Spin-orbital Tidal Dynamics and Tidal Heating in the TRAPPIST-1

M. Efroimsky[1], V. V. Makarov[1], C. T. Berghea[1]

[1] *USNO*

ABSTRACT

Tidal friction and tidal dissipation of rotational and orbital kinetic energy is important for many known exoplanet systems, where the inner planets are often found close to the host stars. Even planets in the habitable zones may be subject to significant tidal forces if the host star is an M dwarf. Using the multi-planet system TRAPPIST-1, locked in a complex chain of mean-motion resonances, we investigate the possible states of exoplanets and their tidal evolution scenarios. The tidal dissipation in the inner planets is so powerful, that their rotation and even internal temperature and phase state can be defined by the past tidal evolution, more than by the direct gravitational interaction within the system. We describe physical mechanisms that should put an end to a runaway internal heating and estimate the reaching the state of solidus in the mantle is the most efficient one. The innermost planet is likely to be "semimolten", and its rotation can be pseudosynchronous (rather than synchronous) with the orbital motion. The amount of tidal heating is so high that even the shape of the planet could undergo drastic changes in the past.

TRAPPIST-1. GENERAL PROPERTIES

TRAPPIST-1 is one of the most fascinating planetary systems discovered so far (Gillon et al. 2017). Orbiting an M dwarf only 12 pc away are seven earth-size planets (0.4 to 1.4 solar masses), more than in any other known system. Another fascinating property of this planetary system is that it is very tightly packed, with the outermost planet orbiting the star in less than 19 days, raising the question of how such systems form and remain stable. Indeed, Quarles et al. 2017 found that fine tuning of the initial orbit parameters is required to find stable solutions.

MOTIVATION

It has often been assumed in the literature - incorrectly - that all close-in exoplanets are tidally synchronized. Facing the stars with one side for billions of years, such planets should be quite limited in their ability to support a highly developed biological life, or even a stable atmosphere rich in volatiles.

The example of our own Mercury indicates that this is not true. As demonstrated in Noyelles et al. (2014), when a realistic tidal model is implemented, a young cold Mercury gets tidally trapped in the 3:2 spin-orbit state with an almost 100% probability – and this happens very quickly (some 10, at most 20 Myr after Mercury's accretion).

A stable non-synchronous final spin-state of a close-in planet can change the inner boundary of the habitable zone. This necessitates the study of entrapment of close-in Earths and super-Earths in spin-orbit resonances.

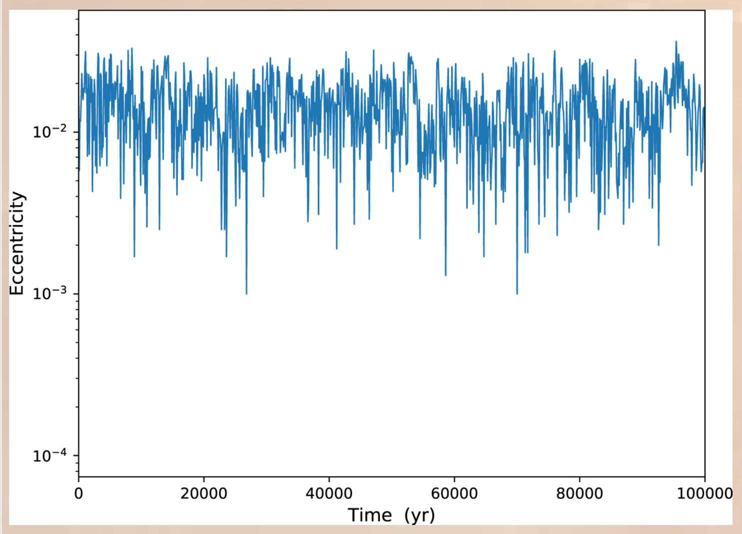
The seven detected planets are in near-MMR to each other as shown in the table below, which presents the rationalization of their periods with deviations below 10%.
Note that the deviations from the exact commensurabilities are such that they help to keep the distant pairs close to small integer ratios. For example, P2/P1 is close to 5/3, and P3/P2 is also close to 5/3. If they were exact ratios, P3/P1 would be 25/9, but the actual closest commensurability is 8/3. Extending it further, P4/P3 is ~3/2, if the ratios were exact, P4/P1 would be 75/18, while the closest observed is 3/2.

