Tides and the Evolution of Planetary Habitability

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ABSTRACT

Tides raised on a planet by its host star's gravity can reduce a planet's orbital semi-major axis and eccentricity. This effect is only relevant for planets orbiting very close to their host stars. The habitable zones of low-mass stars are also close-in and tides can alter the orbits of planets in these locations. We calculate the tidal evolution of hypothetical terrestrial planets around low-mass stars and show that tides can evolve planets past the inner edge of the habitable zone, sometimes in less than 1 billion years. This migration requires large eccentricities (> 0.5) and low-mass stars ($\lesssim 0.35 M_\odot$). Such migration may have important implications for the evolution of the atmosphere, internal heating and the Gaia hypothesis. Similarly, a planet detected interior to the habitable zone could have been habitable in the past. We consider the past habitability of the recently-discovered, $\sim 5\ M_\oplus$ planet, Gliese 581 c. We find that it could have been habitable for reasonable choices of orbital and physical properties as recently as 2 Gyr ago. However, when we include constraints derived from the additional companions, we see that most parameter choices that predict past habitability require the two inner planets of the system to have crossed their mutual 3:1 mean motion resonance. As this crossing would likely have resulted in resonance capture, which is not observed, we conclude that Gl 581 c was probably never habitable.

Subject headings: Extrasolar Terrestrial Planets; Habitable Zones; M stars; Gl 581

1. Introduction

After the discovery of extra-solar planets, the detection of a habitable, terrestrial (rocky) planet became a real possibility. Of particular interest are planets in orbit about low-mass

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stars ($\lesssim 0.5 M_\odot$). The lower stellar mass makes detection of lower mass planets easier and leads to habitable orbits with smaller semi-major axes (which also increase the likelihood of detection by current technologies). The recent detection of putative 5 and 8 $M_\oplus$ planets around an M star (stellar mass $M_* = 0.31 M_\odot$) (Udry *et al.* 2007) near the circumstellar "habitable zone" (HZ) (Kasting *et al.* 1993; Franck *et al.* 2000; von Bloh *et al.* 2007; Selsis *et al.* 2007; hereafter S07) suggests that Doppler surveys (*i.e.* Butler *et al.* 2006; Naef *et al.* 2007) are becoming sensitive enough to detect terrestrial planets in the HZ of low-mass stars. Not surprisingly, M stars now appear to be attractive targets for detecting habitable planets (Tarter *et al.* 2007).

The *habitable zone* is defined, following Kasting *et al.* (1993), as the range of distances from a star at which liquid water could be stable at the surface of a planet. The definition usually implicitly assumes that the star is the main source of heat. Thus, it excludes locations where other sources of heat might be available, such as moons, like Jupiter's Europa, where tidal heating is a major factor maintaining near-surface liquid water. In that sense, the phrase *habitable zone*, as usually used in astrophysics, is a misnomer. Nevertheless, here we use the conventional definition, while explicitly emphasizing that life could exist outside this zone.

The detection of Gl 581 c and d (Udry *et al.* 2007) has demonstrated that planets can form near the HZ of low-mass stars. For such stars the habitable zone is so close to the star that tidal effects may be important (Mardling & Lin 2004). Tides raised between the star and planet introduce torques on the planet resulting in orbital evolution, usually decay of semi-major axis, a, and eccentricity, e. Here we quantify the effects of tidal forces in such zones. We find that Earth-sized planets with large initial eccentricities could migrate out of the HZ of low-mass stars in less than 1 billion years.

The proper definition of an HZ is not obvious. As described in S07, the boundaries of the HZ are a complex function of both stellar and planetary properties. For any individual planet, the definitions we choose may not be appropriate. Nonetheless, we will show a general trend that must be considered when assessing a planet's habitability, both in the past and in the future.

We consider the evolution of terrestrial planets beginning from a location that is almost assuredly habitable to a region that is probably not habitable. We call the time to complete this traversal the "habitable lifetime", τ_{HL}. For relatively massive stars ($\gtrsim 0.35 M_\odot$), the HZ is far enough away from the star that tides cannot cause significant tidal evolution[1]. However for planets with relatively large eccentricities ($\gtrsim 0.5$) orbiting low-mass stars ($\lesssim 0.35 M_\odot$)

[1]Note we only consider tidal effects after the star has reached the main sequence

tides can pull a planet out of the HZ in less than 1 Gyr. The large number of low-mass stars and significant fraction of known exoplanets with large e suggest that tides may limit the total number of habitable planets in the galaxy.

We assume that potentially habitable planets can form with a range of masses and orbits in the HZ of low-mass stars (see Chambers [2004]; Raymond, Quinn & Lunine [2007] or Lissauer [2007] for a discussion of the formation of such planets). Of course, the formation of a planet in the HZ does not mean a planet is, will be, or has been habitable. Many other factors are required such as favorable composition (Lissauer 2007), a thick atmosphere, substantial mass for sustained plate tectonics ($m \gtrsim 0.3 M_\oplus$) (Williams, Kasting & Wade 1997; Raymond, Scalo & Meadows 2007), which on Earth drives the carbonate-silicate cycle (Walker, Hays & Kasting 1981), and substantial water content (*e.g.* Raymond, Quinn & Lunine 2004), both for life and to facilitate plate tectonics (Regenauer-Lieb, Yuen & Barlund 2001). Nonetheless we will call planets "habitable" if their orbital properties are such that they permit water to be stable on the surface.

The recently announced Gl 581 system contains a planet, c, that is probably just interior to the HZ (S07). In Table 1 we list the properties of the planets in this system; m_p is the planet mass, P is the orbital period, a is the semi-major axis, e is the eccentricity, ϖ is the longitude of periastron, and T_{peri} is the time of periastron passage in Julian Days. Tidal theory predicts planet c orbited with larger values of semi-major axis and eccentricity in the past. Therefore it may have been habitable in the past, but tides subsequently moved the planet into an uninhabitable orbit. We find that if planet c was the only planet in the system, plausible physical properties predict it was habitable. However, when we consider constraints from the mutual interactions of the additional planets, we find that planet c has likely never been habitable.

Tides strong enough to induce significant orbital evolution can also heat the interior of a planet through tidal working. The same type of heating causes Io's intense vulcanism (Peale, Cassen & Reynolds 1979). Therefore we might expect an increased heating rate on the planets we consider here as well. The orbital evolution we consider could also have implications for the evolution of a habitable planet's atmosphere. In some cases, the orbit-averaged flux can increase by a factor of 2 as the orbit shrinks (assuming constant stellar luminosity).

In § 2 we review tidal theory, present our definition of the HZ, and describe how we determine the habitable lifetime. In § 3 we present our results for hypothetical terrestrial planets. In § 4 we describe how our model applies to the Gl 581 c planet. Finally, in § 5 we draw our conclusions and discuss directions for future research.

2. Methodology

2.1. Tidal Theory

We evaluate the effects of tides using the classical, second order equations assembled by Goldreich & Soter (1966) (see also Kaula 1964; Greenberg 1977):

$$\frac{da}{dt} = -\Big(21\frac{\sqrt{GM_*^3}R_p^5k}{m_pQ_p}e^2 + \frac{9}{2}\frac{\sqrt{G/M_*}R_*^5m_p}{Q'_*}\Big)a^{-11/2} \tag{1}$$

$$\frac{de}{dt} = -\Big(\frac{21}{2}\frac{\sqrt{GM_*^3}R_p^5k}{m_pQ_p} + \frac{171}{16}\frac{\sqrt{G/M_*}R_*^5m_p}{Q'_*}\Big)a^{-13/2}e \tag{2}$$

where a is semi-major axis, G is Newton's gravitational constant, m_p is the mass of the planet, k is the planet's Love number, Q_p is the planet's tidal dissipation function, Q'_* is the star's tidal dissipation function divided by two-thirds its love number, R_p is the planet's radius, and R_* is the star's radius. The first terms in these equations are due to the tide raised on the planet by the star, and the second terms are due to tides raised on the star by the planet. Eqs. (1 – 2) are only valid if the planet's orbital period is less than the star's rotation period, otherwise the signs of the second two terms will change. For the cases we consider, this condition is irrelevant because the second terms of Eqs. (1 – 2) are 6 – 7 orders of magnitude smaller than the first. This difference is largely due to the mass difference between a terrestrial planet and a star. Note that tidal theory predicts decay for both a and e. As tides slowly change a planet's orbit, the planet may move into or out of the HZ.

The equations above were derived under the implicit assumption that e values are small. Here we apply them to cases that include conditions with large e values. Thus higher-order corrections may potentially be important. Several models of tidal evolution that are not restricted to small values of e have been derived (Hut 1981; Eggleton, Kiseleva & Hut 1998; Mardling & Lin 2002). However, such models must include specific assumptions about how a body responds to the ever-changing tidal potential. The tidal forcing involves components with a various frequencies, but the nature of the response of a planet or star is uncertain. It is not clear how the tidal phase lag depends on the frequency of each harmonic. This issue becomes increasingly critical when e is large and a wide range of different comparable-amplitude frequencies are involved. For a model valid to a high order in e, the validity of parameterizing tidal effects through a single constant Q is questionable. Moreover, tidal heating could lead to core/mantle melting and a time-dependent Q value. Not enough is known about the actual response of real bodies to evaluate these higher-order effects. Therefore, to the best of current knowledge, Eqs. (1 – 2) above are reasonable representations of tidal evolution. As the theory matures, the effect of higher-order terms could be included and this study should be revisited. Note that the higher order theories that have been derived all predict faster evolution than Eqs. (1 – 2) (all the higher order terms have the same sign as those in Eqs. (1 – 2), so their predictions for the habitable lifetime, τ_{HL}, would be even shorter than those we derive below. In that sense, our approach provides a conservative estimate of the tidal effects on terrestrial planets.

