ON THE SURVIVAL OF SHORT-PERIOD TERRESTRIAL PLANETS

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ABSTRACT

The currently feasible method of detecting Earth-mass planets is transit photometry, with detection probability decreasing with a planet’s distance from the star. The existence or otherwise of short-period terrestrial planets will tell us much about the planet-formation process, and such planets are likely to be detected first, if they exist. Tidal forces are intense for short-period planets and result in decay of the orbit on a timescale that depends on properties of the star as long as the orbit is circular. However, if an eccentric companion planet exists, orbital eccentricity ($e_i$, where $i$ is the inner orbit) is induced, and the decay timescale depends on properties of the short-period planet, reduced by a factor of the order of $10^2 e_i^2$ if it is terrestrial. Here we examine the influence of companion planets on the tidal and dynamical evolution of short-period planets with terrestrial structure, and we show that the relativistic potential of the star is fundamental to their survival.

Subject headings: celestial mechanics — planetary systems — relativity — stars: late-type — stars: low-mass, brown dwarfs

Online material: color figure

1. INTRODUCTION

In the past few years, the radial velocity method has been used to detect more than 100 extrasolar planets (Marcy et al. 2000) with minimum masses in the range 0.11–17 $M_J$. With the current lower detection limit of 3 m s$^{-1}$, discovering Earth-mass planets with periods longer than a few days in this way is untenable. In principle, Earth-mass planets with periods less than 3 days may be marginally detectable with 1 m s$^{-1}$ velocity precision (R. Narayan et al. 2004, in preparation), but a large number of observations is needed to reduce the noise associated with the stellar radial velocity “jitter” (Saar et al. 1998).

Hopes for detecting Earth-mass planets in the near future lie with transit photometry and microlensing. So far, four gas giants have been observed crossing the faces of their stars (Charbonneau et al. 2000; Henry et al. 2000; Udalski et al. 2002; Konacki et al. 2003), while one planet has been discovered using microlensing techniques (Bond et al. 2004). While the transit of a gas giant results in a maximum reduction of the star’s brightness of around 1%–2%, an Earth-mass planet would dim the star’s light by only a few parts in 10,000. Nonetheless, such high-precision photometry is currently feasible in the Microvariability and Oscillations of Stars (MOST) satellite and will be employed in the Kepler (Koch et al. 2001) mission. Simple geometrical arguments give the probability of seeing a planet cross the face of its parent star along our line of sight as $R_p/2a$, where $R_p$ is the radius of the star and $a$ is the distance of the planet from the star during the transit. Thus, it is likely that short-period Earth-like planets, if they exist, will be discovered first, especially since a weak signal can be strengthened by the integration of many orbits. This is true not only for planets discovered directly with transit photometry but also for those discovered using microlensing techniques, since follow-up transit photometry is necessary for their confirmation and study.

In § 2 we review the process of tidal damping, in § 3 we discuss the dynamical effect of the presence of a companion, and in § 4 we present a discussion.

2. ORBIT EVOLUTION DUE TO TIDAL DAMPING

During the formation epoch, tidal interactions between Jupiter-mass protoplanets and their nascent disks can cause them to spiral in toward their host stars (Goldreich & Tremaine 1980; Lin & Papaloizou 1986), a migration scenario (Lin et al. 1996) adopted to account for the origin of extrasolar planets with periods of a few days (Mayor & Queloz 1995). Other scenarios have been suggested (Rasio & Ford 1996; Nagasawa et al. 2003; Murray et al. 1998), all of which involve significant excitation of orbital eccentricity. Once a planet is in the vicinity of the star, however, tidal forces will tend to circularize the orbit as well as synchronize the planetary spin (Rasio et al. 1996). Earth-mass terrestrial planets may also be brought close to their host stars via one or more of these processes, and their discovery (or otherwise) will shed much light on the planet-formation process. For example, along their migration paths, gas giants induce residual terrestrial planets to undergo orbital evolution through their resonant and secular interaction. The detection of both short-period gas giants and terrestrial planets around any host stars would provide overwhelming support for the core-accretion scenario.

