1, the current surface heat fluxes for these two planets would be $h_b = 3$ W m$^{-2}$ and $h_c = 1$ W m$^{-2}$, comparable to Io's heat flux ($\sim 2$ W m$^{-2}$; note that the $Q'$ value for Io is probably similar to the Earth's; Yoder 1995; Aksnes & Franklin 2001).

The short-term periodic variations of the heating due to the periodic variations in eccentricities (from Figure 1) are also interesting. The top two curves in Figure 3 show the changes in $h$ that correspond to the orbital changes in the top panel of Figure 1: $h_c$ oscillates between 0.5 and 1.5 W m$^{-2}$, always more than the Earth's heating. However, $h_b$ nearly reaches 100 W m$^{-2}$, and maintains that rate most of the time. Although the heating rates oscillate, the periods of oscillation are much shorter than heat transport (predominantly mantle overturn) in the Earth (see,

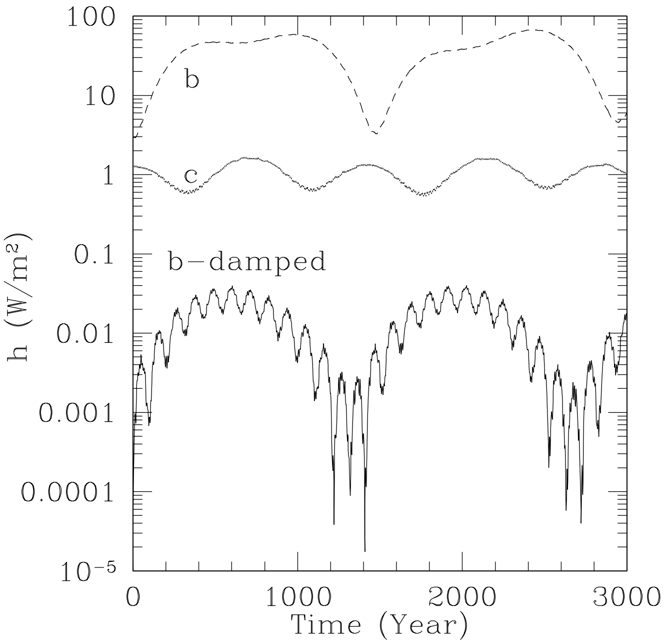


**Figure 3.** Tidal heating fluxes of terrestrial-like planets in HD 40307. The upper two curves correspond to the changes in $e$ shown in Figure 1 (top), which used initial conditions from the nominal orbital elements in Table 1. The curve labeled "b-damped" corresponds to the changes in $e$ shown in Figure 1 (bottom), in which orbits are initially circular.

e.g., Davies 1999), so the planet's surface flux would probably be the average heating rates ($\approx$30 W m$^{-2}$), an order of magnitude more than that of super-volcanic Io.

Assuming the system has damped to the minimum eccentricities allowed by mutual perturbations (Figure 1 bottom), the heating rates, are much lower; $h_b$ is shown in the lowest curve in Figure 3. Here the heating rate oscillates by many orders of magnitude, but remains much less than the Earth's. Planet c's tidal heating in this damped case is always less than 1 mW m$^{-2}$. Therefore, if the eccentricities have damped to minimum values, these planets would have heat fluxes much less than the terrestrial planets in our solar system.

For the planets orbiting HD 40307 to be rocky, they must have begun tidal evolution with low-eccentricity orbits and with planet b interior to the 2:1 resonance with c. However, it is unlikely that the planets acquired most of their mass in such a configuration, as that scenario predicts an implausibly large preplanetary nebula. According to Kuchner (2004), such in situ formation requires a primordial disk with surface-density profile $\Sigma(r) = 6379(r/0.1\mathrm{AU})^{-0.925}$ g cm$^{-2}$. This disk contains 21.6 $M_\oplus$ inside 0.15 AU, probably 15–100 times more than our solar system had (Weidenschilling 1977; Hayashi 1981).[6] This result is consistent with the assumption that HD 40307's gas-to-dust ratio is half the solar nebula's because [Fe/H] = −0.31, in which case its disk would have been 30–200 times more massive than the solar nebula. These values represent a disk mass comparable to the stellar mass, and far in excess of the typical star-disk mass ratio of 1% (Andrews & Williams 2005). We conclude that these planets did not form in situ; they must have formed further out and migrated in prior to the dispersal of the gas disk.

So far we have considered the implications of rocky planets. Could they instead be mini-Neptunes with a thick gaseous envelopes and $Q' = 10^5$? If the current $e_b$ has the value given in Table 1, the tidal history (shown by dashed lines in Figure 2) would not have included dangerous resonance crossings in the last 6.1 Gyr. Furthermore, such planets would have heating fluxes several orders of magnitude smaller than terrestrial planets, and their internal structures would probably not be significantly affected by tidal heat. If, however, the mass (and hence radius) of planet b is significantly greater than the observational minimum, then there may have been more evolution. We find that if $m_b = 15\ M_\oplus$, then HD 40307 b would have been at the 2:1 resonance 6.1 Gyr ago. Such a mass corresponds to an orbit inclined by 75° to the line of sight. In other words, planet b's orbit must be more than 15° from face-on.