Eqs. (1 – 2) are only valid when the star's orbit-averaged torque on the planet's tidal bulge is zero. When this situation occurs, the planet is said to be "tidally locked" to its star. For a planet on an eccentric orbit, the torque is greatest at pericenter at which point the star is moving with an angular velocity greater than the mean motion. Therefore the rotational frequency of the planet Ω is larger than its orbital frequency n (tidal locking does not mean that one side of the planet faces the star for all times, this situation only occurs for a circular orbit). To second order in e these two frequencies are related by the following equation,

$$\Omega = n(1 + \frac{19}{2}e^2) \tag{3}$$

(Murray & Dermott 1999; Goldreich 1966). Note that this equation neglects effects of a permanent quadrupole moment (we ignore this effect as their is currently no hope of measuring it in an exoplanet). Even for modest eccentricities, the spin and orbital frequencies can be significantly different due to the coefficient in front of the e^2 term. A planet with an eccentricity of 0.32 has a spin period half that of its orbital period.

The time for a planet to become tidally locked is given by

$$t_{lock} = \frac{8 m_p Q_p a^6}{45 G M_*^2 k r_p^3} \Delta\Omega \tag{4}$$

(Goldreich & Soter 1966; Rasio *et al.* 1996), where $\Delta\Omega$ is the difference between the initial spin, and the spin given by Eq. (3). For an Earth-mass, terrestrial planet ($k = 0.3, Q_p = 100$) planet orbiting a 0.3 $M_\odot$ star with $e = 0$ $a = 0.1$ AU, this timescale is about 10^6 years. We consider planets initially with much larger eccentricities, but eccentricity probably does not affect this timescale significantly (Peale 1977). This time is very short compared to other timescales associated with planet formation, and we may assume the planets are tidally locked to the star as soon as they are formed.

In order to determine τ_{HL} for possible planets, we consider a range of values of M_*, m_p, a and e. We will set $Q'_* = 10^{5.5}$, $Q_p = 21.5$, and $k = 0.3$, reasonable choices based on limited observational constraints for stars (Ogilvie & Lin 2007; Jackson, Greenberg & Barnes 2007) and the Earth (Dickey *et al.* 1994; Mardling & Lin 2004). However, the time-averaged value of Q of the Earth is probably closer to 100 (Lambeck 1977), which is similar to the values of other terrestrial planets in the Solar System (Yoder 1995). Nonetheless we choose $Q_p = 21.5$ to be consistent with past work (Mardling & Lin 2004).

From our choices of M_* and m_p we must determine radii. For the planet, we will use the scaling relationship

$$\frac{R_p}{R_\oplus} = \Big(\frac{m_p}{M_\oplus}\Big)^{0.27} \tag{5}$$

(Valencia, O'Connell & Sasselov 2006). For the stellar radius, we use an empirical relation derived from observations of eclipsing binaries (Gorda & Svechnikov 1999):

$$\log_{10}\frac{R_*}{R_\odot} = 1.03\log_{10}\frac{M_*}{M_\odot} + 0.1, \tag{6}$$

where $R_\odot$ and $M_\odot$ are the solar radius and mass, respectively. Note that Eq. (6) is only valid when $M_* \lesssim M_\odot$.

2.2. The Eccentric Habitable Zone

For circular orbits, the HZ is defined as the range of orbits in which a terrestrial planet, with an atmosphere favorable for habitability, can support liquid water on the surface (Kasting *et al.* 1993; S07). However, extra-solar planet orbits are often highly eccentric. For these orbits, Williams & Pollard (2002) showed that, despite large variations in surface temperature, the key for long-term climate stability is the orbit-averaged flux,

$$F = \frac{L}{4\pi a^2\sqrt{1-e^2}}, \tag{7}$$

(Williams & Pollard 2002; Adams & Laughlin 2006), where F is the orbit-averaged flux and L is the stellar luminosity. Note, however, that potential water loss at periastron and potential cloud freeze-out at apoastron have not been accounted for, despite their implications for habitability. We define the eccentric habitable zone (EHZ) as the range of orbits for which a planet receives as much flux over 1 orbit as a planet on a circular orbit in the "classical" HZ (Kasting *et al.* 1993; S07). We must also scale the location of the EHZ to the luminosity of the stars we are considering. Lower mass stars have lower luminosities, and hence the EHZ's are closer to the star. We therefore define the inner and outer edges of the EHZ, l_{in} and l_{out} (in AU), respectively, as

$$l_{in} = (l_{in\odot} - a_{in}T_* - b_{in}T_*^2)\Big(\frac{L}{L_\odot}\Big)^{1/2}(1-e^2)^{-1/4}, \tag{8}$$

and

$$l_{out} = (l_{out\odot} - a_{out}T_* - b_{out}T_*^2)\Big(\frac{L}{L_\odot}\Big)^{1/2}(1-e^2)^{-1/4}, \tag{9}$$

where l_{in} and l_{out} are the inner and outer edges of the HZ, respectively, in AU, $l_{in\odot}$ and $l_{out\odot}$ are the inner and outer edges of the HZ in the solar system, respectively, in AU, $a_{in} = 2.7619 \times 10^{-5}$ AU/K, $b_{in} = 3.8095 \times 10^{-9}$ AU/K^2, $a_{out} = 1.3786 \times 10^{-4}$ AU/K, and $b_{out} = 1.4286 \times 10^{-9}$ AU/K^2 are empirically determined constants, $T_* = T_{eff} - 5700$ K, and $L_\odot$ is the solar luminosity (S07). Terms involving T_* relate stellar intensity at different wavelengths and atmospheric windows of predicted habitable planets. Eq. (8 – 9) are only valid for $T_{eff} < 3700$ K. T_{eff} is the effective temperature of the star, given by

$$T_{eff} = \left(\frac{L}{4\pi\sigma R_*^2}\right)^{1/4} \tag{10}$$

where σ is the Stefan-Boltzman constant.Therefore a planet with a given e is on the inner edge of the EHZ if $a = l_{in}$. Note that as e changes so do the locations of l_{in} and l_{out}.

The values of $l_{in\odot}$ and $l_{out\odot}$ are therefore the key parameters in the identification of the edges of the EHZ. We consider three criteria identified in S07: 1) 0% cloud cover, 2) 50% cloud cover, and 3) 100% cloud cover[2]. S07 give values of $l_{in\odot}$ of ~ 0.89, ~ 0.72, and ~ 0.49 AU for the three possibilities, respectively. For the outer edge, S07 give $l_{out\odot} = 1.67, 1.95$, and 2.4 AU, for the three cloud cover models, respectively. We arbitrarily choose the 50% cloud cover case to be the limits of the EHZ. This choice is the middle of the possibilities, and roughly corresponds to the cloud cover on the Earth.

The stellar mass is related to the luminosity in the following way,

$$\lambda = 4.101\mu^3 + 8.162\mu^2 + 7.108\mu + 0.065, \tag{11}$$

where $\lambda = \log_{10}(L/L_\odot)$ and $\mu = \log_{10}(M_*/M_\odot)$ (Scalo *et al.* 2007). With these definitions, we plot the shape of the EHZ as a function of stellar mass and initial eccentricity, e_0, in Fig. 1. As both e_0 and M_* increase, the location of the EHZ moves out and grows wider. If, for a certain star, $T_{eff} < 3700$ K, we set it to 3700 K in Eqs. (8 – 9) as done in S07.

2.3. Determination of the Habitable Lifetime

The habitable lifetime, τ_{HL}, depends on the initial orbit of a planet. Rather than explore all possible orbits, we will consider one type of starting location: the inner 0% cloud cover boundary (*i.e.* $l_{in\odot} = 0.89$ AU). Although this choice of initial condition is arbitrary, it demonstrates how tides will change the orbits, and, hence, habitability. As stated in the

[2]Note that S07 also give values of $l_{in\odot}$ and $l_{out\odot}$ based on assumptions regarding the past and present habitability of Venus and Mars coupled with stellar evolution, but we will ignore those models here.

previous section, we consider a planet uninhabitable when it crosses the 50% cloud cover boundary ($l_{in\odot} = 0.72$ AU). We vary the planet's initial eccentricity e_0 and M_* in increments of 0.01 and 0.01 $M_\odot$, respectively, and consider four different planet masses: 5, 1, 0.5, and 0.1 $M_\oplus$.

In order to calculate τ_{HL} we numerically integrate Eqs. (1 - 2) and (8) with a timestep of 10,000 years. Convergence tests showed that this timestep is two orders of magnitude smaller than necessary to produce reliable results. We integrate the tidal equation until either $a < l_{in}$(50% cloud cover) or $\tau_{HL} > 10$ Gyr.

3. Habitable Lifetimes

In this section we present results for τ_{HL} as defined in § 2.3. Fig. 2 shows contour lines of τ_{HL} for planets with masses of 5, 1, 0.5 and 0.1 $M_\oplus$. There are two prominent features in each panel. First is the abrupt change in τ_{HL} from 10 Gyr to less than 1 Gyr between $e_0 = 0.53$ and 0.54. This feature occurs because the time to circularize the orbit is less than 10 Gyr. When e reaches zero, the evolution of a effectively stops, and the planet is stuck on one side of the boundary or the other. Orbits with $e_0 \lesssim 0.53$ become circular with a just larger than l_{in}. However, when $e_0 \gtrsim 0.54$, the orbits circularize with a slightly less than l_{in}.

These different types of evolution are shown in Fig. 3. Note that the evolution of both cases is very similar, but the final relationship between a and l_{in} is such that one planet remains in the EHZ, but the other does not. Note that the EHZ changes because e is changing. The difference is therefore not due to some fundamental feature of tidal theory (other than changes in semi-major axis become negligible for small eccentricities), rather our definition of the EHZ leads to the different values of τ_{HL}.

