Initiation of Plate Tectonics on Exoplanets with Significant Tidal Stress

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Abstract

Plate tectonics is a geophysical process currently unique to Earth, has an important role in regulating the Earth’s climate, and may be better understood by identifying rocky planets outside our solar system with tectonic activity. The key criterion for whether or not plate tectonics may occur on a terrestrial planet is if the stress on a planet’s lithosphere from mantle convection may overcome the lithosphere’s yield stress. Although many rocky exoplanets closely orbiting their host stars have been detected, all studies to date of plate tectonics on exoplanets have neglected tidal stresses in the planet’s lithosphere. Modeling a rocky exoplanet as a constant density, homogeneous, incompressible sphere, we show the tidal stress from the host star acting on close-in planets may become comparable to the stress on the lithosphere from mantle convection. We also show that tidal stresses from planet-planet interactions are unlikely to be significant for plate tectonics, but may be strong enough to trigger Earthquakes. Our work may imply planets orbiting close to their host stars are more likely to experience plate tectonics, with implications for exoplanetary geophysics and habitability. We produce a list of detected rocky exoplanets under the most intense stresses. Atmospheric and topographic observations may confirm our predictions in the near future. Investigations of planets with significant tidal stress can not only lead to observable parameters linked to the presence of active plate tectonics, but may also be used as a tool to test theories on the main driving force behind tectonic activity.

Keywords: Extra-Solar Planets, Geophysics, Tectonics, Terrestrial planets, Tides, solid body.

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1. Introduction

Plate tectonics plays a critical role in regulating the Earth’s climate. Mineral weathering continually reduces the amount of carbon dioxide in the Earth’s atmosphere, storing carbon dioxide in the crust (Southam et al., 2015). When plate tectonics pushes the Earth’s crust into the mantle (subduction), this carbon dioxide is re-released into the atmosphere through volcanism. For this reason, tectonics may play a critical role in maintaining life here on Earth (Kasting et al. 1993; Kopparapu et al. 2014, although see Tosi et al. 2017).

Because plate tectonics plays such a crucial role on the Earth’s climate, whether or not terrestrial planets can sustain plate tectonics is relevant for studies of exoplanetary climates and habitability. The criterion for determining if a terrestrial planet may undergo plate tectonics is if the stresses on a planet’s lithosphere from mantle convection may overcome the yield stress of the lithosphere to initiate subduction (Korenaga, 2013). If this condition is not met, the lithosphere behaves as a single, rigid plate on top of the convecting mantle below (the stagnant lid regime). In our own solar system, the Earth has active plate tectonics, while Mercury, Venus, and Mars have stagnant lids (Gregg, 2015).

The discovery of Super-Earths (planets with masses $M_\oplus < M \lesssim 10 M_\oplus$; Batalha et al. 2011) led many to consider the possibility of plate tectonics on exoplanets. Early investigations argued plate tectonics on super Earths was inevitable, since the yield stress on these planets should be less due to the greater surface gravity on super-Earths compared to Earth (O’Neill and Lenardic, 2007; Valencia et al., 2007). Later studies argued surface gravity played a near-negligible role compared to the influence of water reducing the planet’s lithospheric yield stress (Korenaga, 2010). Numerous theoretical and numerical works have followed, some of which see mobile plate-like behavior in their models, while others do not (Kite et al., 2009; Valencia and O’Connell, 2009; van Summeren et al., 2011; Foley et al., 2012; O’Rourke and Korenaga, 2012; Stamenković et al., 2012; Weller and Lenardic, 2012; Noack and Breuer, 2014).

Many transit surveys are targeting M-dwarf stars, because temperate terrestrial exoplanets are easier to detect around them due to their close ($\lesssim 0.1$ au) orbital semi-major axis (Nutzman and Charbonneau, 2008; Shields et al., 2016). M dwarfs are particularly interesting since they improve their planets’ odds to transit for a given incident flux (transits will happen dozens of times per year), while producing signals that can be up to two orders of magnitude stronger (including atmospheric signatures) compared to comparable planets orbiting single Sun-like stars (Rodler and López-Morales, 2014; Barstow and Irwin, 2016; Morley et al., 2017; He, Triaud and Gillon, 2017).

From exoplanetary statistics, we can infer $\sim 50\%$ of all stars with effective temperatures cooler than 4000$^\circ$ K harbor terrestrial planets (Dressing and Charbonneau, 2013; Bonfils et al., 2013; Dressing and Charbonneau, 2015; Morton and Swift, 2014; He, Triaud and Gillon, 2017), with $\sim 20\%$ of these planets expected to be in the habitable-zone (Morton and Swift, 2014; Dressing and Charbonneau, 2015), with some estimates pointing to higher fractions (Bonfils
et al., 2013; He, Triaud and Gillon, 2017). The temperate TRAPPIST-1 planetary system (Gillon et al., 2016, 2017), as well as Proxima Centauri b (Anglada-Escudé et al., 2016) and Ross 128 b (Bonfils et al., 2017), have already been discovered orbiting M-dwarf stars. Due to the influence of plate tectonics on a planet’s climate, whether rocky planets (habitable or not) around an M-dwarf stars may support active plate tectonics is of great interest.

Super-Earths and sub-Neptune mass planets are frequent: planets more massive than Earth are encountered revolving around roughly half of Sun-like stars (Mayor et al., 2011; Howard et al., 2012), and 70-80% of M dwarfs (Bonfils et al., 2013), orbiting their host stars closer than Mercury orbits our Sun. Recent results examining the Kepler data point out which planets of this population are likely to be rocky ($R < 1.5 R_\oplus, m < 4.5 M_\oplus$; Rogers 2015; Fulton et al. 2017; Owen and Wu 2017; Ginzburg et al. 2017), raising the possibility of planets tectonics on these planets. A sub-population, called hot super-Earths, are planets with periods of order a few days (e.g. Fischer et al. 2008; Dawson and Fabrycky 2010). Because of their proximity to their host stars, these planets are likely tidally locked, with a large temperature contrast between the day and night sides of $\sim 1000^\circ$K (Léger et al., 2011; Castan and Menou, 2011; Demory et al., 2016). Since a planet’s viscosity is temperature dependent, the day and night sides of these planets may have different tectonic activity, with a fully convective dayside without a rigid lithosphere, while the nightside may be able to sustain plate tectonics (van Summeren et al., 2011).