If the planets are gaseous, did they form in situ, or did they migrate in from further out? If the planets formed in situ, the preplanetary nebula would have required about half as much mass as for the rocky-planet case described above (assuming the cores' masses are roughly equal to the envelopes' masses), but that value is still improbably large. More likely, as with rocky planets, the planets could have formed further out and migrated in via interactions with the disk (Lin et al. 1996). Theoretical models of this phenomenon (e.g., Snellgrove et al. 2001; Lee & Peale 2002) suggest resonance capture could be an outcome of this process, but resonances are not observed (Mayor et al. 2009). However, such a commensurability could have been destroyed by subsequent mergers, scattering or turbulence (Terquem & Papaloizou 2007; Adams et al. 2008; Lecoanet et al. 2009). Therefore the migration scenario is consistent with the observed orbits. We conclude that if the planets are mini-Neptunes, they likely formed at larger radii and migrated in via disk torques to their present orbits.

The terrestrial and gaseous planet models considered above are not a complete exploration of parameter space. For example, the responses of the planets to tides are encapsulated in $Q'$, a notoriously uncertain parameter, even in the solar system. To address this uncertainty, we solved Equations (1)–(2) for a range of values of $Q'_p$ and $e$ ($1500 \leqslant Q'_b \leqslant 3500$ and $10^{-4} \leqslant e_0 \leqslant 0.01$) to determine how long ago the resonance crossing would have occurred. If it occurred more than 6.1 Gyr ago, the case is allowed, but if the crossing occurred within the last 6.1 Gyr, then the case is forbidden. For $e_b < 10^{-3}$, these restrictions do not strictly apply since the eccentricity may have damped to those values an arbitrarily long time ago. If, however, $e_b$ is found to be greater than $10^{-3}$, then it would constrain $Q'_b$ to be $\gtrsim$2200.

## 4. CONCLUSIONS

The small minimum masses of the planets orbiting HD 40307 are tantalizingly close to masses of the rocky, "terrestrial" planets in our solar system. By considering the dynamical features and history of the system, we have determined implications of their being predominantly rocky or gaseous. We find both possibilities are consistent with the observations, but the likelihood that they are terrestrial depends on the actual values of the current eccentricities, which are at or below the detection threshold.

Mayor et al. (2009) report two sets of $e$ values, either all ∼0.01 or all zero. The latter case is ruled out by mutual perturbations between the planets (see Figure 1). Instead, the

[6] We assume that $\Sigma = \Sigma_0(r/1\mathrm{AU})^{-x}$, where $(\Sigma_0, x) = (7.75$ g cm$^{-2}$, 1.5) or (5.895 g cm$^{-2}$, 1.0) and extend the disks in to $r = 0$. These disks are calibrated to the MMSN and contain 5 $M_\oplus$ from 0.4–4 AU.

lowest possible eccentricities are $\sim 10^{-3}$. If the values are that small, tides probably damped them from higher values, and they may have reached this state recently, or at any time in the past. These ambiguities preclude a definitive assessment of the composition of the planets. However, if or when the eccentricities are measured more precisely, such a determination will be possible through tidal analysis.

If the planets are terrestrial (i.e., $Q' \sim 500$), then either (1) the system must be less than 2 Gyr old, which is unlikely (see the Appendix), or (2) tidal evolution began with planet b just inside the 2:1 resonance with c, and with modest eccentricity (less than 0.3). In either case, the planets must have formed at larger distances and migrated inward. In case (1), the inner planet is a "super-Io," with intense volcanism, a type of rocky body suggested by Jackson et al. (2008a). In case (2), the planets could be terrestrial-like bodies: rocky, with thin atmospheres and modest volcanism.

If the planets are "mini-Neptunes," then the orbital history, formation scenarios, and internal structures are all consistent with previous models of such bodies. The only constraint tidal evolution can provide is that $i > 15°$ (assuming $Q'_b = 10^5$). As this constraint is less stringent than the requirements for a terrestrial body, our analysis favors the mini-Neptune model somewhat.

In order to distinguish between super-Earth and mini-Neptunes through dynamical analyses, the eccentricities need to be determined to within at least $10^{-3}$. Such high precision is only measurable for planets that undergo primary and secondary transits, but none has (so far) been reported for this system. Photometric observations of the transit would allow a calculation of the planet's radius, but this value is not enough to determine if the planets are super-Earths because composition-radius degeneracies exist in current models of small-mass exoplanets (Adams et al. 2008; Raymond et al. 2008). Therefore dynamical models of the system's history may be the most effective way to determine the composition of the planets.