The apparently sudden transition from long to short habitable lifetimes can be shown by considering how a and e are related:

$$\ln\left(\frac{a}{a_0}\right) = e^2 - e_0^2, \tag{12}$$

where a_0 and e_0 are the initial values of a and e, if the effects of the tide raised on the star by the planet is negligible (which is the case here) (Jackson, Greenberg & Barnes 2007). If we assume $e = 0$ (*i.e.* the tidal evolution has effectively ended, and $t = \infty$), $a = l_{in}$(50% cloud cover) and $a_0 = l_{in}$(0% cloud cover), then the value of e_0 that solves Eq. (12) should correspond to the critical value ($e_0 \sim 0.535$) seen in Fig. 2 (note that a_0 is also a function of e_0 and Eq. [12] must be solved numerically). In the cases we consider, this equation is independent of mass. The values of a and a_0 have the same dependence on luminosity (and hence mass, *c.f.* Eq. [11]), and, for the stars we consider, we have set $T_{eff} = 3700$ in order to follow the example of S07. Therefore we expect the critical value of e_0 to be independent of both stellar and planetary mass. Solving Eq. (12) for the values of l_{in} we have chosen, we find the critical value of e_0 is 0.53490, in agreement with Fig. 2.

The second feature of the contours is the downturn that occurs for $e_0 \gtrsim 0.65$, in other words, τ_{HL} gradually increases with e_0. This dependence follows from the change in the EHZ at larger values of e_0, as shown in Fig. 1. At these values not only is the EHZ wider, but a_0 is also larger. Therefore planets' orbits will evolve more slowly (note the a dependence in Eqs. [$1-2$]), and have further to go before they reach l_{in}(50% cloud cover).

We also see in Fig. 2 that lower mass planets tend to have longer habitable lifetimes. This relationship follows from the dependence of da/dt on m_p in Eqs. $(1-2)$. Low-mass stars, like the ones considered here, are likely to host low-mass planets (Laughlin, Bodenheimer & Adams 2004; Ida & Lin 2005; Raymond, Scalo & Meadows 2007), and therefore disks around M stars may preferentially form planets with relatively long habitable lifetimes. However, they may not contain enough volatiles for life because the impacts that deliver them may have large enough energies that the volatiles will be lost to the planet (Lissauer 2007).

Models of the evolution of habitable atmospheres have focused on planets with static orbits (*e.g.* Kasting & Catling 2003). Figure 2 shows that such a model may be inappropriate for determining habitability and biosignatures of planets around M stars (Segura *et al.* 2005; S07). In Fig. 4 we plot the orbit-averaged stellar flux for a planet with $\tau_{HL} = 4.5$ Gyr orbiting a 0.2 $M_\odot$ star (assuming the stellar luminosity is constant). This figure also shows how the spin frequency of the planet Ω evolves relative to its mean motion n, see Eq. (3). The tidally evolving planet does not orbit such that only one side faces the star until the orbit has become circular at $t \approx 6$ Gyr.

Note as well that there exists a family of orbits with $\tau_{HL} \approx 4.5$ Gyr, about the age of the Earth. Therefore these calculations suggest that if a planet with the correct ingredients for life formed with that orbit, and life subsequently developed in a manner similar to the Earth, that life would be eliminated by the ultimate global warming event: The passage of the planet through the inner edge of the HZ due to tidal evolution.

4. Application to the Gl 581 System

In this section we apply the ideas of § 2 to the recently announced Gl 581 planetary system (Udry *et al.* 2007). This system contains three planets with orbits and masses listed in Table 1. Planet c is probably interior to the 50% cloud cover HZ, and planet d is probably exterior (S07). The age of the star is uncertain. Its kinematics and metallicity suggest that it is at least a few Gyr old (Bonfils *et al.* 2005; Delfosse *et al.* 1998), but its very low X-ray luminosity (Delfosse *et al.* 1998) indicates it may be as old as 8 – 10 Gyr old (Ribas, private communication; Selsis, private communication). We therefore tidally evolve planet c backward for 10 Gyr by changing the signs of Eqs. (1 – 2) (Jackson, Greenberg & Barnes 2007). First we consider how Gl 581 c would evolve if it were an isolated planet, then we consider how the additional companions constrain its evolution and the planets' physical properties.

4.1. Past Evolution of Gl 581 c

If Gl 581 c were the only planetary companion to its host star, then its past tidal evolution is adequately modeled by Eqs. (1 – 2). For this particular system, we have specific constraints on physical and orbital properties. The planet's radius R_c lies in the range $1.6 \lesssim R_c \lesssim 2R_\oplus$, assuming the observed minimum mass is the actual mass (S07; Valencia, O'Connell & Sasselov 2006; Fortney, Marley & Barnes 2007; Valencia, Sasselov & O'Connell 2007a, 2007b; Sotin, Grasset & Moquet 2007), and its best-fit eccentricity e_c is 0.16, although any value between 0 and 0.3 is about equally likely (Udry *et al.* 2007). For tidal parameters, we appeal to values in our Solar System. The current values of k and Q for the Earth are about 0.3 and 21.5, respectively, from Lunar Laser Ranging (Dickey *et al.* 1994; Mardling & Lin 2004), but over the lifetime of the Earth-moon system, the Q value is probably close to 100 (Lambeck 1977), similar to the value of Mars (Yoder 1995). The star's mass, radius, luminosity and effective temperature are $0.31M_\odot, 0.38R_\odot, 0.0135L_\odot$ and 3200 K, respectively (Bonfils *et al.* 2005). Planet c is currently inside the 100% cloud cover HZ, but such an atmospheric condition is unlikely (S07). We therefore seek to identify physical and orbital parameters that allow Gl 581 c to have been habitable in the past, *i.e.* inside the 50% cloud cover HZ.

First we consider the effects of varying eccentricity. In Fig. 5 we show how long ago Gl 581 c would have been inside the 50% cloud cover HZ, as a function of its current eccentricity, for 2 different, plausible values of Q_c, assuming $k = 0.3$. At low e_c values, the time is longer because tidal evolution is slower with smaller e, while at larger values the time is longer due to the strong coupling between a and e, and because the edge of the HZ is farther out, *c.f.* Eqs. (1 – 2) and (8). Therefore there exists a critical value of e_c that minimizes the time since the planet was habitable. In this case, that value is 0.32 in which case the planet would have been inside the 50% cloud cover HZ as recently as 3 Gyr ago.

Next we consider how the planet's radius constrains past evolution. For most cases we considered, the Gl 581 c planet could have been inside the 50% cloud cover HZ for many Gyr, assuming a system age of 10 Gyr. In Fig. 6 we plot the evolution of the EHZ and a_c for three different values of R_p, and assuming its current eccentricity is 0.16. All the cases plotted assume $Q_c = 21.5, k = 0.3$. The shading represents the 100%, 50%, and 0% cloud cover models, and white is outside the HZ, as in Fig. 1. Even for the extreme case $r_c = 2R_\oplus$, the planet could never have been in the 0% cloud cover HZ. In this case, it is hard to imagine how Q_c could be so low, since the planet is most likely a "water world" (Raymond, Quinn & Lunine 2004; Léger *et al.* 2004) and for such a planet dissipation of tidal energy would be less efficient (Q would be larger). If the system is 10 Gyr old, this case predicts planet c was habitable for 8 Gyr and tides would have sterilized planet c 2 Gyr ago.

4.2. Possible Interactions Between Planets b and c

So far we have ignored interactions between planets b and c, but as we run backwards in time, we need to remember that their mutual gravitational interactions will cause the eccentricities to oscillate on a timescale of $\sim 10^3$ years, and we must consider the possibility that as their periods change, they could hit a mean motion resonance. The first significant resonance would be the 3:1 ratio of orbital periods. If they ever crossed this resonance, the planets would have almost assuredly been captured into the resonance (Lee & Peale 2002). Such a scenario would invalidate the conclusions of the previous section because the system is not observed to be in resonance today.

Planet b is also subject to tidal forces so we must account for its tidal evolution. Currently its outer 3:1 resonance lies at $\sim$ 0.085 AU, and therefore if it did not experience significant evolution, then planet c has orbited inside that distance since the system formed. If, however, planet b experienced significant tidal evolution, then both planets could have migrated such that the 3:1 was always instantaneously beyond the orbit of planet c. The value of Q'_b is unknown for the Neptune-mass planet. If the planet is gaseous ($k = 3/2$), then $Q_b \sim 10^6$ (Jackson, Greenberg & Barnes 2007), but if it is terrestrial, then the value is probably closer to 100. In Fig. 7 we plot the evolution of a_b and e_b for values of Q_b between 10^4 and 10^6. We assume the planet has the same bulk density as Neptune, and therefore the radius of $3.74R_\oplus$. This choice is somewhat arbitrary, but is consistent with the radius of the Neptune-mass planet GJ 436 (Gillon *et al.* 2007; Deming *et al.* 2007). The evolution depends strongly on Q_b, and in order for planet c to have been habitable and avoided the 3:1 resonance, then $Q_b \lesssim 5 \times 10^4$.

In fact, Q_b must be less than 4×10^4 in order to avoid the 3:1 resonance, as shown in Fig. 9. This figure plots the evolutions of b and c (without mutual interactions, and

$Q_c = 21.5, r_c = 1.8R_\oplus$), and the instantaneous 3:1 resonance of planet b. We see that in this case planet c just misses the 3:1 resonance.

To this point, we have not considered the secular interactions between the planets. Secular interactions cause the eccentricities and orientations of the orbits to oscillate with time (see *e.g.* Barnes & Greenberg [2006] for a review of secular theory). In Fig. 8 we show the secular interactions for the currently observed system, excluding planet d. This simulation was performed with HNBODY[3], and includes general relativistic effects. Our integration reveals that the current values of the eccentricities are near their extrema. We presume that using the observed values provides a reasonable estimate of the tidal evolution, however we may be overestimating the tidal effects on planet c, and underestimating the tidal effects on planet b. A more sophisticated treatment that combines the secular and tidal evolutions was beyond the scope of this investigation (see § 5).

Tidal theory predicts the eccentricities would be larger in the past. The amplitude of the eccentricity oscillations (due to gravitational interactions between planets) scales with e (among other quantities), and eccentricity oscillations would therefore have been larger in the past. Larger eccentricity values can often lead to dynamical instability (*e.g.* Barnes & Quinn 2004; Barnes & Greenberg 2007). Therefore we also require that the mutual, tidal evolutions of planets b and c predict dynamically stable orbits. Such a consideration shows that if Q_c is small enough to exclude a 3:1 resonance capture (*i.e.* $< 4 \times 10^4$), then the orbits of planets b and c would have been unstable 10 Gyr ago. This instability arises from the large e values the planets had then ($e_b = 0.74, e_c = 0.47$).