Short-period planets are also capable of raising a substantial tide on their host stars. In order to avoid noise introduced by stellar jitter, the present planet-search campaigns focus on target stars with quiet chromospheres and slow spin rates. With one exception (Butler et al. 1997), all stars observed hosting short-period (‘‘hot’’) Jupiters have spin periods considerably longer than the orbital period of the planet. Mature solar-type stars tend to be subsynchronous because stellar
winds carry away spin angular momentum through magnetic braking (Soderblom et al. 1993). Within these slowly spinning stars, the induced tidal oscillations act to dissipate their acquired tidal energy, the tidal response tends to lag the lines of center of the star and planet, and the resulting torque tends to spin up the star at the expense of orbital energy and angular momentum.

The simplest quantitative description of tides is the equilibrium tide model (Goldreich & Soter 1966; Hut 1981; Eggleton et al. 1998), which is adequate for analyzing the tidal response of terrestrial planets. In gaseous planets and stars, tidal perturbations can excite resonant responses that strongly enhance the dissipation rate (Zahn 1966). In radiative stars, the response is mostly in the form of g-mode oscillations, whereas in fully convective envelopes of rapidly spinning gaseous planets and stars, it is in the form of inertial waves (Ogilvie & Lin 2004).

Since we are primarily interested in the fate of terrestrial planets in this paper, here we adopt the equilibrium tide model.

To leading order in the orbital eccentricity, the timescale, $\tau_\alpha$, for orbital decay is given by (Mardling & Lin 2002)

$$\frac{1}{\tau_\alpha} = \left( \frac{\dot{a}_i}{a_i} \right)_\text{star} + \left( \frac{\dot{a}_i}{a_i} \right)_\text{planet}, \quad (1)$$

where

$$\left( \frac{\dot{a}_i}{a_i} \right)_\text{star} = -\frac{9}{2} \left( \frac{n_i}{Q'_i} \right) \left( \frac{M_i}{M_*} \right) \left( \frac{a_i}{a} \right)^5 \left[ 1 - \left( \frac{P_{\text{orb}}}{P_{\text{spin}}} \right) \right] \quad (2)$$

and

$$\left( \frac{\dot{a}_i}{a_i} \right)_\text{planet} = -\frac{171}{4} \left( \frac{n_i}{Q'_i} \right) \left( \frac{M_i}{M_*} \right) \left( \frac{R_*}{a_i} \right)^5 e_i^2 \quad (3)$$

are the contributions to orbital decay (or expansion) from tidal dissipation within the star and planet, respectively, and the assumption has been made that the planet spins synchronously with the orbital motion. Here $P_{\text{orb}}$ and $P_{\text{spin}}$ are the orbital and stellar spin periods, respectively; $a_i$ is the semimajor axis of the orbit; $n_i$ is the mean motion (orbital frequency); $M_i$, $R_i$, and $Q'_i$ are the mass, radius, and modified $Q$-value of the planet, respectively, the latter containing information about damping efficiency and rigidity (Goldreich & Soter 1966; see Table 1); and $M_*$, $R_*$, and $Q'_*$ are the corresponding values for the star. If the orbit is perfectly circular, the planet makes no contribution to orbital shrinkage, and the orbital decay timescale depends entirely on properties of the star. Otherwise the planet dominates the tidal decay process, particularly if it is Earth-like. In the case of slow stellar rotation and small eccentricity, the ratio of contributions to orbital decay from the planet and the star using $Q'$-values from Table 1 is $12.5e_i^2$ for a Sun-Jupiter pair, $1.3\times10^5 e_i^2$ for a Sun-Earth pair, and $2.2\times10^5 e_i^2$ for an M dwarf-Earth pair. The discrepancy between the Jupiter system and the Earth systems is mostly due to the factor $10^4$ difference in $Q'$-values of gas giants and terrestrials. Thus, even a small orbital eccentricity allows a planet, if it has terrestrial structure, to dominate the tidal decay process and can reduce the decay timescale considerably.

The timescale, $\tau_\alpha$, for eccentricity damping (or excitation) is given by an expression similar to equation (1) (Goldreich & Soter 1966; Mardling & Lin 2002), except that it does not depend on $e_i$ to leading order in $e_i$. Nonetheless, unless the star spins rapidly, the planet dominates the tidal circularization process (Dobbs-Dixon et al. 2004). Table 2 lists orbital decay and eccentricity damping timescales and other system parameters, including transit probabilities for various real and hypothetical single-planet systems. Included are three of the shortest period planets discovered to date, as well as HD 209458. The values of $a_i$ for the three hypothetical systems (Sun-Jupiter, Sun-Earth, and M dwarf-Earth) were chosen to indicate how close to the host star we can expect to find planets in these types of systems. Note especially the steep dependence of $\tau_\alpha$ on the eccentricity when the planet is Earth-like.