Many super Earths exist in multi-planetary system, called Systems of Tightly-packed Inner Planets, such as Kepler-11 (Lissauer et al., 2011), Kepler-33 (Lissauer et al., 2012), Kepler-32 (Swift et al., 2013), Kepler-80 (MacDonald et al., 2016), and Kepler-444 (Campante et al., 2015). STIPs are characterized by multiple planets orbiting their host stars at distances smaller than Mercury’s semi-major axis, and often have close encounters with other planets at distances $< 0.03$ au that can excite their orbital eccentricities, or move them out of tidal synchronization (Vinson and Hansen, 2017; Delisle et al., 2017).

Although some studies considered plate tectonics on close-in, tidally locked exoplanets (van Summeren et al., 2011), the ability of tides to drive mantle convection (Barnes et al., 2009; Papaloizou et al., 2017), as well as the influence of tides on aquatic life (Sleep, 2012; Balbus, 2014; Lingam and Loeb, 2017), all works to date have neglected the influence of tidal stress in a terrestrial planet’s lithosphere. As we will show, this may not be a good approximation. The tidal influence of the host star on slightly eccentric planets with periods of order a day, as well as planets rotating non-synchronously, will generate stresses on exoplanetary lithospheres comparable to stresses from mantle convection. These tidal stresses may aid the mantle convective stresses in overcoming the lithosphere’s yield stress to initiate subduction, making plate tectonics on exoplanets closely orbiting their host stars more likely. We will also consider the tidal stress acting on a planet from a close passage by another planet, which may also aid tectonic activity in terrestrial exoplanets. Section 2 sets up the model which we will use to calculate tidal stresses acting on a rocky exoplanet. Section 3 applies this model to non-synchronously rotating exoplanets, slightly eccentric ultra-short
period planets, and systems of tightly packed inner planets. Section 4 discusses theoretical uncertainties in our analysis, as well as implications of our work. In Section 5 we briefly describe various observing methods that may confirm our predictions, as well a pathway to investigate plate tectonics in regimes where tidal stresses are less relevant. Section 6 summarizes our results.

2. Model of Tidally Stressed Elastic Exoplanet

We model the exoplanet as a constant density, incompressible sphere of mass $m$, radius $R$, and density $\rho$. The Maxwell stress tensor, encapsulating the internal stresses of the planet, is given by (Landau and Lifshitz, 1959):

\[ \mathbf{T} = \rho \mathbf{I} + 2\mu \mathbf{u}. \]  

Here $p$ is the pressure, $\mathbf{I}$ the identity matrix, $\mu$ is the planet’s shear modulus\(^1\), while $\mathbf{u}$ is the (incompressible) planet’s strain tensor:

\[ \mathbf{u} = \frac{1}{2} [ (\nabla \cdot \xi) + (\nabla \cdot \xi)^T ], \]

where $\xi$ is the displacement of the body from equilibrium. We assume the planet is homogeneous ($\mu = \text{constant}$).

The planet is tidally perturbed by a body of mass $m'$ and distance $d \gg R$, with potential

\[ \phi' \simeq \left( \frac{r}{R} \right)^2 \sum_{m=-2}^{2} \Phi_{2m}' Y_{2m}(\theta, \varphi). \]

Here,

\[ \Phi_{2m}' = \frac{4\pi G m' R^2}{5d^3} Y_{2m}^* \left( \frac{\pi}{2}, 0 \right), \]

$Y_{lm}$ are spherical harmonics (with $\theta$ and $\varphi$ polar and azimuthal angles, respectively), and $d$ is the distance of the planet from the perturber.

We take hydrostatic equilibrium to be a state without shear stress. The equations of hydrostatic equilibrium are

\[ -\frac{d\rho}{dr} - \rho \frac{d\phi}{dr} = 0 \]

\[ \frac{1}{r^2} \frac{d}{dr} \left( r^2 \frac{d\phi}{dr} \right) = 4\pi G \rho, \]

where $\phi$ is the planet’s gravitational potential. The boundary conditions are

\(^1\)The shear modulus has units of pressure, and is a material property related to how the planet responds to shear stress. The higher the planet’s shear modulus, the lower the deformation when shear stress is applied to a planet.
\( \frac{d\phi}{dr} |_{r=0} = 0 \) and \( p(R) = 0 \). One may show the solutions for \( \phi \) and \( p \) are

\[ \phi(r) = -\pi G\rho \left( 2R^2 - \frac{2}{3}r^2 \right), \]

\[ p(r) = \frac{2\pi}{3} G\rho^2 (R^2 - r^2). \]

The planet’s state of hydrostatic equilibrium is disturbed by the tidal influence of the perturber, requiring internal stresses to resist its influence. For an incompressible, constant density, homogeneous sphere, the perturbed equations of elastostatic equilibrium are (Landau and Lifshitz, 1959)

\[ -\nabla \delta p + \mu \nabla^2 \xi - \rho \nabla \delta \phi = 0, \]

\[ \nabla \cdot \xi = 0, \]

\[ \nabla^2 \delta \phi = 0, \]

where \( \delta p \) and \( \delta \phi \) are the Eulerian perturbations to the planet’s pressure and gravitational potential, respectively. Equations (9)-(11) are solved with the boundary conditions \( \xi(0) = 0 \), the perturbed gravitational potential \( \delta \phi \) is continuous at \( r = R \), the first radial derivative of the Lagrangian perturbation to the gravitational potential is continuous at \( r = R \), or

\[ \left( \frac{\partial \delta \phi}{\partial r} \right)_{r=R^-} = \left( \frac{\partial \delta \phi}{\partial r} \right)_{r=R^+}, \]

and the radial traction vanishes at the surface of the planet, or

\[ \hat{r} \cdot \Delta \mathbf{T}(R) = \left\{ -\delta p \hat{r} + \mu \hat{r} \cdot \left[ (\nabla \xi) + (\nabla \xi)^T \right] - (\xi \cdot \nabla p) \hat{r} \right\}_{r=R} = 0. \]