Even if we begin the backward integration with the two planet's average eccentricity (over the secular cycle), planet c was probably not habitable. Planet c's average eccentricity is lower than its observed value, and it has probably experienced less tidal evolution than predicted above. Therefore it is unlikely it could have ever been inside the 50% cloud cover EHZ. On the other hand, b's average eccentricity is larger than the current value, and its tidal evolution would have probably been more significant. In that case, tidal evolution is more likely to predict dynamical instability. We conclude that the requirements that planets b and c avoid the 3:1 resonance and be stable at all times cannot be satisfied if $Q_c = 21.5$ and $k = 0.3$.

However, if the two planets have properties similar to analogous bodies in the Solar System, then the system would have been stable, and never in a 3:1 resonance. In Fig. 10 we show the evolution of the 2 planets assuming the inner planet is Neptune-like ($Q_b = 10^6, R_b = 3.74R_\oplus$), and planet c is a typical terrestrial planet ($Q_c = 100, k = 0.3, R_c = 1.8R_\oplus$) (Yoder

[3]Publicly available at http://janus.astro.umd.edu/HNBody

1995). In this case, the 3:1 resonance crossing occurred nearly 10 Gyr ago, and the system 10 Gyr ago is stable (assuming low amplitude apsidal libration). This scenario invokes the simplest assumptions, and is therefore the preferable explanation. We conclude that Gl 581 c is probably a terrestrial planet with $Q \sim 100$, but was never inside the 50% cloud cover EHZ.

5. Conclusions

The detection of a terrestrial planet around a low-mass star is insufficient to determine that planet's past and future habitability. The tidal forces between planet and star can significantly change the orbits, and hence limit the habitable lifetime. Planets detected in the HZ with large eccentricities may be bound for hotter temperatures and ultimately a global extinction. On the other hand, planets detected interior to the HZ may have been habitable in the past. Gl 581 c was most likely not habitable in the past, but § 4.1 shows that if its companion planets were on different orbits, past habitability would have been possible.

For plausible physical and orbital properties of hypothetical terrestrial planets, tides may evolve the planets' orbits past the inner edge of the HZ over a timescale comparable to the age of the Earth. Therefore in order for planets to be habitable long enough for complex life to develop, they must form with eccentricities low enough that tides don't eventually make them inhospitable to life. Alternatively planets that form beyond l_{out} may evolve into the habitable zone, but the "flux" of planets out, through the inner edge of the EHZ, is larger than that of planets in, through the outer edge, because of the very steep dependence of da/dt on a. Therefore, on average and assuming uniform distribution in a, tides tend to reduce the total number of habitable planets around M stars in the galaxy.

Our work has shown that tides may shorten habitable lifetimes of planets that form with eccentricities larger than about 0.5. Although the formation mechanism of such planets is unknown, the existence of giant planets with such eccentricities suggests even terrestrial-sized planets may form with similar values. However, the majority of known exoplanets probably formed with eccentricities below 0.5 (see, *e.g.* Jackson, Greenberg & Barnes 2007), thus most habitable lifetimes will not be significantly shortened due to tides.

This work predicts that the vast majority of terrestrial planets in HZs around low-mass stars ($\lesssim 0.2 M_\odot$) will be detected on nearly circular orbits because the time to circularize the orbit is less than 1 Gyr, *c.f.* Fig. 3. Should space-based transit missions like COROT and Kepler find terrestrial planets on non-circular orbits around old (more than a few Gyr), low-mass stars ($< 0.35M_*$) in small orbits ($a \lesssim 0.1$ AU), then that system is likely to contain additional companions (Mardling & Lin 2004) which pump up eccentricities due to mutual interactions.

The increasing stellar flux on a planet due to orbital decay could impact its atmospheric conditions and composition. Previous models of habitable atmospheres have considered planets at a single semi-major axis value (*i.e.* Kasting *et al.* 1993; Kasting & Catling 2003; Segura *et al.* 2005; Tinetti, Rashby & Yung 2006; Kiang *et al.* 2007). The tidal change in the orbit of a habitable planet may affect the relative abundances of biosignatures, such as the simultaneous presence of oxygen and methane (Sagan *et al.* 1993). Future work on the evolution of a habitable atmosphere and the identification of biosignatures should consider the change in stellar flux due to tidal evolution.

When a planet is detected such that it was most likely in the HZ in the past, it would be interesting to determine if it did, in fact, support life in the past. In the foreseeable future, such a determination will have to be made through analysis of disk-averaged spectra of planets (Tinetti *et al.* 2006; Tinetti, Rashby & Yung 2006; Kaltenegger, Traub & Jucks 2007). Future work on the evolution of habitable atmospheres should explore the possibility of detecting signatures of extinct life on planets around M stars.

Future work should also address the determination of habitable lifetimes in multiple planet systems as well as incorporate higher order corrections to the tidal equations. Such improvements will require substantial advancement in our understanding of the deformations of solid and gaseous bodies due to tides. The Gl 581 systems demonstrates the need to develop a theory that describes two tidally damped orbits that also experience significant mutual interactions (note that Mardling [2007] has derived expressions for systems in which 1 planet experiences tidal evolution). However, the results of § 4.2 suggest that such improvements are unlikely to change our assessment for the Gl 581 system.

Planets with masses $\lesssim 0.3M_\oplus$ are likely too small to support plate tectonics, which are thought to be necessary for life (Williams, Kasting & Wade 1997; Raymond, Scalo & Meadows 2007). This work suggests some of these smaller planets may be heated internally by tides, such as in the Galilean satellites (Peale, Cassen & Reynolds 1979). In some cases, in which τ_{HL} is long enough for life to develop, the tidal working of the body may supply enough heat to drive plate tectonics after radiogenic heating has become negligible. Therefore these low-mass planets, previously thought to be uninhabitable, may, in fact, be good locations for life. Future work should explore this possibility.

Perhaps the most distressing aspect of this work (from a SETI perspective) is the prediction that planets can be habitable long enough for complex life to develop, but then that life is extinguished by tides. Yet this work suggests that such a "tidal extinction" may occur on some planets around low-mass stars.

The results presented here may have significant implications in the context of the Gaia hypothesis (Lovelock & Margulis 1974), which proposes that biology can change the physical conditions on a planet, such as its atmosphere, so as to promote the continuing existence of life. In other words, evolution favors organisms that help maintain a habitable environment. According to that hypothesis, an inhabited planet may avert a tidal extinction due to its organisms developing adaptations that not only change themselves, but also change the atmosphere such that the sterilizing effects of increased stellar radiation are mitigated. Therefore the Gaia hypothesis predicts that we may observe biosignatures on planets that are on orbits interior to the nominal HZ, if they were formerly in the HZ. In that case we might need to refine the definition of the HZ into two branches: the "physical" HZ (*i.e.* the definition proposed by Kasting, Whitmire & Reynolds [1993] that applies to planets before life gains a foothold), and the "biologically-extended" HZ (*i.e.* a larger region in which evolved life can stave off sterilization). For example, planet Gl 581 c was probably never in the physical HZ, but if it once had been, then it might have remained habitable even after reaching its current orbit, according to the Gaia hypothesis. The detection of other similar new planets may provide observational tests of the Gaia hypothesis. The detection of such a planet would be a landmark event, not only in the detection of life beyond the Solar System, but because it will reveal fundamental features of life, evolution, and planetary habitability.

We conclude that tides can move habitable planets into non-habitable orbits and described how this phenomenon is relevant for astrobiological models. Future work into the search for habitable worlds, through planet-hunting, atmospheric modeling, geophysical modeling, etc., should bear in mind the effects of tidal evolution of planets around M stars.

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Table 1: Best-Fit Orbital Elements of the Gl 581 Planetary System

Planet	m ($M_\oplus$)	P (d)	a (AU)	e	ϖ (^{o})	T_{peri} (JD)
b	15.7	5.363	0.041	0.02	273	2452998.76
c	5.03	12.932	0.073	0.16	267	2452993.38
d	7.7	83.6	0.25	0.2	295	2452936.9

Figure 1 – Semi-major axes that are habitable as a function of stellar mass and eccentricity from Eqs. (8 – 11). The shading represents different choices of cloud cover for the limits of the HZ. Darkest gray assumes no cloud cover, medium gray assumes 50% cloud cover, light gray assumes total cloud cover, and white is uninhabitable.

Figure 2 – Contours of τ_{HL} of terrestrial planets, that begin at the inner edge of the 0% cloud cover EHZ, as a function of stellar mass and initial eccentricity e_0. The terrestrial planets have a mass of 5 $M_\oplus$ (top left), 1 $M_\oplus$ (top right), 0.5 $M_\oplus$ (bottom left), and 0.1 $M_\oplus$ (bottom right), and a radius determined by Eq. (5). Planets with initial eccentricities below 0.53, or orbiting stars with a mass greater then 0.35 $M_\odot$ are habitable for at least 10 Gyr. Lower mass planets tend to have longer habitable lifetimes.

Figure 3 – Evolution of the semi-major axes (solid line) for two hypothetical planets relative to EHZ boundaries (shown by the shading, *c.f.* Fig. 1). These planets are in orbit about a 0.15 $M_\odot$ star. *Top:* Evolution of a planet with $e_0 = 0.52$. This planet's semi-major axis decreases until its eccentricity reaches zero after 750 million years, at which point the tidal evolution effectively stops. The tidal evolution stopped just before the planet crossed the inner edge of the EHZ, and the planet will be habitable indefinitely. *Bottom:* Evolution of a planet with $e_0 = 0.54$. Although very similar to the other planet's evolution, this planet's larger initial eccentricity results in more torque so that when e reaches zero, the planet is just interior to the 50% cloud cover HZ. The habitable lifetime for this planet is 7.5×10^8 years.