We also note that if planet b is gaseous, then it may be undergoing evaporative mass loss (Baraffe et al. 2004; Hubbard et al. 2007). Indeed, Raymond et al. (2008) showed that a 25 $M_\oplus$ planet at 0.05 AU could be evaporated to its core in 4–5 Gyr, although this depends on the star's X-ray history. If planet b had its atmosphere removed in the past, then the tidal models presented in Section 3 may be inadequate as we have not considered time-varying $Q'_b$. Furthermore, even if HD 40307 b is gaseous today, then it may one day be reduced to a solid core, making it terrestrial.

Our analysis also admits the possibility that HD 40307 b is an exotic planet, unlike any in our solar system, with end-member properties ranging from a volcanic super-Io to mini-Neptunes. $Q'$ values may range from $\sim 10^3$ to $\sim 10^4$, perhaps resulting from an unusual internal structure.

The dynamical properties of planetary systems may be used to constrain the physical properties of exoplanets as Figure 4 demonstrates. As more potentially terrestrial-like planets are detected, dynamical analyses will continue to play a role in constraining their physical and orbital properties.

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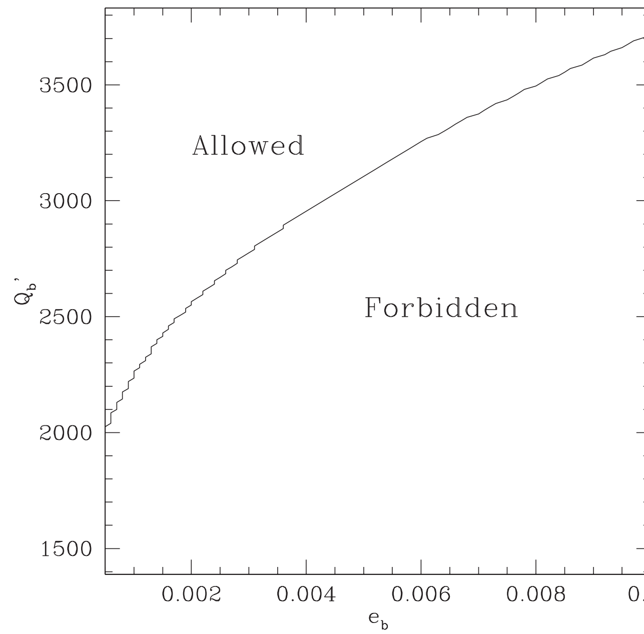


**Figure 4.** Values of $Q'_b$ and $e_b$ that predict resonance crossing less than 6.1 Gyr ago (forbidden region) and those that do not (allowed region). This plot demonstrates how the orbital properties of the system can constrain the physical properties of planet b. Note that the Earth's $Q'$ value is $\sim$500 and Neptune's is $\sim 10^5$.

## APPENDIX

## THE AGE OF HD 40307

Based on two techniques that use the rotation rate and the magnetic activity strength respectively, we estimated the age of HD 40307. Dwarf stars with spectral types ranging from late-F to mid-M have both a radiative zone and a convective zone, the interface of which is thought to be responsible for magnetic field generation and the heating of the upper atmosphere (Parker 1993; Ossendrijver 2003; Thompson et al. 2003), a phenomenon that gives rise to magnetic activity. These stars begin their lives rotating quickly but slowly lose angular momentum over time via solar-type winds. This loss of angular momentum as a function of stellar age has been observed and can be quantified (e.g., Skumanich 1972). Using the age–rotation relation for a star with a radiative–convective zone interface, we calculated an age of 6.7 ± 2.0 Gyr based on a 48 day period, and using the 30% quoted uncertainty from Barnes (2003; I sequence).

Since the rotation rate is linked to magnetic field generation and the subsequent chromospheric activity in solar-type stars, a reduced rotation rate will result in less magnetic activity. Using the cluster derived age-activity relations from Soderblom et al. (1991), we calculate an age (averaging the three relations) of 5.4 ± 1.6 Gyr, based on an $R'_{HK}$ value of −4.99 (Noyes et al. 1984). These results are confirmed using the age-activity relation of Donahue (1998), which also yield an age of 5.4 Gyr. Recently, Mamajek & Hillenbrand (2008) refined the age-activity relations for F-K dwarfs using additional stellar clusters with improved age estimates. Their relations yield an age of 6.3 ± 0.9 Gyr for HD 40307. The Donahue (1998) study uses coeval binary systems to quantify the uncertainty in these relations. For the early K-type dwarfs, the age discrepancy in binary pairs is smaller than the uncertainty in the age-activity relation, confirming an uncertainty of ∼1.6 Gyr.

Combining the results from the rotation and activity analysis, we estimate the age of HD 40307 to be 6.1 ± 1.6 Gyr.

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