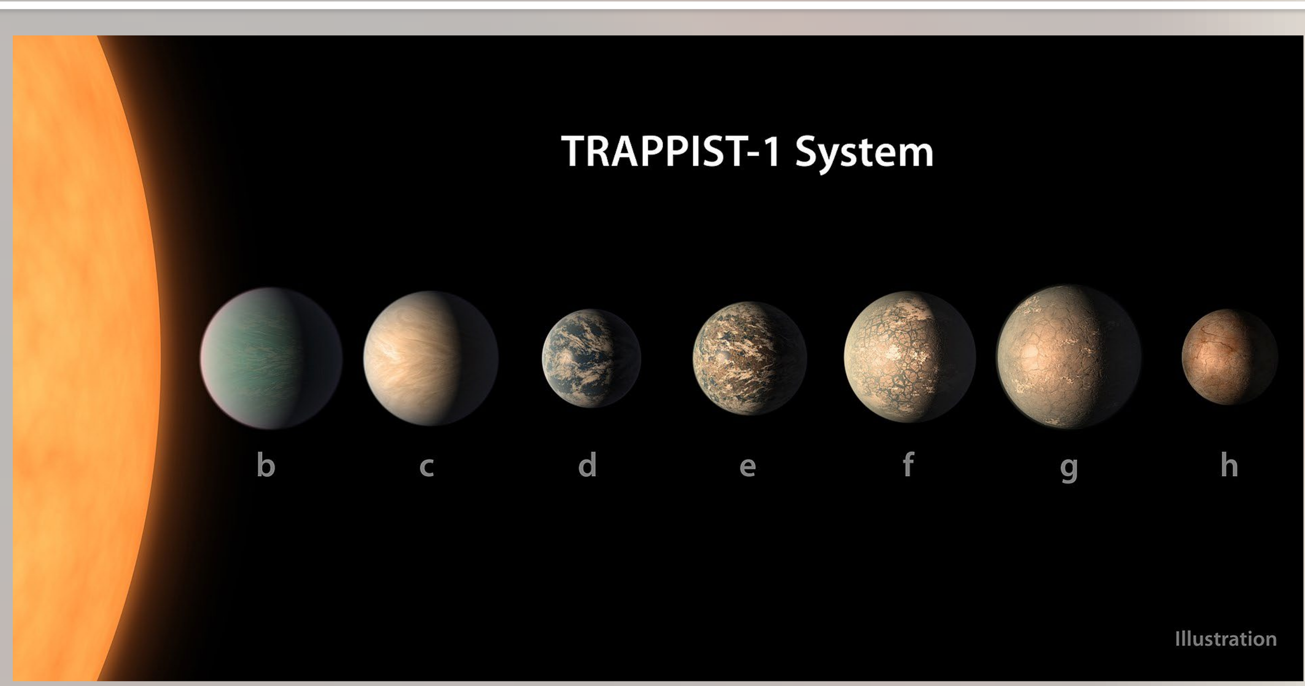
$$\{2, \{\tfrac{5}{3}\}, \{-3.97612\}\}$$
$$\{3, \{\tfrac{8}{3}, \tfrac{5}{3}\}, \{0.509214, 0.326892\}\}$$
$$\{4, \{4, \tfrac{5}{2}, \tfrac{3}{2}\}, \{0.920252, 0.738682, 0.413141\}\}$$
$$\{5, \{6, \tfrac{15}{4}, \tfrac{7}{3}, \tfrac{3}{2}\}, \{1.53655, 1.35611, -2.63287, 0.622021\}\}$$
$$\{6, \{\tfrac{41}{5}, \tfrac{46}{9}, 3, 2, \tfrac{4}{3}\}, \{-0.293052, -0.20455, 1.65232, 1.24432, 0.626194\}\}$$
$$\{7, \{\tfrac{25}{2}, \tfrac{23}{3}, \tfrac{14}{3}, 3, 2, \tfrac{3}{2}\}, \{-0.649568, 1.04822, -0.715093, 2.47898, 1.86858, 1.25021\}\}$$

(planet number *I,* closest commensurability to planets 1,… *i*-1, deviations from commensurability in percent)

ORBITAL STABILITY OF TRAPPIST-1: N-BODY PROBLEM

We begin with one of the long-term stable configurations found by Quarles et al. (2017). We are mainly interested in how the eccentricities vary over long timescales (10 Myr). They will be used to estimate the likely spin–orbit end states of the planets, assuming an Earth-like rheology described by the Maxwell model. The eccentricity variations are shown in this figure for planet TR1-7 (for brevity we name the planets TR1-1, TR1-2, .., TR1-7 instead of the traditional notation TRAPPIST-1 b, c,.., h).





The eccentricity variations are small for all the planets (0.004 – 0.009). The mean values are also small, with the largest value 0.017 for TR1-3.

We also show that the motion of planets is chaotic, with Lyapunov times of the order of years.