Figure 4 – *Top:* Orbit-averaged stellar flux received by a tidally evolving planet relative to that of the Earth $F_\oplus$ (solid line), see Eq. (7), as well as at periastron and apoastron (dotted lines). The planet orbits a 0.2 $\mathrm{M}_\oplus$ star with initial orbital elements of $a_0 = 0.0877$, and $e_0 = 0.84$. The tidal lifetime of the planet, 4.5 Gyr in this case, corresponds to the age of the Earth, and is shown by the dashed line. Note, however, the extreme difference between flux at periastron and apoastron (a factor of 200). *Bottom:* Ratio of the rotation frequency of the tidally evolving planet to its instantaneous mean motion, *c.f.* Eq. (3). Initially the planet rotates nearly 10 times faster than it revolves, but after $\sim$ 6 Gyr, the orbit has circularized and $\Omega = n$.

Figure 5 – Time since Gl 581 c would have been habitable as a function of its current eccentricity. We set $R_c = 1.8R_\oplus$, and consider Q values of 100 and 21.5. The $Q = 21.5$ case permits habitability as recently as 3 Gyr ago.

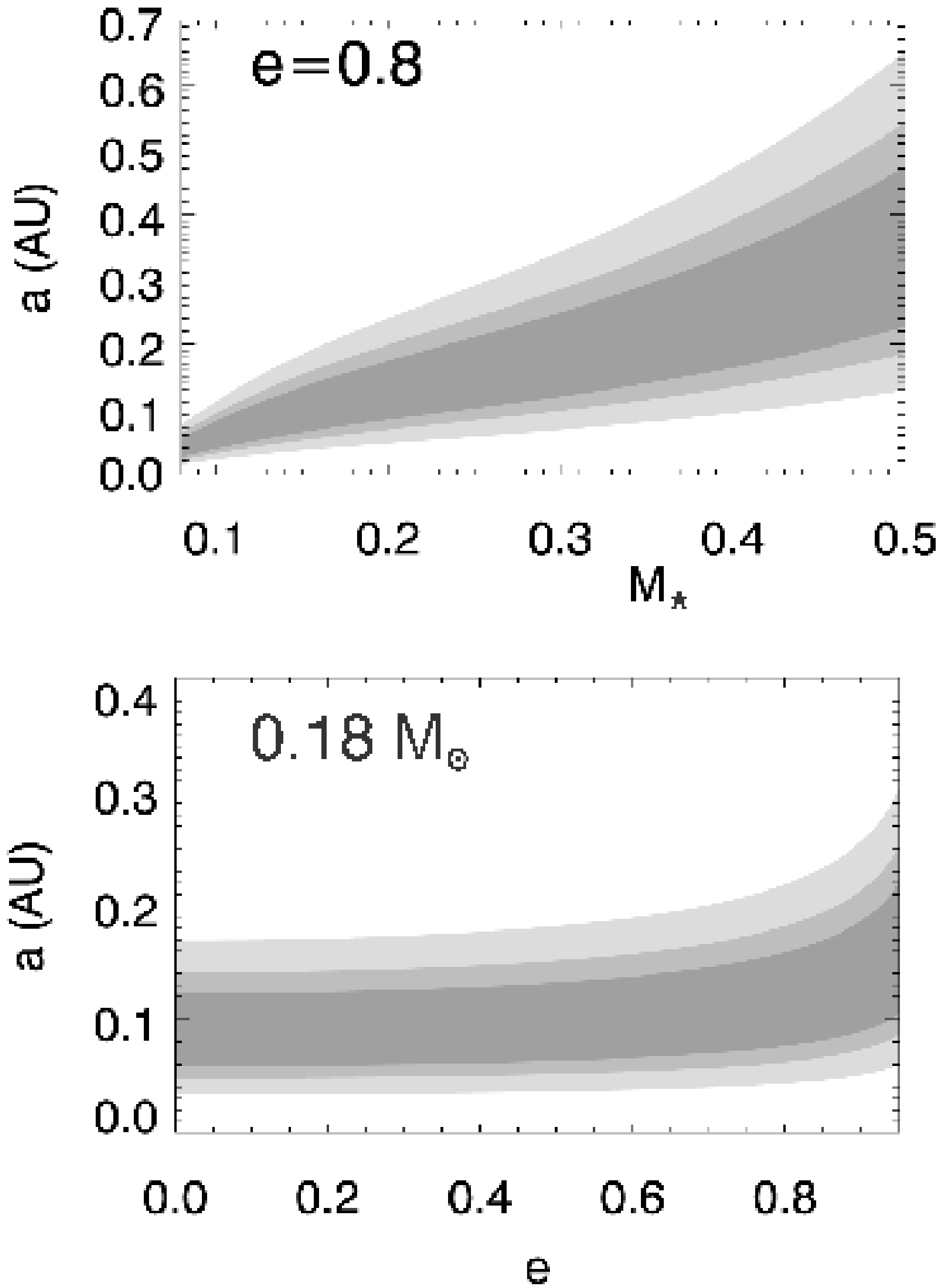
Figure 6 – Evolution of Gl 581 c for three different possible radius values. The shading represents different definitions of the HZ, *c.f.* Fig. 1.

Figure 7 – Evolution of a_b and e_b for various choices of Q_b, assuming $k = 3/2$. The evolution is negligible unless $Q_b \lesssim 10^5$.

Figure 8 – Apsidal evolution of the Gl 581 b and c planets, see Table 1. *Top:* The apsidal oscillation is circulation. *Bottom:* Evolution of e_b (solid line) and e_c (dashed line). The orbits are currently near the extrema of their eccentricity values.

Figure 9 – Evolution of planets b (dashed line), c (solid line) and the instantaneous location of b's outer 3:1 mean motion resonance (dotted line) for $Q_b = 4 \times 10^4, k = 3/2$. In this case planet c would have just avoided the 3:1 resonance. The shading corresponds to different definitions of the HZ, *c.f.* Fig. 1. 10 Gyr ago the configuration was unstable.

Figure 10 – Evolution of planets b (short-dashed line), c (solid line) and the instantaneous location of b's outer 3:1 mean motion resonance (dotted line) for $Q_b = 10^6, R_b = 3.74R_\oplus, k = 3/2$ and $Q_c = 100, R_c = 1.8R_\oplus, k = 0.3$. In our model, this evolution is the most believable, and prevents planet c from crossing the 3:1 mean motion resonance and reaching the 50% cloud cover habitable zone (medium grey). This evolution permits stable interactions 10 Gyr ago.



e=0.8
a (AU)
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.1
0.2
0.3
0.4
0.5
M_*
0.18 $M_\odot$
a (AU)
0.0
0.1
0.2
0.3
0.4
0.0
0.2
0.4
0.6
0.8
e