### 3. Eccentricity Excitation Due to a Companion

HD 209458 is included in Table 2 as one of only four transit systems discovered so far (Brown et al. 2001). Its data allow an estimate of the planet radius of $1.35 R_J$, which we use here to estimate timescales. The planet’s relatively large size can be accounted for by inflation due to tidal dissipation of energy (Bodenheimer et al. 2001) if $e_i \sim 0.03$ and $Q'_i = 10^4$, with the corresponding orbital decay timescale being comparable to the age of the universe. The observationally estimated eccentricity is small ($<0.05$) but not zero (D. Fischer 2000, private communication), even though $\tau_\alpha$ is smaller than the estimated age of HD 209458 (see Table 2). In order to resolve this paradox, the existence of a second planet has been conjectured (Bodenheimer et al. 2001) that secularly excites the eccentricity (Murray & Dermott 1999).

This eccentricity-excitation mechanism puts severe constraints on the existence of systems containing short-period terrestrial planets with companion planets. Figure 1a shows the evolution of the eccentricity of an Earth-mass planet in a 2.3 day orbit ($a_i = 0.02$ AU) around an M dwarf of mass $0.2 M_\odot$ that spins with a period of 40 days. It has a Jupiter-mass companion at a distance of 0.7 AU that has an eccentricity of 0.2. The initial eccentricity of the inner planet is zero. However, it is excited by the presence of the companion to a maximum value that depends on the strength of additional perturbing accelerations, including the spin and tidal bulges of the star and planet, as well as the relativistic potential of the star (Mardling & Lin 2002).

In the absence of any of these accelerations, the inner eccentricity is excited to a value of 0.015 (Fig. 1a, upper solid curve). Taking half this value to represent the equilibrium inner
et al. 1997). The fractional contribution that the relativistic inhibition of the growth of the inner eccentricity (Holman & Murray 1999; Novak et al. 2003) is only 0.0035, corresponding to an orbital decay of 2 × 10^6 yr. For all stars we took Q = 10^6; for the known systems and the hypothetical Jupiter systems Q = 10^8, while for the hypothetical Earth systems Q = 21.5. The symbol \( \infty \) corresponds to \( \tau_0 > 10^{11} \) yr.

* The last row of entries corresponds to the approximate habitable zone for such a star.

The eccentricity (see following paragraphs), the orbital decay timescale would be 7.1 Gyr. However, if all the perturbing accelerations listed above are included, the maximum inner eccentricity is only 0.0035, corresponding to an orbital decay timescale of 84.3 Gyr. This suggests that relativity plays a major role in the survival of short-period terrestrial planets with companions (assuming that nature produces such systems in the first place). In fact, it is the contribution it makes to the apsidal advance of the inner orbit that is responsible for the inhibition of the growth of the inner eccentricity (Holman et al. 1997). The fractional contribution that the relativistic potential makes to the apsidal advance, compared to that made by a companion planet, is given by \( \gamma/(1 + \gamma) \), where \( \gamma = 4Z^2(M_i/M_o)a_o/a_i \), and this is illustrated in Figure 1a, the relativistic potential is responsible for 95% of the apsidal advance of the inner orbit, while in the case of Mercury’s orbit around the Sun, it contributes only 7%.

Even more extreme is the case in which a short-period terrestrial planet has an Earth-mass companion. For example, for a Sun-Earth-Earth system with semimajor axes 0.03 and 0.5 AU, the relativistic potential is responsible for 99.9% of the apsidal advance of the inner orbit. If the eccentricity of the outer planet is 0.3, the orbital decay timescale is 702 Gyr, while in the absence of relativity it would be only 0.47 Gyr.