The solution for \( \xi \) may be decomposed in the form (see Zanazzi and Lai 2017)

\[ \xi = \sum_{m=-2}^{2} \left[ \xi_{r:2m} Y_{2m} \hat{r} + \xi_{\perp:2m} r \nabla Y_{2m} \right], \]

where

\[ \xi_{r:2m} = \xi_{1m} \left( \frac{r}{R} \right)^3 + 2\xi_{3m} \left( \frac{r}{R} \right) \]

\[ \xi_{\perp:2m} = \xi_{2m} \left( \frac{r}{R} \right)^3 + \xi_{3m} \left( \frac{r}{R} \right), \]

with \( \xi_{im} \) being constants determined by the planet’s boundary conditions. In
Figure 1: Color map of the re-scaled strain magnitude $\bar{u}$ [Eq. (28)] inside the planet, with yellow contours tracing the specific values of $\bar{u}$ indicated.
addition, we may decompose

\[
\delta \phi = 2 \sum_{m=-2}^{2} \Phi_{2m} \left( \frac{r}{R} \right)^2 Y_{2m}(\theta, \varphi),
\]

(17)

\[
\delta p = 2 \sum_{m=-2}^{2} P_{2m} \left( \frac{r}{R} \right)^2 Y_{2m}(\theta, \varphi),
\]

(18)

with \( \Phi_{2m} \) and \( P_{2m} \) being undetermined constants. Applying the boundary conditions [Eq. (12)-(13)], the solution for the constants are

\[
P_{2m} = \frac{2\bar{\mu}/19 - 5/2}{\bar{\mu} + 1} \rho \Phi'_{2m},
\]

(19)

\[
\xi_{1m} = \frac{3/2}{g} \frac{\Phi'_{2m}}{\bar{\mu} + 1}
\]

(20)

\[
\xi_{2m} = \frac{5/4}{g} \frac{\Phi'_{2m}}{\bar{\mu} + 1}
\]

(21)

\[
\xi_{3m} = -\frac{2}{g} \frac{\Phi'_{2m}}{\bar{\mu} + 1}
\]

(22)

\[
\Phi_{2m} = \frac{3/2}{\bar{\mu} + 1} \Phi'_{2m},
\]

(23)

where the re-scaled rigidity \( \bar{\mu} \) is given by

\[
\bar{\mu} \equiv \frac{19\mu}{2\rho g R}
\]

(24)

\[
= 2.038 \left( \frac{\mu}{10^{12} \text{ dynes/cm}^2} \right) \left( \frac{R}{R_{\odot}} \right)^4 \left( \frac{m}{M_{\odot}} \right)^{-2}.
\]

(25)

We define the dimensionless tidal bulge

\[
h \equiv \frac{G M R}{g d^3 (1 + \mu)},
\]

(26)

and strain amplitude \( u \) via

\[
u^2 \equiv \frac{1}{2} \text{Tr}(\mathbf{u} \cdot \mathbf{u}),
\]

(27)

where \( \text{Tr}(\mathbf{U}) \) denotes the trace of the tensor \( \mathbf{U} \). In the Appendix, we explicitly calculate \( u \) [Eq. (27)] assuming \( \xi \) has the form (14). The magnitude of the strain amplitude \( u(r, \theta, \varphi) \) represents how deformed the planet is under the influence of tidal stress. Since \( u \propto h \), we also define the re-scaled strain amplitude

\[
\bar{u} \equiv u/h.
\]

(28)

In Figure 1, we plot the rescaled strain amplitude \( \bar{u} \) for the elastic planet, perturbed by the tidal potential from the planet’s host star. On the surface
\( (r = R) \), the re-scaled strain amplitude reaches a maximum of

\[
\max_{r=R,\theta,\phi} \left[ \bar{u}(r, \theta, \varphi) \right] = 1.15, \tag{29}
\]

while deep in the core \((r \sim 0)\), the re-scaled strain amplitude reaches a maximum of

\[
\max_{r,\theta,\varphi} \left[ \bar{u}(r, \theta, \varphi) \right] = 3.46. \tag{30}
\]

From Fig. 1, we see the re-scaled strain \( \bar{u} \) is of order unity almost everywhere in the planet’s interior, except at \((r, \theta) \approx (R, 0)\). Since \( u = \bar{u} \), tidal stress causes the planet to undergo strains \( u \) of order \( h \) almost everywhere in the planet.

When the planet’s strain amplitude \( u \) exceeds a critical value \( u_{\text{crit}} \) somewhere in the planet’s interior, the planet can no longer maintain elasto-static equilibrium, and begins to permanently deform under the influence of the external stress acting on the planet (the von Mises yield criterion, see Turcotte and Schubert 2002). In order for a planet to undergo plate tectonics, the lithosphere must plastically yield (the type of deformation the Earth’s lithosphere is expected to undergo; Kohlstedt et al. 1995) in order to subduct. Laboratory studies of rocks which make up the Earth’s crust give estimates for the yield stress \( Y \) of the Earth’s lithosphere order \( 10^9 - 10^{10} \) dynes/cm\(^2\) (Kohlstedt et al., 1995), while simulations of plate tectonics on Earth only see plate-like behavior when a \( Y \) of order \( 10^8 \) dynes/cm\(^2\) is used (Trompert and Hansen 1998; van Heck and Tackley 2008; Foley and Becker 2009; see Sec. 4 for discussion). In addition, Earthquakes release lithospheric stress of order \( 10^7 - 10^9 \) dynes/cm\(^2\) (Turcotte and Schubert, 2002), suggesting \( Y \) may also lie in this range. Since the Earth’s shear modulus has a characteristic value \( \mu = 10^{12} \) dynes/cm\(^2\) (Turcotte and Schubert, 2002), we take \( u_{\text{crit}} = Y/\mu \) to lie in the range \( 10^{-5} - 10^{-3} \).

Convective stresses are the drivers of plate tectonics here on Earth, which give values for \( u_{\text{crit}} \) of order \( 10^{-5} - 10^{-3} \), depending on the thickness of the lithosphere (Fowler, 1993; Wong and Solomatov, 2015). In the next section, we will argue there are some astrophysical situations where tides on exoplanets may generate strains of order \( 10^{-5} - 10^{-3} \). This may make plate tectonics on planets with high tidal stress more likely.

