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Late origin of the Saturn system

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ABSTRACT

Saturn is orbited by a half dozen ice rich middle-sized moons (MSMs) of diverse geology and composition. These comprise ~4.4% of Saturn's satellite mass; the rest is Titan, more massive per planet than Jupiter's satellites combined. Jupiter has no MSMs. Disk-based models to explain these differences exist, but have various challenges and assumptions. We introduce the hypothesis that Saturn originally had a 'galilean' system of moons comparable to Jupiter's, that collided and merged, ultimately forming Titan. Mergers liberate ice-rich spiral arms in our simulations, that self-gravitate into escaping clumps resembling Saturn's MSMs in size and compositional diversity. We reason that MSMs were spawned in a few such collisional mergers around Saturn, while Jupiter's original satellites stayed locked in resonance.

1. Introduction

Since the invention of the telescope there has been a quest to explain Saturn's rings (Cuzzi et al., 2010). Equally mysterious, but largely unknown until the space age, are Saturn's middle-sized moons (Fig. 1). These icy bodies ~300–1500 km diameter (Thomas, 2010) are found on a wide range of orbits, from 3.2 to 62 Saturn radii ($R_♄$). The largest four, Iapetus, Tethys, Rhea and Dione, were discovered by Giovanni Cassini in the late 1600s. Celebrated for some time as the 'Sidera Lodicea' honoring King Louis XIV, they were largely ignored for three centuries until the first detailed images were transmitted by the Voyager spacecraft (e.g. Smith et al., 1981; Thomas et al., 1983; Moore and Ahern, 1983). Since then, the fantastic and perplexing moons of Saturn have been observed in great detail by the ongoing Cassini mission (e.g. Porco et al., 2005; Thomas, 2010). Middle-sized moons are today recognized as one of the principal oddities of the outer Solar System (e.g. Nimmo et al., 2011; Schenk et al., 2011), massive enough yet diverse enough to motivate and constrain larger theories of planet formation and evolution.

1.1. Geophysical motivations

Saturn's MSMs are altogether ~1/20 as massive as Titan (Fig. 2), and are perhaps 20 times as massive as the rings. They are distinguished from Saturn's smaller 'moonlets', which are icy bodies tens of km diameter (Janus and others) that orbit close to the Roche limit. MSMs are many thousands of times more massive than moonlets and are distributed to much greater distances from Saturn. The inner moonlets appear to be well explained as accreted piles of outward-spreading ring material (Charnoz et al., 2010), whereas the origin of MSMs remains a mystery (e.g. Canup, 2010; Mosqueira et al., 2010a; Charnoz et al., 2011; Sekine and Genda, 2012), not only in the Saturn system but around other giant planets. The five major satellites of Uranus are 'middle-sized' (~500–1600 km diameter), and Neptune has relics of a population of MSMs. None are found at Jupiter.

Enceladus is one of the smallest of Saturn's MSMs, and its major geological activity (Spencer et al., 2006) is extraordinary and unexplained. Other moons, notably Rhea, show past or recent signs of deformation and activity (Schenk et al., 2011), and possibly past rings or moons of their own. Some show relatively uneventful surface histories, appearing as cratered frozen-down ice spheres, while at others it is difficult to disentangle crater production from erasure (Lissauer et al., 1988). Saturn's MSMs rotate synchronously in their orbits, the result of past or ongoing tidal dissipation in their interiors. In the case of distant Iapetus, whose tides raised on Saturn are weak, de-spinning by an accreted subsatellite has been proposed (Levison et al., 2011). Determinations of shape and bulk density (Thomas et al., 2007) suggest the existence of interior mass concentrations or inhomogeneities, while limb profiles reveal nonhydrostatic shapes even if one removes the signatures of the major craters (Nimmo et al., 2011). These lines of evidence suggest interior thermal evolution, and/or fossilized rotational and tidal deformation.

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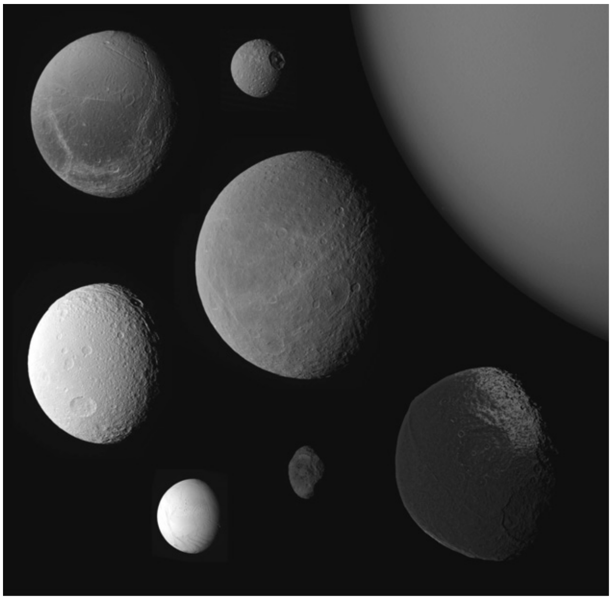

Fig. 1. A diversity of moons. Montage of the regular satellites of Saturn at common phase angle (~45°) and to scale. Clockwise from Titan (upper right) are Iapetus, Hyperion, Enceladus, Tethys, Dione and Mimas, with Rhea in the center. NASA/JPL/SSI; montage by E. Lakdawalla.

