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Tidal Constraints on Planetary Habitability

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Abstract. We review how tides may impact the habitability of terrestrial-like planets. If such planets form around low-mass stars, then planets in the circumstellar habitable zone will be close enough to their host stars to experience strong tidal forces. We discuss 1) decay of semi-major axis, 2) circularization of eccentric orbits, 3) evolution toward zero obliquity, 4) fixed rotation rates (not necessarily synchronous), and 5) internal heating. We briefly describe these effects using the example of a 0.25 $M_\odot$ star with a 10 $M_\oplus$ companion. We suggest that the concept of a habitable zone should be modified to include the effects of tides.

1. Introduction

Exoplanet surfaces are probably the best places to look for life beyond the Solar System. Remote sensing of these bodies is still in its infancy, and the technology does not yet exist to measure the properties of terrestrial exoplanet atmospheres directly. Indeed, the scale and precision of the engineering required to do so is breathtaking. Given these limitations, a reliable model of habitability is essential in order to maximize the scientific return of future ground- and space-based missions with the capability to remotely detect exoplanet atmospheres.

Here we review one often misunderstood issue: the effect of tides. If the distance between a star and planet is small, $\lesssim$0.1 AU, the shape of the planet (and star) can become significantly non-spherical. This asymmetry can change the planet's orbital motion from that of spherical planets. Simulating the deviations from the spherical approximation is difficult and uncertain as observations of the Solar System, binary stars and exoplanets do not yet provide enough information to distinguish between models. Without firm constraints, qualitatively different models of the planetary response to tides exist. The two most prominent descriptions are the "constant-phase-lag" and "constant-time-lag" models (Greenberg 2009). In the former, the tidal bulge is assumed to lag the perturber by a fixed angle, but in the latter it lags by a fixed time interval. Depending on the mathematical extension in terms of e, the two models may diverge significantly when $e \gtrsim 0.3$. Throughout this review the reader should remember that the presented magnitudes of tidal effects are model-dependent. For more on these differences and the details of tidal models, the reader is referred to recent reviews by Ferraz-Mello *et al.* (2008) and Heller *et al.* (2009).

We consider tidal effects in the habitable zone (HZ) model proposed by Barnes *et al.* (2008) which utilizes the 50% cloud cover HZ of Selsis *et al.* (2007), but assumes that the orbit averaged flux determines surface temperature (Williams & Pollard 2002). We use the example of a 10 $M_\oplus$ planet orbiting a 0.25 $M_\odot$ star. This choice is arbitrary, but we note that large terrestrial planets orbiting small stars will be preferentially discovered by current detection techniques. This chapter is organized as follows: In § 2 we discuss orbital evolution, in § 3 we describe rotation rates, in § 4 we consider the obliquity, and in § 5 we examine tidal heating.

2. Orbital Evolution

Orbital evolution due to tides should be considered for any potentially habitable world. The asymmetry of the tidal bulge leads to torques which transfer angular momentum between rotation and orbits, and the constant flexing of the planet's figure between pericenter and apocenter dissipates energy inside the planet. These two effects act to circularize and shrink most orbits. In the constant-phase-lag model, the orbits of close-in exoplanets evolve in the following way (Goldreich & Soter 1966; see also Jackson *et al.* 2009):

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

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

where a is the semi-major axis, G is Newton's gravitational constant, m_p is the mass of the planet, Q'_p is the planet's tidal dissipation function divided by two-thirds its Love number, 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 stellar radius. The Q' values represent the body's response to tidal processes and combines a myriad of internal properties, such as density, equation of state, etc. It is a difficult quantity to measure, so here we use the standard values of $Q'_* = 10^6$ and $Q'_p = 500$ (Mathieu 1994; Mardling & Lin 2002; Jackson *et al.* 2008a). The first terms in Eqs. (1 – 2) represent the effects of the tide raised on the planet, the second the tide raised on the star.

Eqs. (1 – 2) predict a and e decay with time. As tides slowly change a planet's orbit, the planet may move out (through the inner edge) of the habitable zone (HZ). This possibility was considered in Barnes *et al.* (2008), who showed