3. Exoplanets with High Tidal Stress

When considering how tidal stresses influence an elastic exoplanet, two timescales need to be considered. The first is the time it takes an elastic shear wave to propagate over the entire planet (e.g. Quillen et al. 2016):

\[
t_{\text{elast}} = \frac{R}{\sqrt{\mu/\rho}}
= 1.81 \times 10^{-2} \left( \frac{R}{R_{\oplus}} \right) \left( \frac{\mu}{10^{12} \text{ dynes/cm}^2} \right)^{-1/2} \left( \frac{\rho}{6 \text{ g/cm}^3} \right)^{1/2} \text{ days}, \tag{31}
\]
We assumed in Section 2 the planet lies in elasto-static equilibrium, which requires \( h^{-1} |d\dot{h}/dt| \ll t_{\text{elast}}^{-1} \). When \( h^{-1} |d\dot{h}/dt| \gtrsim t_{\text{elast}}^{-1} \), one needs to do a different calculation of the tidal stress on the planet using the impulse approximation (Quillen et al., 2016).

The second timescale is the time it takes a material to viscously relax to external stress (Maxwell time; Turcotte and Schubert 2002):

\[
t_{\text{Max}} = \frac{\eta}{\mu} = 31.7 \left( \frac{\eta}{10^{21} \text{ poises}} \right) \left( \frac{\mu}{10^{12} \text{ dynes/cm}^2} \right)^{-1} \text{ years},
\]

where \( \eta \) is the material’s dynamic viscosity, which we have evaluated at the viscosity characteristic of the Earth’s upper mantle (Turcotte and Schubert, 2002). In order for the planet to not viscously relax to the tidal stress acting on the planet, we require \( h^{-1} |d\dot{h}/dt| \gg t_{\text{Max}}^{-1} \). Viscous relaxation will limit the ability of tidal stresses to cause plastic yielding in a planet’s lithosphere.

This section directly applies our model to observed exoplanetary systems. We emphasize the degree to which we have idealized the interior structure of these planets: we assume a constant density incompressible planet, with a uniform shear modulus which takes a value characteristic of the Earth’s shear modulus. More massive planets with rocky compositions will not be incompressible (e.g. Seager et al. 2007), and the shear modulus varies in magnitude within a body depending on the local pressure, temperature, and composition (e.g. Dziewonski et al. 1975; Yoder 1995; Turcotte and Schubert 2002). These approximations are reasonable given the level of knowledge on the interior structures and compositions of planets outside our solar system, but makes our calculation of tidal stress acting on a planet unreliable beyond an order of magnitude estimate. For this reason, we do not explicitly state our error bars with the estimated values of tidal stresses acting on exoplanets, even though the system’s parameters have well defined uncertainties.

In the following subsections, we will consider three examples which satisfy \( t_{\text{Max}}^{-1} \ll h^{-1} |d\dot{h}/dt| \ll t_{\text{elast}}^{-1} \): tides from the host stars of non-synchronously rotating planets in Habitability Zones of M-dwarf’s, tides from the host stars of slightly eccentric Ultra-Short Period (USP) planets, and tides from other planets in tightly packed planetary systems.

### 3.1. Non-synchronously rotating planets

Because of their close proximities to their host stars, tides work to drive the rotation of planets toward synchronization with the planet’s orbital period. Planets may escape synchronous rotation through capture into a spin-orbit resonance (Goldreich and Peale, 1966; Makarov et al., 2012; Ribas et al., 2016), atmospheric tides (Correia et al., 2003; Leconte et al., 2015; Auclair-Desrotour et al., 2017), and resonant planet-planet interactions (Delisle et al., 2017; Vinson and Hansen, 2017). If this occurs, the (dimensionless) tidal bulge on the host star

\[
h = \frac{1}{1 + \bar{\mu}} \left( \frac{M}{m} \right) \left( \frac{R}{a} \right)^3,
\]

where \( \bar{\mu} = \frac{\mu}{\mu_m} \).
Table 1: TRAPPIST-1 (Gillon et al., 2017) and GJ 1132 b (Berta-Thompson et al., 2015) planetary properties and dimensionless tidal bulge \( h \) [Eq. (35)]. TRAPPIST-1 has a mass \( M = 0.08 \pm 0.01 \text{M}_\odot \) (Gillon et al., 2017), while GJ 1132 has a mass \( M = 0.181 \pm 0.002 \text{M}_\odot \) (Berta-Thompson et al., 2015). The planet’s semi-major axis is computed via 
\[
    a = \left(\frac{2\pi}{P_{\text{orb}}}\right)^{2/3} \left(\frac{GM}{1\text{M}_\odot}\right)^{1/3},
\]
where \( M \) is the stellar mass and \( a \) is the planet’s orbital semi-major axis, will vary on a timescale 
\[
    \frac{1}{h} \frac{dh}{dt} \sim \frac{1}{|P_{\text{orb}} - P_{\text{rot}}|},
\]
where \( P_{\text{rot}} \) is the rotation period of the planet’s spin, and \( P_{\text{orb}} \) is the planet’s orbital period. As long as \( t_{\text{Max}} \gg |P_{\text{rot}} - P_{\text{orb}}| \gg t_{\text{elast}}, \) the tides on the planet from the host star will generate stress of order 
\[
    h = 1.6 \times 10^{-4} \left(\frac{M}{0.1\text{M}_\odot}\right) \left(\frac{m}{1\text{M}_\oplus}\right)^{-1} \left(\frac{R}{\text{R}_\oplus}\right)^3 \left(\frac{a}{0.025\text{au}}\right)^{-3},
\]
In Table 1, we list \( h \) for the temperate planets TRAPPIST-1 b, c, d, e, and f, as well as GJ 1132 b. We see \( h \gtrsim 10^{-4} - 10^{-5} \) for all planets listed (assuming \( \mu = 10^{12}\text{dynes/cm}^2 \)), implying tides may generate stresses of order the lithospheric yield stress on these planets. We have looked through the Extrasolar Planets Encyclopaedia (Schneider et al., 2011), and found that 42 likely rocky \( (R < 1.6\text{R}_\oplus, \text{Rogers 2015; Fulton et al. 2017}) \) exoplanets have \( h > 10^{-5} \), whose tectonic activity could potentially be affected by tidal processes. We list these planets in Table B.3.

We will discuss the prospects for detecting evidence of plate tectonics in section 5, but we will point out here that the habitability of temperate planet can be affected by tectonics, and may play an important role in stabilizing a planet’s climate (e.g. Kasting et al. 1993; Kopparapu et al. 2014). The planets TRAPPIST-1 c, d, e, and f have equilibrium temperatures between 400°K and 150°K, considered temperate (Gillon et al., 2017).