Fig. 1.—

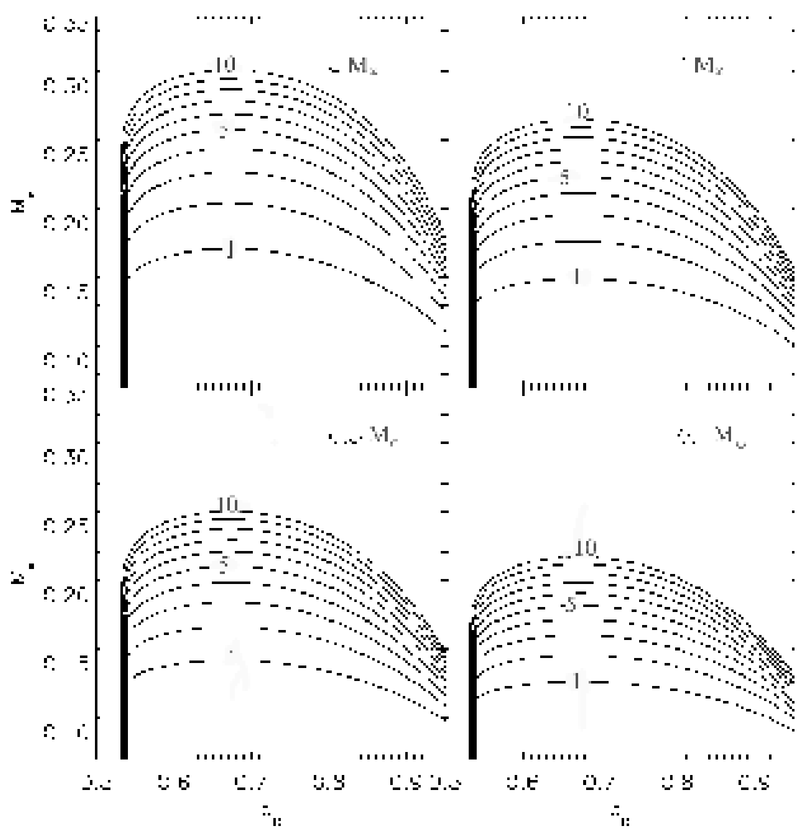


Fig. 2.—

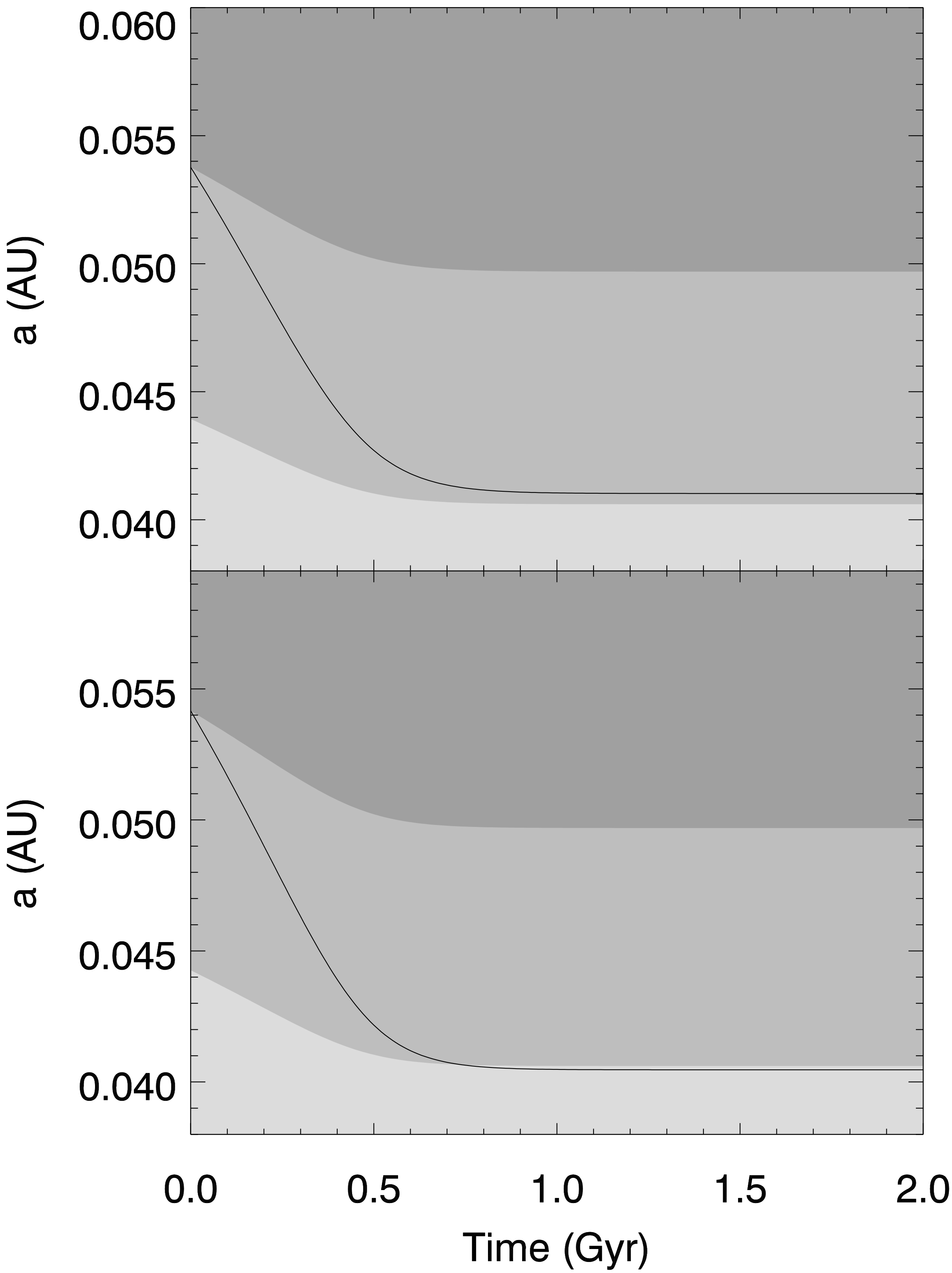

0.060
0.055
0.050
0.045
0.040
a (AU)
0.055
0.050
0.045
0.040
a (AU)
0.0
0.5
1.0
1.5
2.0
Time (Gyr)