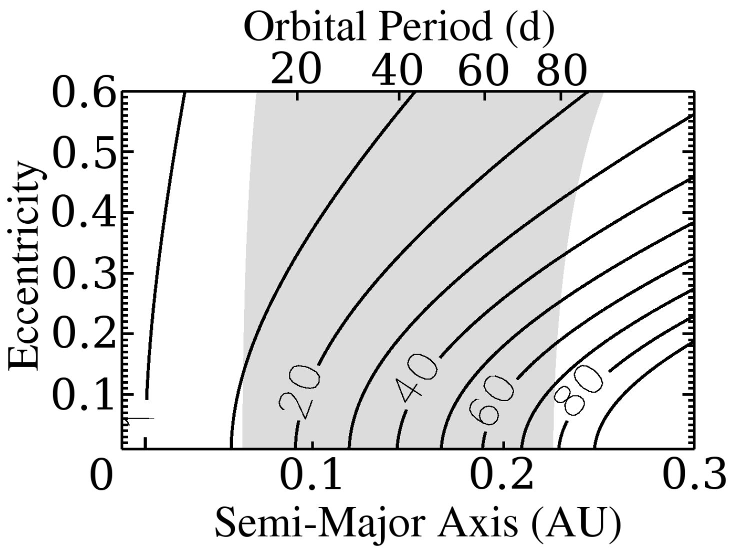

Figure 1. Contours of equilibrium rotation period in days for a 10 $M_\oplus$ planet orbiting a 0.25 $M_\odot$ star. The gray region is the HZ from Barnes *et al.* (2008).

for some example cases the time for a planet to pass through the inner edge of the HZ. Such sterilizing evolution is most likely to occur for planets with initially large eccentricity near the inner edge of the HZ of low mass stars ($\lesssim 0.3\,M_\odot$). Even if a planet does not leave the HZ, the circularization of its orbit can require billions of years, potentially affecting the climatic evolution of the planet.

3. Rotation Rates

Planetary rotation rates may be modified by tidal interactions. Although planets may form with a wide range of rotation rates Ω, tidal forces may fix Ω such that no net exchange of rotational and orbital angular momenta occurs during one orbital period. The planet is then said to be "tidally locked," and the rotation rate is "pseudo-synchronous" or in equilibrium. The equilibrium rotation rate in the constant-phase-lag model is

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

where n is the mean motion (Goldreich 1966). Note that planets only rotate synchronously (one side always facing the star) if $e = 0$ (the constant-time-lag model makes the same prediction). Therefore, the threat to habitability may have been overstated in the past, as independently pointed out by several recent investigations (Barnes *et al.* 2008; Ferraz-Mello *et al.* 2008; Correia *et al.* 2008).

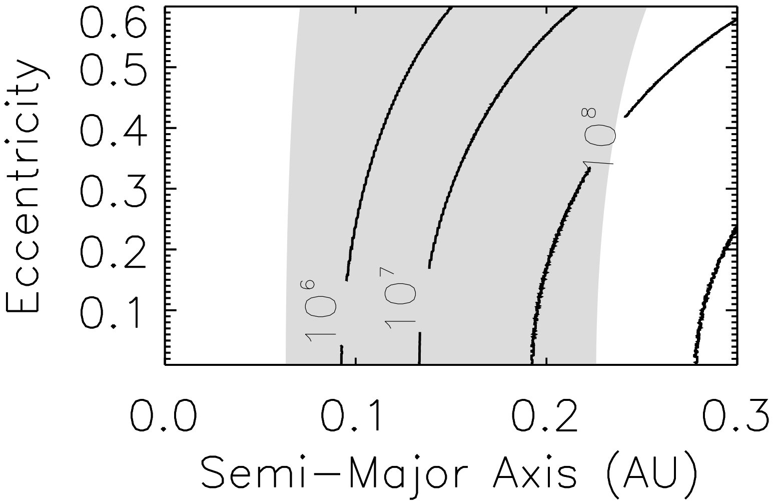

Figure 2. Time in years for a 10 $M_\oplus$ planet orbiting a 0.25 $M_\odot$ star to evolve from an obliquity $\psi = 23^\circ\!.5$ to 5°. The gray region is the HZ from Barnes *et al.* (2008).

Fig. 1 shows the values of the equilibrium rotation period for a 10 $M_\oplus$ planet orbiting a 0.25 $M_\odot$ star as a function of a and e.

