CAN MOONS HAVE MOONS?

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ABSTRACT

Each of the giant planets within the Solar System has large moons but none of these moons have their own moons (which we call *submoons*). By analogy with studies of moons around short-period exoplanets, we investigate the dynamical stability of submoons. We find that 10 km-scale submoons can only survive around large (1000 km-scale) moons on wide-separation orbits. Tidal dissipation destabilizes the orbits of submoons around moons that are small or too close to their host planet; this is the case for most of the Solar System's moons. A handful of known moons are, however, capable of hosting long-lived submoons: Saturn's moons Titan and Iapetus, Jupiter's moon Callisto, and Earth's Moon. Based on its inferred mass and orbital separation, the newly-discovered exomoon candidate Kepler-1625b-I can, in principle, host submoons, although its large orbital inclination may pose a difficulty for dynamical stability. The existence, or lack thereof, of submoons, may yield important constraints on satellite formation and evolution in planetary systems.

Subject headings: planets and satellites – exoplanets – tides

1. INTRODUCTION

In all known planetary systems, natural satellites occur in a restricted dynamical phase space: planets orbit stars and moons orbit planets. It is natural to ask, can submoons orbit moons? If so, why don't any of the known moons of the Solar System have their own submoons? One possibility is that the formation mechanism of planetmoon systems precludes their formation. Another possibility, is that these bodies are dynamically unstable and are rapidly scoured from their system after formation. Here, we investigate the latter hypothesis.

What are the requirements for stability of a submoon? To ensure dynamical stability, the host moon must have a Hill sphere that is larger than its physical radius as well as its Roche limit. The submoon must also survive any long-term dynamical effects such as tidal evolution.

2. TIDAL CONSIDERATIONS

Tidal stresses deform extended objects and internal dissipation leads to changes in the objects' rotation states and orbits (e.g., Darwin 1879; Goldreich & Soter 1966; Ferraz-Mello et al. 2008). Tidal evolution in a star-planet-moon system has been studied in the context of Venus and Mercury's lack of moons (Counselman 1973; Ward & Reid 1973; Burns 1973) and in the more general case of moons orbiting exoplanets on shortperiod orbits (Barnes & O'Brien 2002; Sasaki et al. 2012; Sasaki & Barnes 2014; Piro 2018).

Tidal evolution in an isolated planet-moon system may cause the moon's orbit to widen if the planet spins quickly or shrink if the planet spins slowly (e.g. Peale et al. 1980; Burns & Matthews 1986). However, stellar tidal friction acts to slow the planet's rotation, with a direct consequence for the moons' migration (Ward & Reid 1973; Burns 1973). Depending on the configuration, moons may migrate inward and crash into their host planets or migrate outward until they reach the stability limit. In some cases moons can first migrate outward, then change direction and migrate inward as the planet spins down (Barnes & O'Brien 2002; Sasaki et al. 2012).

Here we apply this concept to planet-moon-submoon systems. Barnes & O'Brien (2002) show that under tidal evolution there is a maximum mass of a moon that can survive for a given time T around a close-in exoplanet. They derived a simple analytical approach that applies across different outcomes of tidally-driven migration. To allow for a comparison with the known moons, we re-frame their analysis to ask: what are the physical and orbital requirements for a moon to host a stable submoon with specified properties? We adapt Eq. 8 of Barnes & O'Brien (2002) to derive the critical size of a moon R_{moon} that can host a long-lived submoon. We find that

$$R_{moon} \ge \left[\frac{39M_{sub} \, k_{2,moon} \, T\sqrt{G}}{2 \left(4\pi \rho_{moon}\right)^{8/3} Q_{moon}} \left(\frac{3M_p}{\left(f \, a_{moon}\right)^3}\right)^{13/6}\right]^{1/3},\tag{1}$$

where M_{sub} is the (fixed) mass of the submoon in question, R_{moon} , a_{moon} , ρ_{moon} , Q_{moon} and $k_{2,moon}$ are the moon's radius, orbital radius, bulk density, tidal quality factor, and tidal Love number, respectively, M_p is the planet mass, T is fixed at 4.6 Gyr, and G is the gravitational constant. A submoon's orbit is stable out to a fraction fof its moon's Hill sphere; Domingos et al. (2006) showed that $f \approx 0.4895$ for prograde, low-eccentricity orbits. Eq. 1 has the advantage of simplicity while capturing the basic mechanism at play. However, we note that it inherently assumes that the submoon is low-mass and neglects effects such as the influence of the submoon on the moon's rotation and the influence of the moon on the planet's rotation; see Sasaki et al. (2012) and Piro (2018) for a more comprehensive treatment.