### 3.2. Eccentric Ultra-Short Period Planets

Numerous super-Earth mass planets have been detected with orbital periods \( P_{\text{orb}} < 1 \text{ day} \), such as 55 Cnc e (Fischer et al., 2008; Dawson and Fabrycky, 2010; Nelson et al., 2014; Demory et al., 2016), CoRoT-7b (Léger et al., 2009; Bruntt

| Planet       | \( m \) (M\(_\odot\)) | \( R \) (R\(_\oplus\)) | \( P_{\text{orb}} \) (days) | \( h \) \((\times 10^{-5})\) |
|--------------|----------------|----------------|-----------------------------|-----------------|
| TRAPPIST-1 b | 0.86           | 1.06           | 1.51                        | 46.49           |
| TRAPPIST-1 c | 1.38           | 1.03           | 2.42                        | 21.11           |
| TRAPPIST-1 d | 0.41           | 0.76           | 4.05                        | 4.47            |
| TRAPPIST-1 e | 0.64           | 0.90           | 6.10                        | 2.46            |
| TRAPPIST-1 f | 0.67           | 1.02           | 9.21                        | 1.08            |
| GJ 1132 b    | 1.62           | 1.13           | 1.63                        | 50.93           |
et al., 2010; Haywood et al., 2014), Kepler 10b (Batalha et al., 2011; Esteves et al., 2015; Weiss et al., 2016), WASP-47e (Becker et al., 2015; Dai et al., 2015; Weiss et al., 2016; Sinukoff et al., 2017), K2 106b (Sinukoff et al., 2017; Guenther et al., 2017). Due to their close proximities to their host stars, USP planets will be tidally circularized and rotating synchronously with rotation periods equal to their orbital periods. This means the “equilibrium” tidal bulge

\[ h_{eq} = \frac{1}{1 + \bar{\mu}} \left( \frac{M}{m} \right) \left( \frac{R}{a} \right)^3 \]  

will satisfy \( dh_{eq}/dt \approx 0 \), so \( h_{eq} \) will viscously relax and not stress the planet.

However, many of these USP planets have exterior planetary companions, which will pump the USP planet’s eccentricity, but theoretical value for USP planetary eccentricities is uncertain. One may delay the tidal damping of the USP planet’s eccentricity by orders of magnitude through secular planet-planet interactions (Wu and Goldreich, 2002). Bolmont et al. (2013) argued planet-planet interactions may pump up the eccentricity of 55 Cnc e to \( e \sim 10^{-3} \) - \( 10^{-2} \). The combination of planet-planet interactions and exciting the USP planet’s second gravitational moment \( (J_2) \) through tidal interactions with the host star, Rodríguez et al. (2016) argued the eccentricity of CoRoT-7b may be pumped up to \( e \sim 0.1 \). Although the magnitude of \( e \) is extremely uncertain, assuming a USP planet in a multi-planetary system has an eccentricity of order \( 10^{-2} \) is not unreasonable.

The small eccentricity \( e \) of the USP planet will cause \( h \) to vary by (assuming \( e \ll 1 \))

\[ \Delta h \approx \frac{6e}{1 + \bar{\mu}} \left( \frac{m}{M} \right) \left( \frac{R}{a} \right)^3 \]  

over the planet’s orbital period \( P_{orb} \), so

\[ \frac{1}{\Delta h} \left| \frac{d\Delta h}{dt} \right| \approx \frac{1}{P_{orb}}. \]  

Since \( t_{\text{Max}} \gg P_{orb} \gg t_{\text{elast}} \) for an USP planet, the variation \( \Delta h \) of the tidal bulge will cause stress in the planet. Evaluating Eq. (37) for parameters characteristic of USP planets, we see

\[ \Delta h = \frac{3.8 \times 10^{-4}}{1 + \bar{\mu}} \left( \frac{e}{0.01} \right) \left( \frac{M}{1 M_\oplus} \right) \left( \frac{m}{5 M_\oplus} \right)^{-1} \left( \frac{R}{1.6 R_\oplus} \right)^3 \left( \frac{a}{0.015 \text{ au}} \right)^{-3}. \]  

Since \( \Delta h \gtrsim 10^{-4} \) for a wide range of USP planet parameter space, we expect the tidal bulge variation due to the planet’s small but non-zero eccentricity to cause stress comparable to the convective stresses on the planet’s lithosphere. Table 2 lists the parameters for a number of ultra-short period (USP) planets, with the time-varying tidal bulge \( \Delta h \) [Eq. (37)] rescaled to the orbital eccentricity \( e = 0.01 \). Some of these planets have measured eccentricities, such as 55 Cnc e \( (e = 0.028^{+0.022}_{-0.019}; \) Nelson et al. 2014), CoRoT-7b \( (e = 0.12 \pm 0.07; \) Haywood
Table 2: Ultra-short period planetary properties in multiplanet systems, with a calculated time-varying dimensionless tidal bulge $\Delta h$ [Eq. (37)]. We take $\mu = 10^{12}$ dynes/cm$^2$ for all bodies, and rescale $\Delta h$ by $0.01/e$ due to uncertainties in the planetary orbital eccentricities (see text for discussion). Listed above are all Ultra-Short Period planets ($P_{\text{orb}} < 1$ day) with detected planetary companions. Planet and system parameters obtained from Demory et al. (2016) (55 Cnc e), Haywood et al. (2014) (CoRoT-7b), Esteves et al. (2015) (Kepler-10b), Sinukoff et al. (2017) (WASP-47e), and Sinukoff et al. (2017) (K2-106b).

| Planet        | $m$ (M$_\oplus$) | $R$ (R$_\oplus$) | $a$ (au) | $M$ (M$_\odot$) | $\Delta h \times (0.01/e)$ |
|---------------|------------------|------------------|----------|-----------------|---------------------------|
| 55 Cnc e      | 8.08             | 1.91             | 0.0154   | 0.95            | $2.5 \times 10^{-4}$      |
| CoRoT-7b      | 4.45             | 1.58             | 0.0171   | 0.91            | $1.5 \times 10^{-4}$      |
| Kepler-10b    | 3.76             | 1.47             | 0.0169   | 0.91            | $1.5 \times 10^{-4}$      |
| WASP-47e      | 9.1              | 1.76             | 0.0167   | 1.00            | $1.6 \times 10^{-4}$      |
| K2-106b       | 9.0              | 1.82             | 0.0131   | 0.92            | $3.6 \times 10^{-4}$      |

et al. 2014), and WASP-47e ($e = 0.03 \pm 0.02$; Weiss et al. 2016). But because the detection of these planetary eccentricities is marginal, we leave the planet’s eccentricity fixed to a conservative value of $e = 0.01$. We note that this exceeds the measured eccentricity of TRAPPIST-1 b ($e = 0.005 \pm 0.001$; Luger et al. 2017).