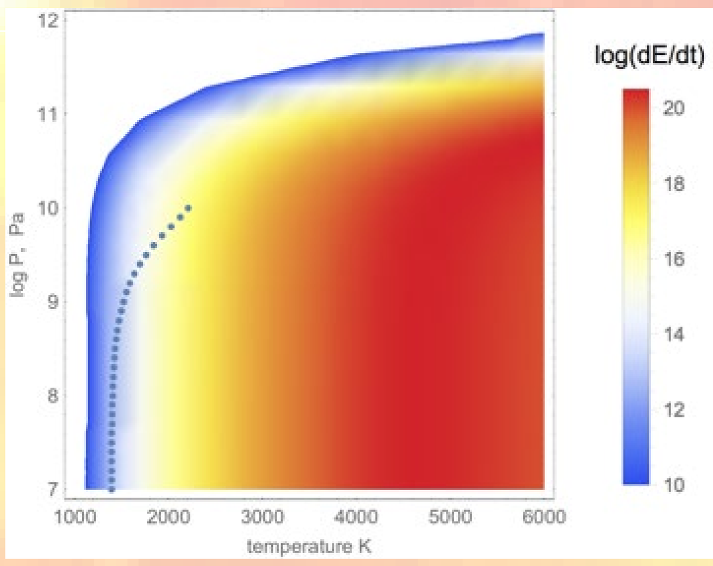
ROTATION AND ENTRAPMENT

$$\ddot{\Theta} = \frac{T_{TRI} + T_{TIDE}}{C}$$

C – the maximal moment of inertia of the planet
T_{TRI} – torque due to the permanent triaxiality
T_{TIDE} – the tidal torque

T_{TIDE} is defined by interplay of self-gravitation and rheology, and has a complex dependence on frequency and temperature. The temperature, in its turn, is defined, for very close-in planets, mainly by the tidal dissipation inside them.

This Figure shows how the rate of tidal dissipation in W depends on the temperature of the silicate mantle in K and the pressure in Pa. Model solidus is shown with dotted line. At a relatively low pressure closer to the surface, solidus occurs much sooner than the maximum dissipation in the Maxwell model. This effectively puts an upper limit on the rate of dissipation in terrestrial planets.



References

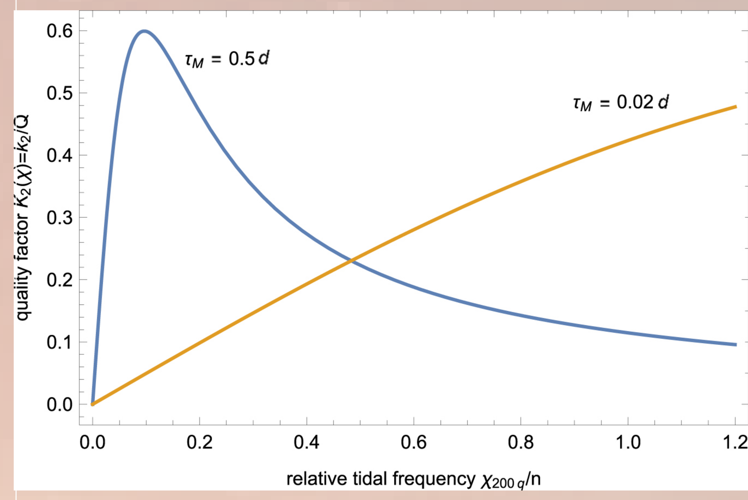
Gillon, M., et al. 2017. "Seven temperate terrestrial planets around the nearby ultracool dwarf star TRAPPIST-1." Nature 542:456
Makarov, V., Berghea, C., Efroimsky, M. 2018. "Spin-orbital tidal dynamics and tidal heating in the TRAPPIST-1 multi-planet system." ApJ 857:142
Noyelles, B., et. al. 2014. "Spin-orbit evolution of Mercury revisited." 2014. Icarus 241 26:44
Quarles, B., et al. 2017. "Plausible Compositions of the Seven TRAPPIST-1 Planets Using Long-term Dynamical Simulations." ApJ 842:L5
Takahashi, E. 1990. " Speculations on the Archean mantle: Missing link between komatiite and depleted garnet peridotite." JGR 95:15941
Stamenković, V., et al. 2012. "The Influence of Pressure-dependent Viscosity on the Thermal Evolution of Super-Earths." ApJ 748:41