4. Obliquity

Tidal effects tend to drive obliquities to zero or π. The constant-time-lag model of Levrard *et al.* (2007) found a planet's obliquity ψ changes as

$$\frac{\mathrm{d}\psi}{\mathrm{d}t} = \frac{\sin(\psi) K_\mathrm{p}}{C_\mathrm{p}\Omega_0 n}\left(\frac{\cos(\psi)\epsilon_1\Omega_0}{n} - 2\epsilon_2\right) \tag{4}$$

where

$$\epsilon_1 = \frac{1 + 3e^2 + \frac{3}{8}e^4}{(1-e^2)^{9/2}} \tag{5}$$

$$K_\mathrm{p} = \frac{3}{2}k_{2,\mathrm{p}}\frac{GM_\mathrm{p}^2}{R_\mathrm{p}}\tau_\mathrm{p} n^2 \left(\frac{M_\mathrm{s}}{M_\mathrm{p}}\right)^2 \left(\frac{R_\mathrm{p}}{a}\right)^6 \tag{6}$$

$$C_\mathrm{p} = r_{\mathrm{g,p}}^2 M_\mathrm{p} R_\mathrm{p}^2 \tag{7}$$

and

$$\epsilon_2 = \frac{1 + \frac{15}{2}e^2 + \frac{45}{8}e^4 + \frac{5}{16}e^6}{(1-e^2)^6} \tag{8}$$

In the preceding equations, $r_{\mathrm{g,p}}$ (= 0.5) is the planet's radius of gyration (a measure of the distribution of matter inside a body), Ω_0 is the initial rotation

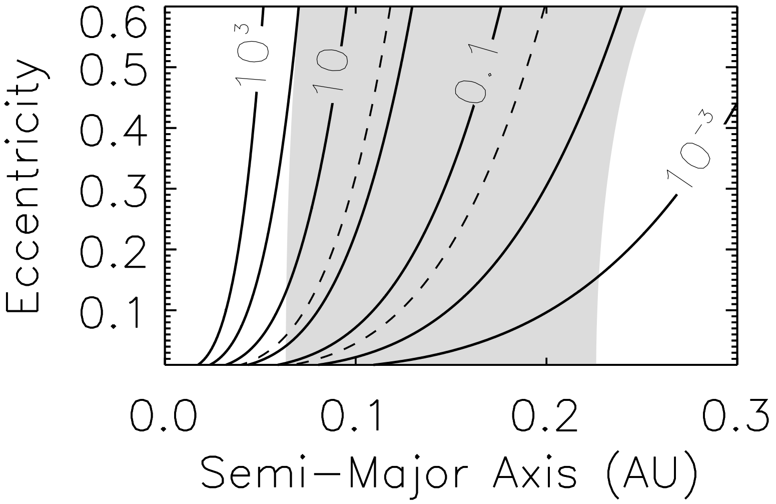

Figure 3. Tidal heating fluxes for a 10 $M_\oplus$ planet orbiting a 0.25 $M_\odot$ star. Contour labels are in W m^{-2}. The dashed contours represent the boundaries of the tidal habitable zone (Jackson *et al.* 2008c; Barnes *et al.* 2009b). The gray region is the HZ from Barnes *et al.* (2008).

frequency, and τ_p is the "tidal time lag", which in this constant-time-lag model replaces Q'_p. We assumed $Q'_p = 500$ for the planet at its initial orbital configuration and set $\tau_\mathrm{p} = 1/(nQ'_\mathrm{p})$, *i.e.* initially the planet responds in the same way as in a constant-phase-lag model. In the course of the orbital evolution, τ_p was then fixed while n and Q_p evolved in a self-consistent system of coupled differential equations. In Fig. 2 we show the time for a planet with an initial obliquity of 23.°5 to reach 5°, a value which may preclude habitability (F. Selsis, personal communication). However, obliquities may easily be modified by other planets in the system (Atobe *et al.* 2004; Atobe & Ida 2007) or a satellite (Laskar *et al.* 1993).

5. Tidal Heating

As a body on an eccentric orbit is continually reshaped due to the varying gravitational field, friction heats the interior. This "tidal heating" is quantified in the constant-phase-lag model as

$$H = \frac{63}{4}\frac{(GM_*)^{3/2}M_*R_p^5}{Q'_p}a^{-15/2}e^2 \tag{9}$$

(Peale *et al.* 1979; Jackson 2008b). However, in order to assess the surface effects of tidal heating on a potential biosphere, it is customary to consider the heating flux, $h = H/4\pi R_p^2$, through the planetary surface. Jackson *et al.* (2008c; see also Barnes *et al.* 2009b) argued that when $h \geq 2$ W m^{-2} (the value for Io; McEwan et al. 2004) or $h \leq 0.04$ W m^{-2} (the limit for plate tectonics; Williams *et al.* 1997), habitability is less likely. Barnes *et al.* (2009b) suggested that these limits represent a “tidal habitable zone”. In Fig. 3 contours of tidal heating are shown for a 10 $M_\oplus$ planet orbiting a 0.25 $M_\odot$ star. The tidal habitable zone is the region between the dashed curves. Note that a and e evolve as prescribed by Eqs. (1 – 2), and hence the heating fluxes evolve with time as well.

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