Figure 1 shows the regions of parameter space where a long-lived, 10 km-scale submoon could exist under the action of planet-moon-submoon tides (see caption for pa-

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rameter choices). Only large moons on wide-separation orbits can host long-lived submoons. This is mainly because massive, distant moons have larger Hill radii that provide more stable real estate for submoons.

Remarkably, Jupiter (Callisto), Saturn (Titan and Iapetus), and Earth (Moon) each have the potential to host long-lived submoons around their current moons. Based solely on its orbital separation and inferred mass and size, the new exomoon candidate Kepler-1625b-I (Teachey & Kipping 2018) also appears capable of hosting a large submoon. However, it is worth noting that Kepler-1625b-I has a significant orbital inclination which may affect the stability of submoons (e.g. Tremaine et al. 2009: Tremaine & Yavetz 2014: Hong et al. 2015). We encourage detailed studies of the dynamical stability of submoons in this intriguing system.

Most of the large regular moons of the giant planets are too close to their host planets to host submoons. This is the case for all of Uranus and Neptune's moons. If submoons formed they have since been removed by tidallyinduced migration. Smaller submoons are stable over a broader range of moon radius and distance from their host planet. The parameter space for stable submoons increases for increasing Q_{moon} and decreasing submoon density.

So why don't Callisto, Iapetus or the Moon have submoons? Of course, for submoons to exist they must have a formation pathway. The large moons of the gas giants

are thought to have formed in circum-planetary disks (e.g. Canup & Ward 2006) or by spreading of dense primordial ring systems (Crida & Charnoz 2012). Earth's large moon is thought to have formed via a giant impact (e.g. Canup 2004), whereas Mars' small moons may have been captured or created after a large impact (see Rosenblatt 2011). If primordial moons did form around Callisto, Iapetus or the Moon they must later have been removed, perhaps during their own tidally-driven migration (Namouni 2010; Spalding et al. 2016) or due to moon-moon dynamical effects (Payne et al. 2013; Hong et al. 2018).

3. CONCLUSIONS

To conclude, we note that while many planet-moon systems are not dynamically able to host long-lived submoons, the absence of submoons around known moons and exomoons where submoons can survive provides important clues to the formation mechanisms and histories of these systems. Further studies of the potential formation mechanisms, long-term dynamical survival, and detectability of submoons is encouraged.

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FIG. 1.— Moons of Moons The parameter space in which the moon of a specified planet could host a long-lived submoon under the action of planet-moon-submoon tides. A submoon would be stable for at least the age of the Solar System in the shaded region to the upper right of each panel. The default size of the submoon is 10km in radius (solid curves), and we also show the critical limits for submoons of 5km (dotted) and 20km (dashed) in radius. The solid dots are each planets actual satellites. This calculation assumes that all moons have bulk densities of 2.5 g cm^{-3} , appropriate for most large satellites of the giant planets. We assume tidal Love numbers $k_{2,moon} = 0.25$ (Moore & Schubert 2000), and tidal quality factor Q = 100. We assumed that all submoons have densities of 2 g cm^{-3} , generally appropriate for smaller bodies. For the case of the Earth we assumed a moon density of the Lunar density of 3.34 g cm^{-3} . For the case of Kepler-1625b, we assumed a planet mass of $4M_J$ (Teachey & Kipping 2018), $k_{2,moon} = 0.12$ (appropriate for the ice giants; Gavrilov & Zharkov 1977) and a very uncertain Q_{moon} of 1000.