Using equations that govern the secular evolution of the orbital elements for a dissipationless point-mass coplanar system (Mardling & Lin 2002; Murray & Dermott 1999; Wu & Goldreich 2002), and assuming small values for the eccentricities and \( a_i/a_o \), one can obtain an estimate of the variation of the inner eccentricity, \( \delta e_i \), that also holds when the minimum eccentricity is zero, at which point \( e_i \) is discontinuous (as in Fig. 1a). This estimate will vary slightly for moderately non-coplanar systems and does not apply to resonant systems (Murray & Dermott 1999; Novak et al. 2003). If tidal dissipation is taken into account, the system behaves like a damped autonomous system with the familiar circulatory and libratory behavior (Fig. 1b). For a given set of initial conditions, the system evolves to a fixed point corresponding to \( \Delta e = \Delta e_o = 2n \pi \), where \( n \) is some integer and \( \Delta e \) and \( \Delta e_o \) are the longitudes of periastron of the inner and outer orbits, respectively, and a finite equilibrium inner eccentricity, \( e_i^{(eq)} \), approximately given by

\[
\frac{e_i^{(eq)}}{e_i} \approx \frac{(5/8)(a_i/a_o)e_o}{1 - (M_i/M_o)\sqrt{a_i/a_o + \gamma}} = \delta e_i/2. \tag{4}
\]

Note that, along with the relativistic potential, \( \gamma \) may include contributions from other perturbing accelerations, such as tidal and spin bulges. Figure 1c shows the dependence of \( e_i^{(eq)} \) on \( M_i/M_o \) in the absence of relativistic and other perturbing accelerations (\( \gamma = 0 \)). The solid curves were obtained by integrating the Newtonian equations of motion for point masses (averaged over the inner orbit), while the dashed curves are given by equation (4). Agreement is good except near the point corresponding to \( M_i/M_o = (a_i/a_o)^{1/2} \). The inclusion of relativistic effects introduces an additional scale that is proportional to \( m_i/a_i \), and this is illustrated in Figure 1d for the case \( a_i/a_o = 10 \). In only one case is the discrepancy between the full solution and that given by equation (4) evident.

Figure 2 shows gray-scale plots of the orbital decay timescale of an Earth-mass planet orbiting a solar-mass star at 0.03 AU as a function of the eccentricity, \( e_o \), and semimajor axis, \( a_o \), of a Jupiter-mass perturber. The equilibrium eccentricity is calculated using the full governing equations (Mardling & Lin 2002), and this is then used in equation (1) to obtain the decay timescale. The top panel includes no perturbing accelerations, while the bottom panel includes the relativistic potential of the star. It is clear that relativity allows many systems to survive

### Table 2: Orbital Decay Timescales

| System                  | \( M_i/M_J \) | \( M_o/M_J \) | \( P_{\text{spin}} \) (AU) | \( P_{\text{orb}} \) | \( \tau_e \) (0.01) | \( \tau_0 \) (0.01) | \( \tau_a \) (0.01) |
|-------------------------|---------------|---------------|--------------------------|----------------|----------------|----------------|----------------|
| Sun-Jupiter             | 1.00          | 1.00          | 28                       | 0.02           | 1.04 days   | 0.12           | 0.16           | 0.06          |
|                         |               |               |                          | 0.03           | 1.91 days   | 0.08           | 2.34           | 2.30          | 0.88          |
|                         |               |               |                          | 0.04           | 2.93 days   | 0.03           | 15.8           | 15.6          | 5.83          |
| Sun-Earth               | 1.00          | 0.003         | 28                       | 0.01           | 8.8 hr      | 0.23           | 0.53           | 0.009         | 8.1–5         |
|                         |               |               |                          | 0.015          | 16.2 hr     | 0.15           | 7.41           | 0.12          | 0.001         |
|                         |               |               |                          | 0.02           | 25.0 hr     | 0.12           | 48.7           | 0.78          | 0.007         |
|                         |               |               |                          | 0.03           | 1.9 days    | 0.08           | \( \infty \)  | 10.9          | 0.10          |
|                         |               |               |                          | 0.05           | 4.1 days    | 0.05           | 2.82           | 0.28          | 0.10          |
| M dwarf-Earth\(^\text{a}\) | 0.2           | 0.003         | 40                       | 0.007          | 10.3 hr     | 0.10           | 0.97           | 0.01          | 8.9–5         |
|                         |               |               |                          | 0.01           | 17.6 hr     | 0.07           | 9.88           | 0.097         | 9.0–4         |
|                         |               |               |                          | 0.012          | 23.1 hr     | 0.06           | 34.4           | 0.32          | 0.003         |
|                         |               |               |                          | 0.02           | 2.32 days   | 0.03           | \( \infty \)  | 8.82          | 0.082         |
|                         |               |               |                          | 0.04           | 6.56 days   | 0.01           | \( \infty \)  | \( \infty \)  | 7.39          |
| OGLE-TR-56              | 1.04          | 0.9           | . . .                     | 0.023          | 1.212 days  | 0.11           | 0.40           | 0.37          | 0.05          |
| HD 83443                | 0.79          | 0.41          | 36.5                     | 0.038          | 2.986 days  | 0.05           | 2.13           | 0.32          | . . .          |
| HD 46375                | 1.00          | 0.25          | . . .                     | 0.041          | 3.024 days  | 0.06           | 5.1            | 0.02          | 0.40          |
| HD 209458              | 1.05          | 0.66          | . . .                     | 0.05           | 3.525 days  | 0.05           | 59.8           | 51.9          | 3.43          |
that would otherwise have suffered tidal destruction during the current lifetime of the star.