3.3. Tightly Packed Planetary Systems

Numerous planetary systems have been discovered in which the spacing between two planetary orbits is less than 0.1 au, such as Kepler-11 (Lissauer et al., 2011), Kepler-32 (Swift et al., 2013), Kepler-33 (Lissauer et al., 2012), Kepler-36 (Carter et al., 2012; Deck et al., 2012), Kepler-80 (MacDonald et al., 2016), Kepler-444 (Campante et al., 2015), and TRAPPIST-1 (Gillon et al., 2016, 2017). Assuming the planetary companion has a mass $m_c$ and semi-major axis $a_c$, with both the planet and its companion in circular orbits, the magnitude of $h$ at closest approach is

$$h = \frac{1}{1 + \mu} \left( \frac{m_c}{m} \right) \left( \frac{R}{|a - a_c|} \right)^3.$$

Since $|a - a_c| \ll |a + a_c|$, $h$ will vary by many orders of magnitude over an orbital period. For a planetary companion with orbital period $P_c$,

$$\frac{1}{h} \left| \frac{dh}{dt} \right| \sim \frac{1}{|P_{\text{orb}} - P_c|}.$$

Calculating $h$ for typical tightly packed planetary system parameters, we see

$$h = \frac{2.9 \times 10^{-6}}{1 + \mu} \left( \frac{m_c}{m} \right) \left( \frac{R}{R_\oplus} \right)^3 \left( \frac{|a - a_c|}{0.003 \text{au}} \right)^{-3}.$$

Even for very tightly packed planetary systems, $h \ll 10^{-5}$, so planet-planet interactions are unlikely to aid stresses on the lithosphere from mantle convec-
tion in subduction of plates on terrestrial exoplanets. However, planet-planet tidal stresses in systems of tightly packed planets are much greater than the stress on the Earth caused by the Moon:

\[ h_{\oplus, \text{Moon}} = \frac{4.8 \times 10^{-8}}{1 + \bar{\mu}} \left( \frac{M}{M_{\text{Moon}}} \right) \left( \frac{m}{M_{\oplus}} \right)^{-1} \left( \frac{R}{R_{\oplus}} \right)^{3} \left( \frac{a}{0.00271 \text{ au}} \right)^{-3}. \]  

(43)

If tidal stresses help induce Earthquakes here on Earth, as suggested in Ide et al. (2016), planet-planet tides are likely to be a much greater source of tectonic activity on terrestrial exoplanets in systems of tightly packed planets.

4. Theoretical Uncertainties and Implications

We assumed the entire planet was a homogenous, constant density incompressible elastic solid. Although the silicate crust of USP planets may melt to form a surface lava ocean (which will have no shear modulus), these oceans will have depths \( \lesssim 1\% \) the planet’s radius (Léger et al., 2011). Unless an USP planet has a lava ocean depth comparable to the planet’s radius, the magnitude of the tidal stress calculated in Sections 2 and 3 are unlikely to change by an order of magnitude. However, we note that only the nightsides of USP planets have the right conditions for plate tectonics, since the dayside surfaces are too hot for mantle convection (van Summeren et al., 2011).

We assumed a constant shear modulus and viscosity characteristic of the cold, terrestrial planets here in our solar system. Both the shear modulus and viscosity of a planet depend on the pressure and temperature of the rocky planet (e.g. Dziewonski et al. 1975; Yoder 1995; Turcotte and Schubert 2002). Inclusion of these effects would probably require relaxing our idealized model for a rocky exoplanet and is outside the scope of this work, but will likely not change the magnitude of the tidal strain by more than an order of magnitude.

When simulating plate tectonics with a pseudo-plastic rheology, one typically needs a yield stress of order \( 10^{8} \) dynes/cm\(^2\) for convective stresses to be able to subduct plates. It is a well known problem that this is much lower than the yield strength of the rock which make up the Earth’s crust, obtained from laboratory experiments (Kohliedt et al., 1995; Korenaga, 2013). Damage theory, which models the reduction and growth of grains in a deformed lithosphere, is a plausible way to obtain plate-like behavior with a realistic rheology (Bercovici and Ricard, 2003; Foley et al., 2012). How self-consistent modeling of damage in the lithosphere changes the results presented in Sections 2 and 3 is outside the scope of this work, but may make tectonic activity more likely for terrestrial exoplanets undergoing significant tidal stress.

Although the exoplanetary model presented in this paper is highly idealized, one could in principal carry out a more detailed calculation of the tidal stress in a planet’s lithosphere with realistic equations of state, given constraints on a planet’s bulk composition and orbit. Such calculations would illuminate the extent tidal stress effectively “weakens” a planet’s lithosphere, compared to planets without such significant sources of tidal stress. If signatures of active
plate tectonics were detected (see Sec. 5 for discussion), a population of tidally stressed planets could help geophysicists and planetary scientists differentiate between theories which claim weakening a planet’s lithosphere with surface water or gravity is the main driver of plate tectonics (O’Neill and Lenardic, 2007; Valencia et al., 2007; Korenaga, 2010), or a steady internal heat source which drives mantle convection (e.g. Barnes et al. 2009).

5. Prospects for gathering empirical evidence of plate tectonics.

The first, tentative observational evidence that geological processes may be affecting an exoplanet were produced on 55 Cnc e (Demory et al., 2016). It is likely that others will follow particularly in systems that are optimal to be followed up, such as the many worlds surrounding TRAPPIST-1 (Gillon et al., 2017; de Wit et al., 2016; Barstow and Irwin, 2016; Morley et al., 2017), or GJ 1132b (Berta-Thompson et al., 2015; Dittmann et al., 2016).