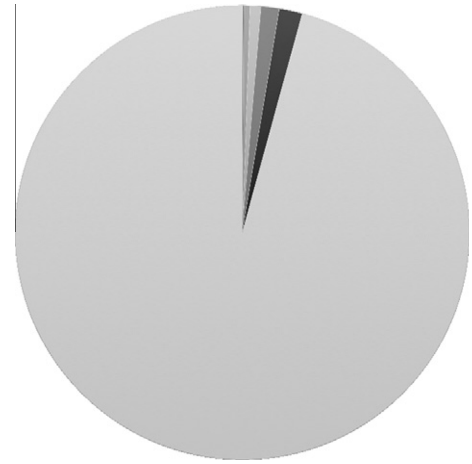

Fig. 2. Satellites of Saturn plotted as a percentage of the total mass. Rhea, Iapetus, Dione and Tethys are the four most massive wedges, in order, and range from pure ice to half rock; they orbit at a_s = 9.2, 62.1, 6.6 and 5.1$R_♄$ respectively. Enceladus, Mimas, Hyperion and Phoebe, which together are the last visible sliver, are equally diverse. Explaining the middle-sized ice rich moons has led to scenarios including accretion out of a massive ice disk (Canup, 2010; Mosqueira et al., 2010a; Charnoz et al., 2011) and hit and run collisions (Sekine and Genda, 2012). We propose that they are the residues of an inefficient final accretion that occurred at Saturn, but not at Jupiter.

Saturn's MSMs have H_2O-dominated surfaces (Cruikshank et al., 2005), further supporting the possibility of thermal evolution and differentiation. Their interiors are predominately ice (c.f. Durham et al., 2005). As a group they measure ~3/4 H_2O by mass, indicated by their global bulk density ρ_s (Anderson and Schubert, 2007), but around this average the bulk compositions of individual MSMs exhibit unexplained and wide-ranging diversity. The radar properties of MSMs also indicate complex and diverse physical and thermal histories, at least in their outer layers (Ostro et al., 2006), and these differences have yet to be explained. There is no obvious trend in bulk composition either with semimajor axis a_s or with size. One dynamical connection with composition is notable but perhaps coincidental, that the iciest of the inner MSMs, Tethys and Mimas (ρ_{Tethys} = 0.98 g cm^{-3}; ρ_{Mimas} = 1.15 g cm^{-3}), are in a 2:1 mean motion orbital resonance, and so are the rockiest, Dione and Enceladus ($\rho_{Enceladus}$ = 1.61 g cm^{-3}; ρ_{Dione} = 1.43 g cm^{-3}).

Much has been written about the geology of the giant satellite Titan, the subject of intensive interest for its hydrocarbon seas and ice continents, its wet 'tropical' climate and massive atmosphere, and its possible subsurface H_2O ocean (Baland et al., 2011) and astrobiological potential. If gas giant planets are common in the universe, then so are Titans. We refer the reader to overviews and interpretations by Lopes et al. (2007), Stofan et al. (2007), Radebaugh et al. (2007), Lorenz et al. (2008), and Moore and Pappalardo (2011) and references therein. Titan is on an eccentric orbit (e = 0.0288, a = 20.3$R_♄$) but otherwise comparable in mass and semimajor axis to Ganymede and Callisto. The orbit periapsis 19.7$R_♄$ is closer to Saturn than the apoapsis 20.9$R_♄$ by >1 planetary radius, causing a strong non-equilibrium tide. In the absence of forcing, Titan's orbit is expected to circularize over a few billion years (Tobie et al., 2005) due to the dissipation of tidal energy through internal heating. Although Titan's internal structure could, for all we know, be non-dissipative, its massive atmosphere and active geology, and possible internal ocean, would seem to indicate deep-seated activity and potentially strong dissipation. If so then either Titan started off with a huge eccentricity, or else the orbital eccentricity is recently acquired or forced.

Rhea is the largest of Saturn's MSMs (D_{rhea} = 1530 km; see Fig. 1). It is controversial (Tiscareno et al., 2010) for exhibiting evidence of past (Schenk et al., 2011) and arguably present (Jones et al., 2008) rings of its own. Rhea has approximately the average bulk composition of MSM-forming material, ρ_{Rhea} = 1.24 g cm^{-3}, and this fact turns out to be useful in discriminating among hypotheses, below. The smallest three MSMs of Saturn – Mimas, Enceladus and Hyperion, $D \sim$ 400, 500, 300 km respectively – exhibit almost inexplicable variations in their fundamental characteristics, as if they formed by completely different mechanisms, and out of different materials. This has led to the idea that some MSMs (for example, 210 km diameter Phoebe; Johnson and Lunine, 2005) are captured, while others have weird histories endogenic to their planet and its satellite system, and specific to their planet's interaction with the dynamically evolving young Solar System.

1.2. Dynamical motivations

In addition to these studies of the shape, mass, geologic history and composition of MSMs, dynamical studies provide powerful physical constraints (e.g. Peale et al., 1980; Meyer and Wisdom, 2008) on their orbital, rotational, tidal and collisional evolution. If orbital evolution is driven by tidal dissipation, then the geology and dynamics of icy satellites are strongly coupled (e.g. Zhang and Nimmo, 2009).

While fundamental aspects of saturnian satellite evolution have been explored and identified, specific scenarios are elusive due to computational and analytical limitations (integrating orbits for billions of Kepler times, including nonlinear interactions) and the large uncertainties in starting conditions and tidal Q. And while the present epoch of saturnian satellite dynamical evolution is anchored in the astrometric record, as discussed below there is presently a debate whether the record shows that Mimas is migrating inwards (Lainey et al., 2012) or outwards.

A broader consensus appears to be emerging if one looks back much earlier, to the waning of the protoplanetary nebula, as to how major satellites might form and evolve dynamically around gas giants. Although the framework is certainly debated, it is believed that major satellites accrete from ices and silicates in the sub-nebulae of giant planets, analogous to miniature Solar Systems (Canup and Ward, 2002; Mosqueira and Estrada, 2003).