Fig. 3.—

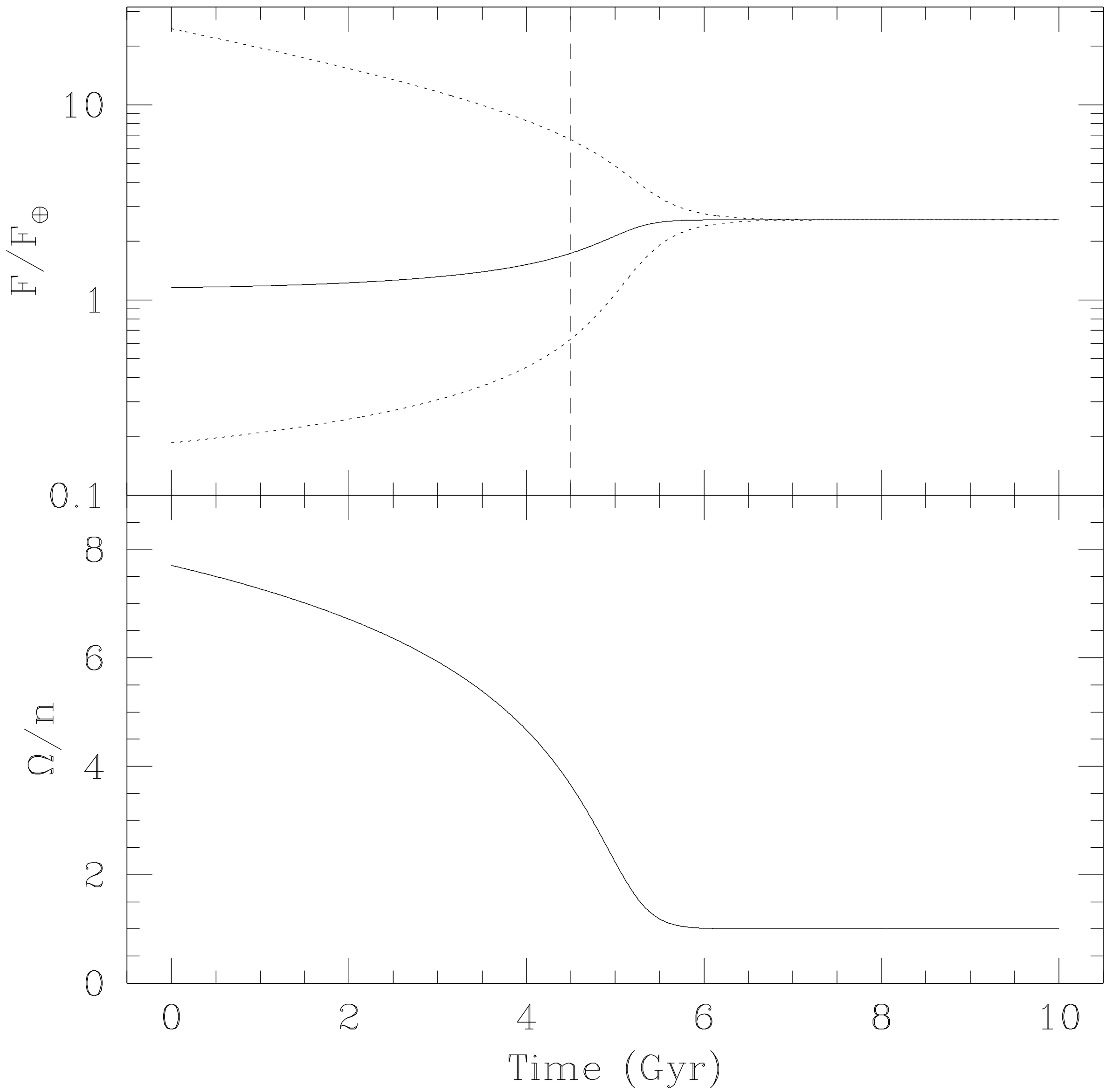


Fig. 4.—

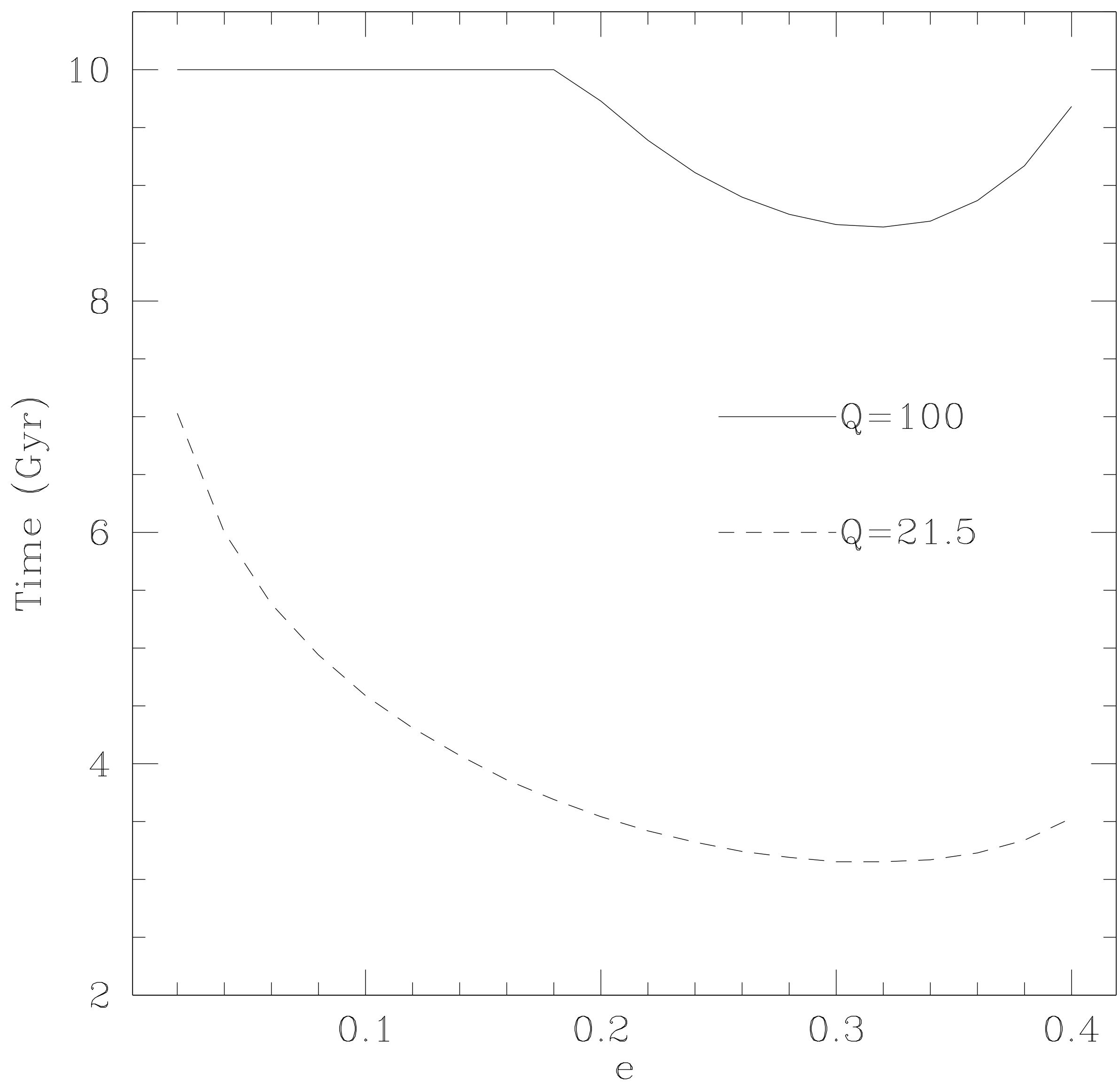


Fig. 5.—

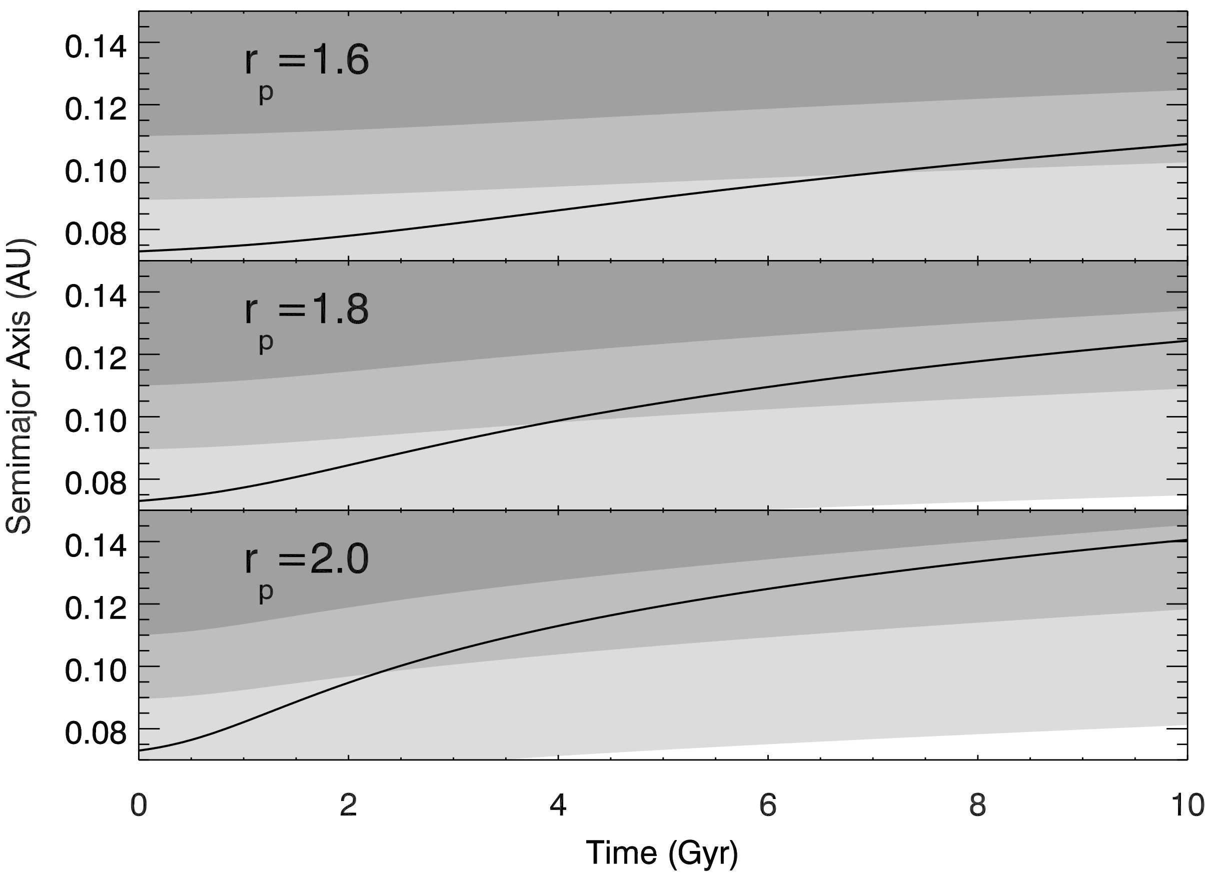

r
p
=1.6
r
p
=1.8
r
p
=2.0
Semimajor Axis (AU)
0.14
0.12
0.10
0.08
0
2
4
6
8
10
Time (Gyr)

Fig. 6.—

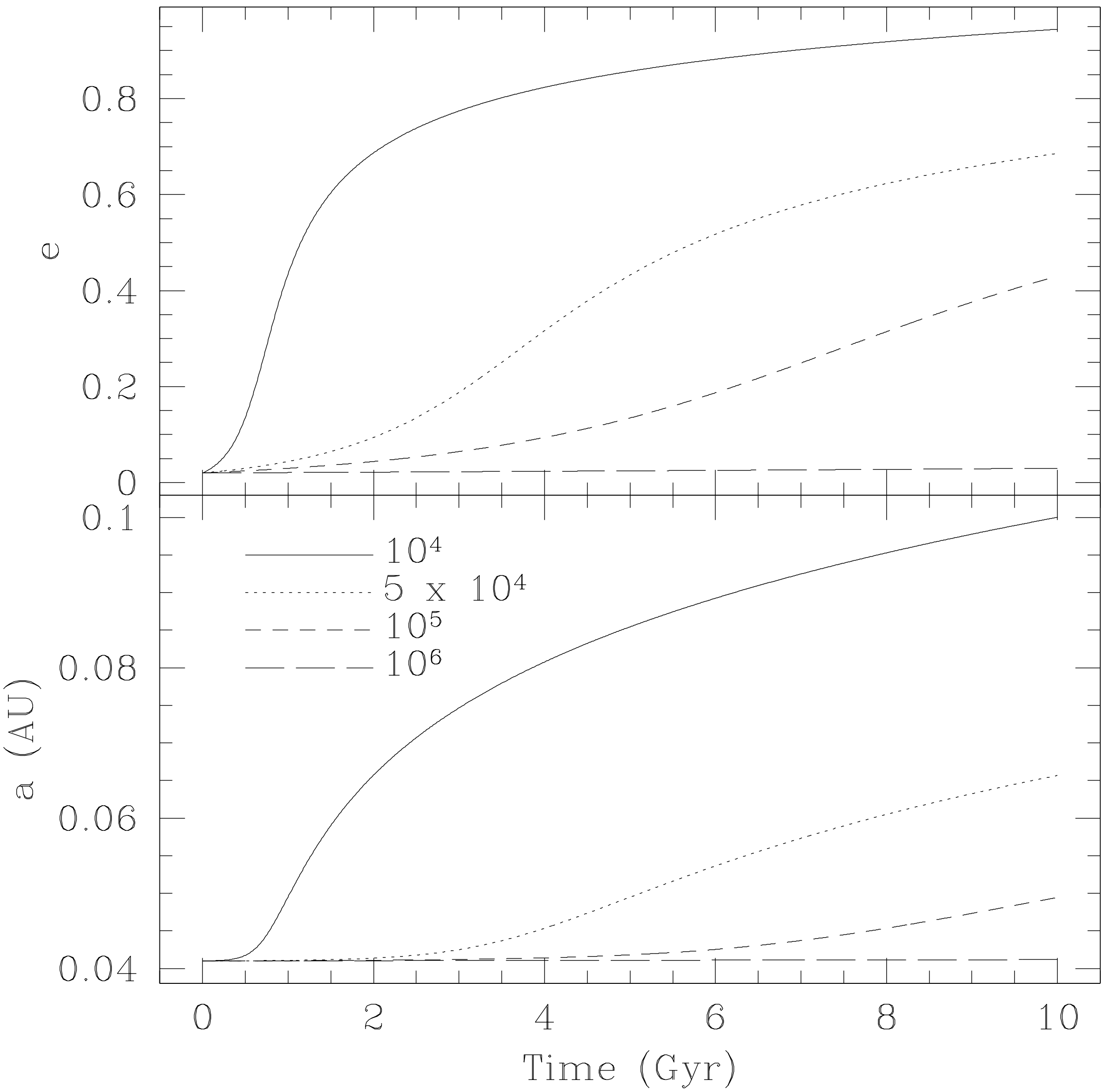

0.8
0.6
e
0.4
0.2
0
0.1
10^4
5 x 10^4
10^5
10^6
0.08
a (AU)
0.06
0.04
0
2
4
6
8
10
Time (Gyr)