Two types of observables may be produced on exoplanets: atmospheric, and topographic. Atmospheric information can be gleaned if a planet transits its host star, by performing spectro-photometry at inferior conjunction (transmission spectroscopy), or at superior conjunction (emission spectroscopy) (Seager and Deming, 2010). In both instances, the chemical content of the atmosphere can retrieved, however different molecules sometimes have broad overlapping features that can be confused. Alternatively, for transiting and non-transiting planets, specific molecules can be identified (in transmission or emission) using high-resolution spectroscopy (Snellen et al., 2010; Rodler and López-Morales, 2014). This method can uniquely identify certain molecules, but it struggles to measure relative abundances. Light gases such as SO$_2$ are produced in large quantities by volcanic eruptions, particularly at zones of subduction, where explosive, Plinian eruptions can inject SO$_2$ high into the stratosphere where its released gases could become detectable (e.g. the Pinatubo in 1991).

We have identified a number of planets, with high $h$ values, that are more likely than others to initiate plate tectonics thanks to significant tidal stresses (Appendix B, Table B.3). We invite observers to collect atmospheric data on those, and identify common molecules indicative of plate tectonics from that subpopulation. Once tracers are identified, work can proceed on a wider range of planets in order to explore the role of mass, radius, gravity, or composition, atmospheric pressure, maybe the presence of large volumes of liquid water, on the onset and persistence of plate tectonics. Careful future studies may shed information as to why plates developed on Earth.

For a subset of planets, topographic information may also be reachable thanks to a technique called eclipse mapping. As a planet disappears behind its host star (at superior conjunction), its disc is progressively occulted by the star. High-cadence, high precision photometric time-series at ingress and egress can produce two-dimensional brightness maps of an exoplanet (de Wit et al., 2012; Majeau et al., 2012; Louden and Kreidberg, 2017). Planet-planet occultations may reveal similar information (Luger et al., 2017). Active volcanoes on the surface of Io represent some of the brightest features at mid-infrared wavelengths.
in the Solar system (Peters and Turner, 2013; de Kleer et al., 2014). Similar phenomena might become observable on planets such as TRAPPIST-1b with the JWST. Geolocating volcanoes on the surface of exoplanets, and examining their distribution may show the outlines of plates just like most volcanoes on Earth exist near subduction zones.

6. Conclusions

What conditions are necessary for the onset and sustenance of plate tectonics is a question of interest to both geophysicists and astrophysicists looking for worlds outside our solar system. Many planets thought to be primarily rocky orbit close ($\lesssim 0.1$ au) to their host stars. By modeling an exoplanet as a constant density, homogeneous, incompressible sphere, we calculate the tidal stresses and strains acting everywhere in the planet (Sec. 2; Fig. 1). Using this model, we show temperate planets rotating non-synchronously, in orbit around M-dwarf stars, and eccentric ($e \sim 0.01$) Ultra-Short Period ($P_{\text{orb}} \lesssim 1$ day) planets undergo tidal stresses from their host stars comparable to the stress on the Earth’s lithosphere from mantle convection, making plate tectonics on these planets more likely (Secs. 3.1-3.2). Planet-planet tides in systems of tightly packed inner-planets do not induce sufficient tidal stress to significantly aid tectonic activity. However, we note that these stresses remain significantly larger than the tidal stress on the Earth from the Moon, potentially implying planet-planet tidal interactions at conjunction are capable of triggering Earthquakes on exoplanets (Sec. 3.3). This work has implications for the geology and habitability of terrestrial exoplanets orbiting close ($\lesssim 0.1$ au) to their host stars.

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Appendix A. Explicit Calculation of Strain Amplitude

Decomposing the symmetric tensor $u$ into spherical coordinates (Landau and Lifshitz, 1959), we may write Eq. (27) as

$$u^2 = \frac{1}{2} \left( u_{rr}^2 + u_{\theta\theta}^2 + u_{\varphi\varphi}^2 \right) + u_{\theta\varphi}^2 + u_{r\theta}^2 + u_{\varphi r}^2. \quad (A.1)$$

Letting $i, j \in \{r, \theta, \varphi\}$, we may decompose $u_{ij}$ as

$$u_{ij} = u_{ij:20} + 2u_{ij:22}, \quad (A.2)$$

where $u_{ij:lm}$ denotes a strain term proportional to the displacements $\xi_{r:lm}$ and $\xi_{\perp:lm}$ [see Eq. (14)]. Explicitly, we have

$$u_{rr:20} = A_{20} \frac{d\xi_{r:20}}{dr} (3 \cos^2 \theta - 1), \quad (A.3)$$

$$u_{\theta\theta:20} = A_{20} \frac{\xi_{r:20}}{r} (3 \cos^2 \theta - 1) - 6A_{20} \frac{\xi_{\perp:20}}{r} (\cos^2 \theta - \sin^2 \theta), \quad (A.4)$$

$$u_{\varphi\varphi:20} = -6A_{20} \frac{\xi_{\perp:20}}{r} \cos^2 \theta + A_{20} \frac{\xi_{r:20}}{r} (3 \cos^2 \theta - 1), \quad (A.5)$$

$$u_{\theta\varphi:20} = u_{\varphi r:20} = 0, \quad (A.6)$$

$$u_{r\theta:20} = -3A_{20} \left( \frac{d\xi_{\perp:20}}{dr} - \frac{\xi_{\perp:20}}{r} + \frac{\xi_{r:20}}{r} \right) \cos \theta \sin \theta, \quad (A.7)$$
and

\[ u_{rr;22} = A_{22} \frac{d\xi_{r;22}}{dr} \sin^2 \theta \cos 2\varphi, \quad (A.8) \]
\[ u_{\theta\theta;22} = A_{22} \frac{\xi_{r;22}}{r} \sin^2 \theta \cos 2\varphi + 2A_{22} \frac{\xi_{\perp;22}}{r} (\cos^2 \theta - \sin^2 \theta) \cos 2\varphi, \quad (A.9) \]
\[ u_{\varphi\varphi;22} = A_{22} \frac{\xi_{r;22}}{r} \sin^2 \theta \cos 2\varphi - 2A_{22} \frac{\xi_{\perp;22}}{r} (\cos^2 \theta - \sin^2 \theta) \cos 2\varphi, \quad (A.10) \]
\[ u_{\theta\varphi;22} = -2A_{22} \frac{\xi_{\perp;22}}{r} \cos \theta \sin 2\varphi, \quad (A.11) \]
\[ u_{r\theta;22} = A_{22} \left( \frac{d\xi_{\perp;22}}{dr} - \frac{\xi_{\perp;22}}{r} + \frac{\xi_{r;22}}{r} \right) \sin \theta \cos \theta \cos 2\varphi, \quad (A.12) \]
\[ u_{\varphi r;22} = -A_{22} \left( \frac{\xi_{r;22}}{r} + \frac{d\xi_{\perp;22}}{dr} - \frac{\xi_{\perp;22}}{r} \right) \sin \theta \sin 2\varphi, \quad (A.13) \]

where

\[ A_{20} = \sqrt{\frac{5}{16\pi}}, \quad A_{22} = \sqrt{\frac{15}{32\pi}}. \quad (A.14) \]