THE MAXWELL MODEL AND THE TIDAL QUALITY FUNCTION K2/Q

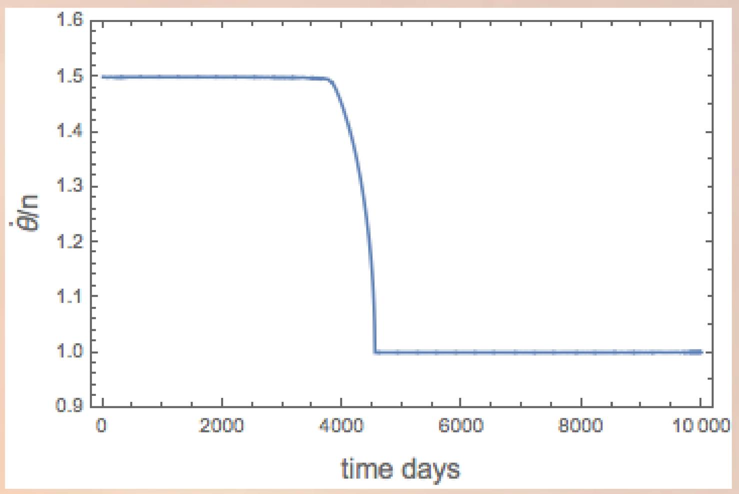
The intensity of tidal interaction is largely defined by the frequency-dependence of the key parameter, k_2/Q. This parameter's value and its frequency-dependence is determined by interplay of the rotator's rheology and self-gravitation. The simplest rheology, which is likely to describe mantles at low frequencies, is that of Maxwell.

Since k_2/Q depends on rheological parameters, and since these parameters are temperature-dependent, k_2/Q is thus sensitive to the temperature. Of a special importance is the exponential temperature-dependence of the viscosity. Owing to this dependence, a rotating body can get captured in a higher spin state, get overheated there, change its rheology – and therefore change its k_2/Q – and then slip out of the higher spin state and continue its tidal despinning towards the synchronism of pseudo-synchronism.

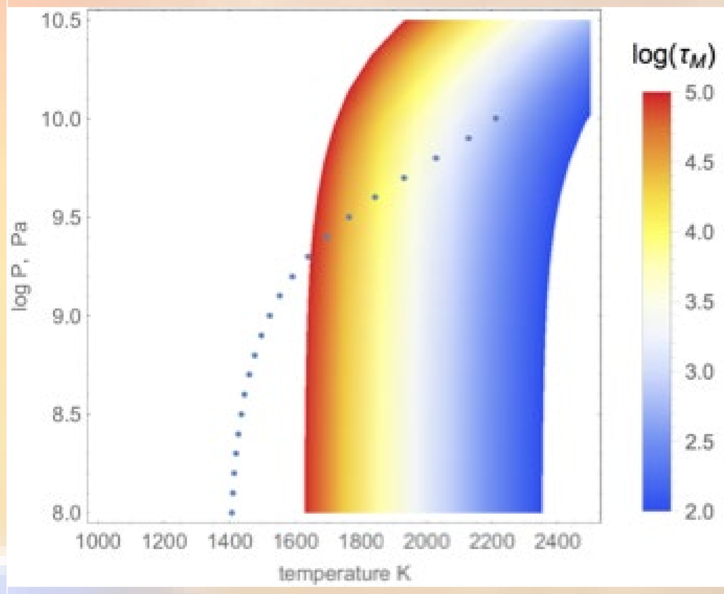
The tidal quality function and the rate of tidal dissipation are strongly dependent on the Maxwell time parameter. A peak close to a commensurate frequency is a necessary condition for capture into the corresponding spin-orbit resonance. When the Maxwell time becomes too short, the peak gets smoothed out, and synchronous rotation becomes the only stable equilibrium possible.



As the internal tidal friction dissipates kinetic energy of rotation, the Trappist planet warms up internally. The rising temperature in the deeper strata of the mantle lower the viscosity and shorten the Maxwell time. If the planet is captured in the 3:2 spin-orbit resonance, this process can result in a sudden destruction of the tidal lock, and the planet starts to spin-down. This Figure shows much accelerated evolution of the relative rate of rotation for TR1-1 with Maxwell time gradually decreasing from 100 days to 1 day.



This Figure shows how the Maxwell time, which governs the rate of tidal dissipation and the tidal torques, depends on the ambient temperature of the silicate mantle and the pressure in Pa. Cold layers of mantle are tidally inactive, because the Maxwell time is too long (viscosity too high). At a relatively low pressure closer to the surface, tidal effects become substantial (similar to Earth's rheology) when temperature reaches ~1900 K. But the point of solidus occurs at lower temperatures, so the peak dissipation is never reached.



CONCLUSIONS

1. While some of the planets (TR-1, TR- 3, and TR-4) were captured in the 3:2 or higher spin–orbit resonances during the initial spin-down, the end product of this scenario is a system where all the planets rotate synchronously with their orbital motion, minimizing the tidal heating.
2. A possible exception may be the closest planet TR-1, which may, depending on its rheology, be trapped in pseudosynchronism.
3. The inner four planets are likely to have massive molten cores and hot mantles with a significant degree of melt.
4. The limited tidal dissipation in the planets means a limited impact on the orbital dynamics and stability of the system.
5. For long-term stability to be maintained, the planet–planet gravitational interaction should keep the eccentricities' values within finite ranges.
6. The tides on the inner planets provide an additional regularisation mechanism adding to the stability of the configuration