

Tidal Effects on the Habitability of Exoplanets: The Case of GJ 581 d

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Tides may be crucial to the habitability of exoplanets. If such planets form around low-mass stars, then those in the circumstellar habitable zone will be close enough to their host stars to experience strong tidal forces. Tides may result in orbital decay and circularization, evolution toward zero obliquity, a fixed rotation rate (not necessarily synchronous), and substantial internal heating [1–4]. Due to tidal effects, the range of habitable orbital locations may be quite different from that defined by the traditional concept of a habitable zone (HZ) based on stellar insolation, atmospheric effects, and liquid water on a planet’s surface. Tidal heating may make locations within the traditional HZ too hot, while planets outside the traditional zone could be rendered quite habitable due to tides.

Consider for example GJ 581 d, a planet with a minimum mass of 7 Earth masses, a semi-major axis a of 0.22 AU, and an eccentricity e of 0.38 ± 0.09 ([5]; revised from $a = 0.25$ AU in [6]). The circumstellar habitable zone of [1], which is a synthesis of [7–8], predicts this planet receives enough insolation to permit surface water, albeit with some cloud coverage, see Fig. 1. The small value of a and large value of e suggest that tides may be important, and their potential effects must be taken into consideration. Given the recent revision of its orbit [5], we examine the habitability of this planet in the context of tides. As more planets in the circumstellar HZ of low mass stars are discovered, a similar analysis should be applied.

Rotation Rate The rotation rate of the planet was tidally locked in less than 1 Gyr. Tidal locking, however, does not mean the planet is rotating synchronously, instead it follows the relation

$$\Omega_{\text{eq}} = n(1 + ke^2), \quad (1)$$

where Ω_{eq} is the equilibrium rotation frequency, n is the mean motion, and k is a parameter that is dependent on the tidal model. If tidal bulges lag by a constant phase, $k = 9.5$ [9,1], but if they lag by a constant time, then $k = 6$ [10]. Therefore, GJ 581 d may rotate faster than synchronous, with a

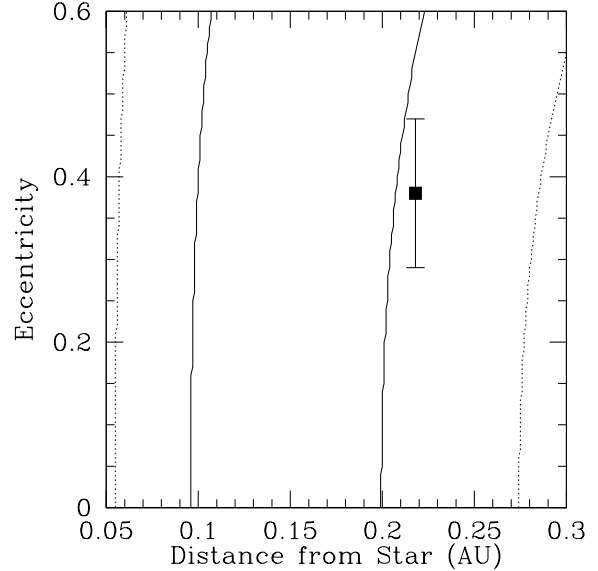


Figure 1: Insolation limits to the habitability of GJ 581 d. Solid curves correspond to the 0% cloud cover HZ model of [1], dotted curves assume 100% cloud coverage. GJ 581 d is the black square, with the 1- σ uncertainty in eccentricity also shown (the errors in a are negligible.)

period of perhaps about half the orbital period of 66.8 days.

Obliquity Tidal evolution tends to drive obliquities to 0 or π (depending on initial conditions). For GJ 581 d, the time for this “obliquity locking” to occur is ~ 100 Myr [4,11]. Should this locking occur, the habitability of GJ 581 d may be in jeopardy, even if it is in the circumstellar HZ, as the poles become a cold trap and can eventually freeze out the atmosphere [12]. However, perturbations from other planets may drive a chaotic obliquity evolution [13]. For this to occur the orbits of the other planets in the system must be inclined relative to GJ 581 d’s orbit.

Large mutual inclinations in the GJ 581 system are likely. An earlier phase of planet-planet scattering [14] is evidenced by GJ 581 d’s large eccentricity, as protoplanetary disk phenomena are un-

likely to produce values larger than 0.3 [15]. Such scattering would have likely driven large relative inclinations ($\gtrsim 30^\circ$) between planets [14]. So, while tides are driving planet d's obliquity toward 0 or π , interactions with other planets are preventing this situation from occurring. Note that the orbital oscillations occur on $\sim 10^3$ year timescales, which is orders of magnitude shorter than the obliquity locking timescale. Whether these obliquities oscillations from the other planets preclude d's habitability is another matter.

Orbital Evolution The GJ 581 system is estimated to be 8 Gyr old [7]. Therefore tides may have played a role in its orbital history. Tides tend to circularize and shrink orbits with time [16]. Although these effects are operating on GJ 581 d, they have resulted in minimal evolution: GJ 581 d has always been in the circumstellar habitable zone. If we assume standard mass-radius relationships for terrestrial planets [17], then GJ 581 d has not drifted an appreciable amount in the last 8 Gyr.

Internal Heating Plate tectonics may be necessary for habitability [17]. On Earth, the internal energy to drive this process comes from endogenic sources: radioactive decay and energy from formation. The sources combine to provide a current heat flux of 0.08 W m^{-2} [18]. This value is close to the lower limit for plate tectonics, 0.04 W m^{-2} derived by [19]. We use their example to make a crude estimate of endogenic heat flux on GJ 581 d, assuming an age of 8 Gyr [6]. They assumed an exponential cooling law:

$$h_{\text{end}} = h_{\text{end},0} R_p \rho_p e^{-\lambda t}, \quad (2)$$

where h_{end} are the radiogenic and primordial heating flux (in W m^{-2}), $h_{\text{end},0}$ is a proportionality constant, ρ_p is the planetary density, λ is the reciprocal of the half-life, and t is the age of the system. As a first estimate, [19] set $\lambda = 1.5 \times 10^{-10}$, corresponding to the half-life of ^{238}U . The actual cooling times and initial radiogenic inventory of GJ 581 d could be very different, and Eq. (2) should be considered an order of magnitude estimate. Scaling from the Earth, the heat flux from non-tidal sources on GJ 581 d is 0.12 W m^{-2} , about 3 times larger than the tectonics limit. Given the uncertainties in this calculation, plate tectonics is not a given on GJ 581 d.

Perhaps tidal heat, similar to Io's, can provide additional energy. Tidal heating H inside a planet

is equal to the change in orbital energy:

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

[20–21]. However, in order to assess the surface effects of tidal heating on a potential biosphere, we can consider the heating flux, $h = H/4\pi R_p^2$, through the planetary surface. The tidal heat flux of GJ 581 d, assuming best fit parameters and planetary tidal dissipation parameter $Q' = 500$, is 0.01 W m^{-2} [3], about 4 times too low for plate tectonics, and perhaps an order of magnitude lower than the endogenic heat flux. Therefore tidal heating, which is also uncertain, could provide a significant heat source for this planet. Perhaps a combination of endogenic and tidal heat drive plate tectonics, facilitating habitability.

We conclude that tidal effects are an important part of assessing GJ 581 d's potential habitability. As more plausibly terrestrial planets are discovered, these tidal issues need to be applied to them as well in order to assess their potential habitability.

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