Fig. 7.—

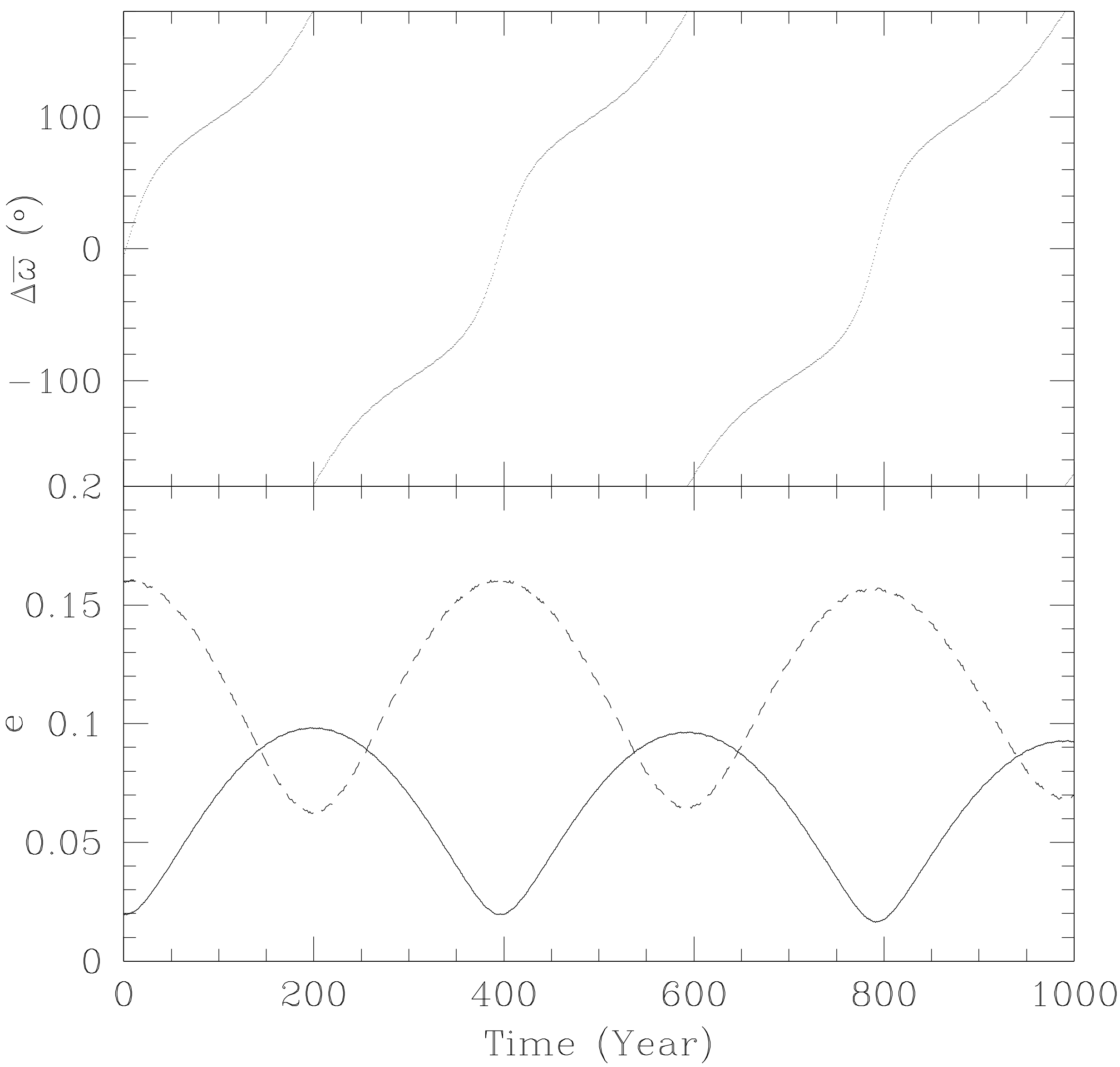

100
0
−100
0.2
0.15
0.1
0.05
0
0
200
400
600
800
1000
Time (Year)
$\Delta\bar{\omega}$ (°)
e

Fig. 8.—

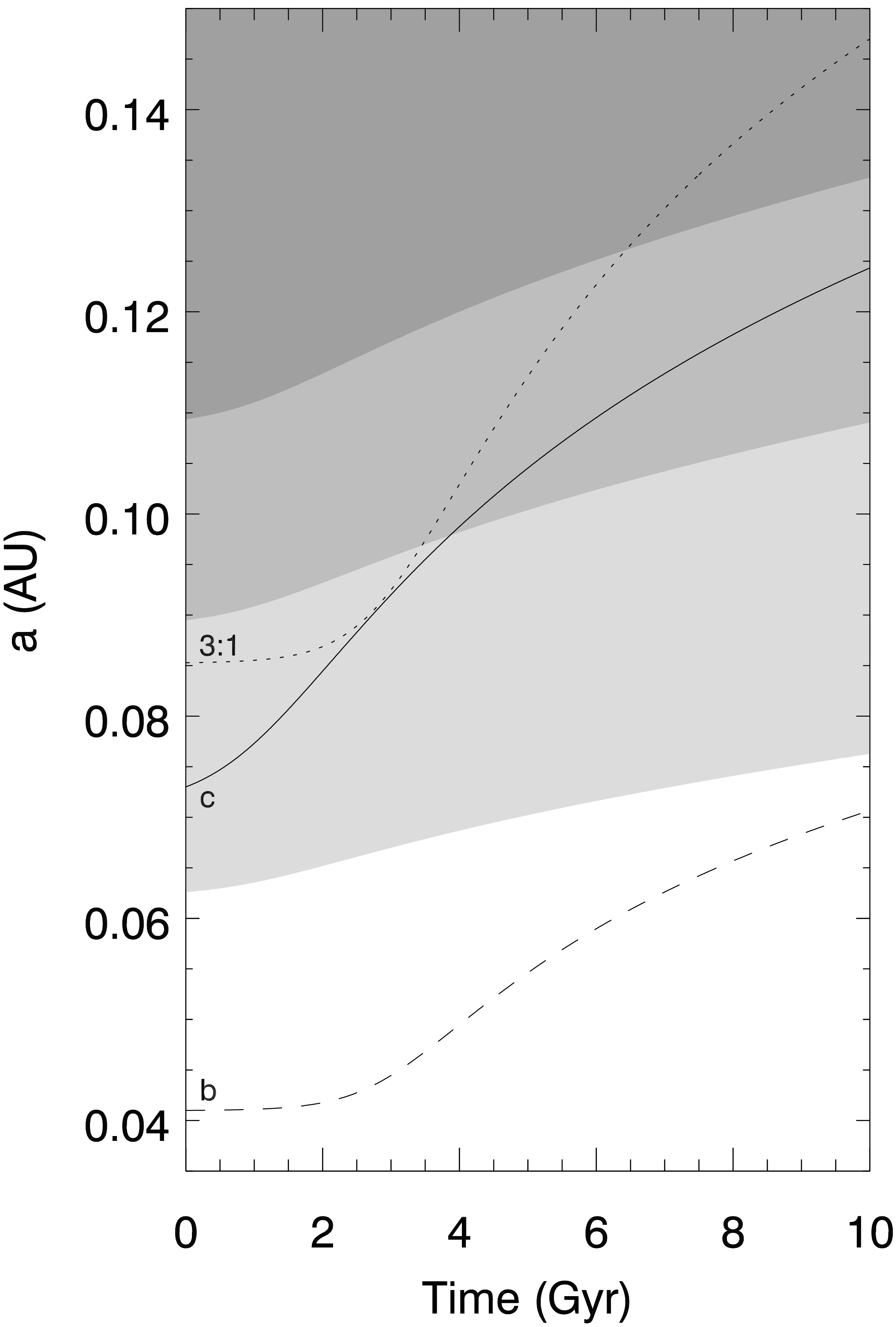


Fig. 9.—

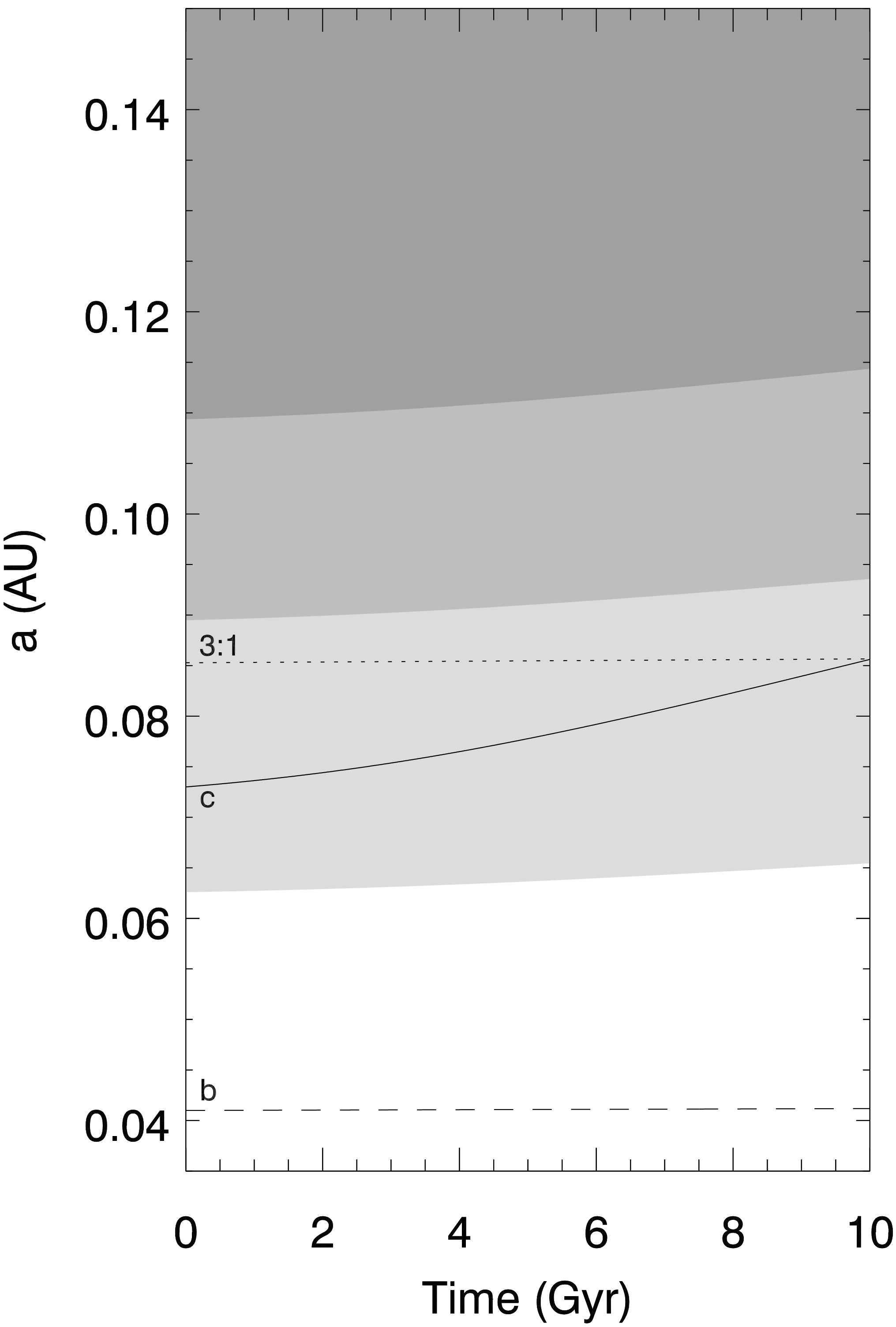


Fig. 10.—