4. DISCUSSION

Of particular interest among short-period terrestrial systems will be those with low-mass stars for which the habitable zone (planet surface temperature in the range 0–100°C) is at a distance where the transit probability is not negligible. Table 2 lists several hypothetical systems composed of a 0.2 $M_\odot$ M dwarf and an Earth-mass planet for which the habitable zone is around 0.04 AU. Planets in such close proximity to their host stars will be tidally locked so that one side of the planet is never directly heated. However, systems for which the habitable zone is further out may have planets locked in other spin-orbit

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**Fig. 1.**—Eccentricity excitation by a companion planet. (a) Eccentricity evolution in the absence of tidal damping; $M_1 = 0.2 M_\odot$, $M_2 = 1 M_\odot$, $M_\odot = 1 M_\odot$, $a_1 = 0.02$ AU, $a_2 = 0.7$ AU, $e_2 = 0.2$, and periastra initially aligned. Top solid curves: no perturbing accelerations; bottom solid curves: relativistic potential only; top dashed curves: spin and tidal bulge only; bottom dashed curves: both relativity and spin and tidal bulges. (b) Eccentricity evolution with tidal damping; circulatory and libratory behavior in the $e_i - (\omega_i - \omega_o)$ plane. System parameters are the same as in (a) for the case with no perturbing accelerations, but with initial $e_i = 0.01$, periastra antialigned, and an unrealistic $Q_i = 0.2$ used to illustrate the behavior. In general, a two-planet system will evolve to a constant $e_i$ with periastra aligned as long as $e_i$ is shorter than the lifetime of the system. (c) Dependence of $e_i^{(0)}$ on $M_1/M_2$ with $\gamma = 0$. Solid curves: Newtonian point-mass equations; dotted curves: eq. (4). Top set of curves: $a_2/a_1 = 10$; bottom set of curves: $a_2/a_1 = 20$. (d) Dependence of $e_i^{(0)}$ on $M_1/M_2$ with relativistic effects included; $a_2/a_1 = 10$. Solid curves, bottom to top: $(a_1/\text{AU}, m_2/M_\odot) = (0.05, 0.0033), (0.5, 0.0033), (0.05, 1)$, and $(0.5, 1)$; dashed curve: eq. (4).

**Fig. 2.**—Orbital decay timescales with and without relativity as functions of the outer eccentricity, $e_o$, and semimajor axis, $a_o$: $M_1 = 1 M_\odot$, $M_2 = 1 M_\odot$, $M_\odot = 1 M_\odot$, $a_1 = 0.03$ AU. Top panel: without relativity; bottom panel: with relativity. [See the electronic edition of the Journal for a color version of this figure.]
resonances. Mercury is locked in a 3:2 spin-orbit resonance that relies on its permanent slight departure from sphericity as well as its substantially noncircular orbit (Goldreich & Peale 1966). Such planets would be heated more evenly and hence would perhaps be better candidates for detecting the signatures of life in their atmospheres.

While the $Q$-values of putative short-period terrestrial-type planets may turn out to be somewhat higher than the Earth’s, either because of the absence of oceans or because of the different temperature profiles caused by the close proximity to the parent star, it is clear that a star’s general relativistic potential must play a major role in the survival of such planets, and hence it is vital that it be included in any studies of this problem.

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