Appendix B. Calculation of tidal stresses for known exoplanets
| Name               | $m$ ($M_\oplus$) | $R$ ($R_\oplus$) | $P_{\text{orb}}$ (days) | $M$ ($M_\oplus$) | $h$ ($\times 10^{-5}$) |
|--------------------|------------------|------------------|--------------------------|-------------------|------------------------|
| CoRoT-7 b          | 4.74             | 1.49             | 0.85                     | 0.93              | 228.24                 |
| EPIC 246393474 b   | 5.31             | 1.50             | 0.28                     | 0.66              | 2044.65                |
| GJ 1132 b          | 1.62             | 1.13             | 1.63                     | 0.181             | 50.93                  |
| GJ 9827 b          | 8.20             | 1.60             | 1.21                     | 0.66              | 98.31                  |
| GJ 9827 c          | 2.51             | 1.26             | 3.65                     | 0.66              | 11.36                  |
| HD 3167 b          | 5.02             | 1.67             | 0.96                     | 0.08              | 212.19                 |
| K2-106 b           | 8.36             | 1.49             | 0.57                     | 0.93              | 365.85                 |
| KOI-1843 b         | 0.32             | 0.57             | 0.18                     | 0.46              | 2045.96                |
| KOI-2700 b         | 0.86             | 1.04             | 0.91                     | 0.63              | 128.56                 |
| Kepler-10 b        | 3.33             | 1.44             | 0.84                     | 0.91              | 245.87                 |
| Kepler-100 b       | 7.34             | 1.28             | 6.89                     | 1.11              | 1.87                   |
| Kepler-102 b       | 0.41             | 0.46             | 5.29                     | 0.81              | 1.89                   |
| Kepler-102 d       | 2.61             | 1.14             | 10.31                    | 0.81              | 1.22                   |
| Kepler-105 c       | 4.45             | 1.28             | 7.13                     | 1.28              | 2.52                   |
| Kepler-114 b       | 7.00             | 1.16             | 5.19                     | 0.71              | 2.62                   |
| Kepler-20 e        | 3.08             | 0.85             | 6.10                     | 0.91              | 1.64                   |
| Kepler-21 b        | 5.09             | 1.60             | 2.79                     | 1.34              | 23.63                  |
| Kepler-338 e       | 8.58             | 1.55             | 9.34                     | 1.10              | 1.48                   |
| Kepler-406 b       | 6.36             | 1.40             | 2.43                     | 1.07              | 21.28                  |
| Kepler-406 c       | 2.71             | 0.83             | 4.62                     | 1.07              | 3.03                   |
| Kepler-408 b       | 6.36             | 0.80             | 2.57                     | 1.08              | 4.14                   |
| Kepler-42 b        | 2.86             | 0.77             | 1.21                     | 0.13              | 34.02                  |
| Kepler-42 c        | 1.91             | 0.71             | 0.45                     | 0.13              | 278.01                 |
| Kepler-42 d        | 0.95             | 0.56             | 1.86                     | 0.13              | 15.03                  |
| Kepler-445 b       | 6.36             | 1.55             | 2.98                     | 0.18              | 17.45                  |
| Kepler-445 d       | 3.50             | 1.23             | 8.15                     | 0.18              | 1.99                   |
| Kepler-446 b       | 4.45             | 1.47             | 1.57                     | 0.22              | 67.67                  |
| Kepler-446 c       | 2.86             | 1.08             | 3.04                     | 0.22              | 12.16                  |
| Kepler-446 d       | 3.18             | 1.32             | 5.15                     | 0.22              | 5.80                   |
| Kepler-60 b        | 4.19             | 1.68             | 7.13                     | 1.10              | 3.97                   |
| Kepler-62 b        | 8.90             | 1.28             | 5.71                     | 0.69              | 2.34                   |
| Kepler-70 b        | 4.45             | 0.75             | 0.24                     | 0.50              | 539.53                 |
| Kepler-70 c        | 0.67             | 0.86             | 0.34                     | 0.50              | 794.95                 |
| Kepler-78 b        | 1.69             | 1.17             | 0.36                     | 0.81              | 1109.18                |
| Kepler-93 b        | 4.00             | 1.45             | 4.73                     | 0.91              | 7.51                   |
| LP 358-499 b       | 2.19             | 1.28             | 3.07                     | 0.52              | 16.35                  |
| LP 358-499 c       | 3.18             | 1.45             | 4.87                     | 0.52              | 7.35                   |
| TRAPPIST-1 b       | 0.86             | 1.06             | 1.51                     | 0.08              | 46.49                  |
| TRAPPIST-1 c       | 1.38             | 1.03             | 2.42                     | 0.08              | 21.11                  |
| TRAPPIST-1 d       | 0.41             | 0.76             | 4.05                     | 0.08              | 4.47                   |
| TRAPPIST-1 e       | 0.64             | 0.90             | 6.10                     | 0.08              | 2.46                   |
| TRAPPIST-1 f       | 0.67             | 1.02             | 9.21                     | 0.08              | 1.08                   |

Table B.3: Exoplanets with with $m < 10 M_\oplus$, $R < 1.6 R_\oplus$, and $h > 10^{-5}$ [Eq. (35)]; gathered from the Extrasolar Planets Encyclopaedia database (Schneider et al., 2011). Here, $m$ is the planet’s mass, $R$ is the planet’s radius, $P_{\text{orb}}$ is the planet’s orbital period, and $M$ is the host star’s mass. The planet’s semi-major axis is computed via $a = (2\pi/P_{\text{orb}})^2/3(M\mu)^{1/3}$, and we take $\mu = 10^{12}$ dynes/cm$^2$ for all bodies.