WHY SO MUTED? THE SOURCES AND DYNAMICAL MECHANISMS RESPONSIBLE FOR DIFFERING REGOLITH COVER ON SATELLITES EMBEDDED IN SATURN'S E RING.

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Introduction: Saturn's E ring, sourced primarily by cryovolcanic material erupted from Enceladus, extends outward from Enceladus' orbit to beyond Dione's orbit [1][2]. Amongst the satellites embedded in this ring, there are observed differences in regolith cover. In particular, the small satellites Telesto, Calypso, Helene, and Polydeuces have more muted surfaces, an absence of small craters, and downslope transport of regolith within large craters than observed on Tethys and Dione on similar distance scales [3][4]. However, these small satellites orbit in a different dynamical environment: Telesto and Calypso are on leading and trailing tadpole orbits about the L4 and L5 Lagrange points in the co-orbital 1:1 mean motion resonance with Tethys, respectively, as are Helene and Polydeuces tadpoles of Dione [e.g. 5, 6].

Previous studies have investigated the dynamical evolution of impact ejecta originating from Telesto and Calypso and concluding that this ejecta preferentially is re-accreted by the originating tadpole moon or the other one rather than Tethys [7]. In addition to impact ejecta as a source of regolith, we investigate here whether ambient E ring material can also be a source of regolith, and whether it can account for observed differences in the amount of regolith on E ring embedded moons in tadpole orbits.

Methods: We investigate the dynamical evolution of E ring particles under the influence of Saturn's gravity, the gravity of massive moons, and interactions with Saturn's plasma environment. For an individual ring particle, it will feel a drag force, F_D, due to collisions with plasma co-rotating with Saturn in its magnetosphere. The acceleration from this force is inversely proportional to the particle grain size and the square of the difference between the plasma's velocity at the ring particle's orbit distance and the particle's orbital velocity [8][9]. Since the ring particle's orbit frequency at the distances of Enceladus, Tethys, and Dione, is smaller than Saturn's rotation frequency, this force acts to expand the orbit of grains erupted at speeds >~the escape speed from Enceladus.

To investigate whether E ring material should concentrate at the L4 and L5 Lagrange points of Tethys and Dione (and potentially be a reservoir of material for supplying the co-orbitals with additional regolith, we perform analytic calculations to assess whether E ring material drifting outward due to plasma drag could become trapped in the tadpole regions of the 1:1 mean motion resonances with Tethys and Dione. We also numerically integrate E ring particle trajectories including these forces using the integrator package REBOUND and REBOUNDx [10-12]. We use initial orbits for the Saturnian System from [13] and estimated masses for the tadpole moons from [7] that assume an average density of 0.6 g/cc. We include Saturn's gravitational harmonics up to J_4 and plasma drag forces arising from collisions with co-rotating O+ ions, the primary constituent of plasma in the region of the Saturnian system of interest.

Results: To provide insight into whether outwardly drifting E ring particles should accumulate in the 1:1 resonances with Tethys and Dione, we compare the timescale for a particle of a given size to drift across the maximum libration width of this resonance to the corresponding libration period for a particle if it were in the resonance. For this estimate, we use the critical libration width and period for the transition between horseshoe and tadpole orbits in the restricted three body problem (e.g. considering the gravitational force of Saturn and the principal moon on the motion of a massless ring particle). The libration period for a particle in the 1:1 resonance liberating around the L4 or L5 Lagrange point is:

$$T_{lib} \approx 2T_{orb}/\sqrt{27\mu}$$

where T_{orb} is the orbital period of the principal moon (e.g. Tethys or Dione) and μ is the mass ratio between that moon and Saturn [14]. This timescale is 1.9 and 2 years for tadpoles of Tethys and Dione, respectively.

The change in an E ring particle's semimajor axis due to plasma drag is about $0.03/R_p$ Saturn radii per year for most of the E ring region, where R_p is the ring particle's size in microns [15]. Using this approximation, a one micron E ring particle would take about 0.3 and 0.5 years to drift across the tadpole region of the 1:1 resonance with Tethys and Dione, respectively.

This rough estimate shows that E ring particles should typically drift outward across the 1:1 resonance faster than they would have librated in the resonance, so E ring particles should not get locked into the resonance. This is supported by observations from Cassini that show no apparent concentration of E-ring material that co-orbits with Tethys or Dione. E ring particles would have to closer to 10 microns in size to concentrate in the co-orbital regions. However, constraints from Cassini VIMS and dynamical models show that the predominant particle sizes are ~1 micron for particles that supply the E ring from the cryovolcanic plumes on Enceladus

[16][17] and in situ measurements of particle sizes in the E ring beyond the orbit of Enceladus show the majority of particles should be several times smaller than that limit [18].

From these constraints, we build a toy model in which the spatial density of E ring particles is roughly similar in the vicinity of Tethys versus in the vicinity of its co-orbital companions, Telesto and Calypso. However, due to their libration in the co-orbital resonance, the co-orbital companions will experience greater changes in their orbits relative to Tethys' orbit. As they undergo this libration, they will sweep out an area in the E ring due to their physical size and the evolution of their orbit, and this area will be replenished with more E ring particles before the next libration cycle since the particle drift timescale is shorter than the libration timescale. By analogy, Helene and Polydeuces will behave similarly relative to Dione.

To estimate if this would result in an enhanced accumulation of E ring material on the co-orbital moons relative to their mid-sized neighbors, we can compare the relative areas swept out by the co-orbitals as they librate versus the area swept about by Tethys (or Dione). In a reference frame co-rotating with Tethys (or Dione), the ratio of these areas, A, would be about:

$$A \sim R_{co} d_{co} / R_2$$

where R_2 is the radius corresponding to the impact cross-section of Tethys (or Dione), R_{co} the radius of the co-orbital, and d_{co} is the distance the co-orbital's semimajor axis traverses away from the semimajor axis of Tethys (Dione) during its libration. For both co-orbitals of Tethys, this ratio is >>1. For the co-orbitals of Dione, this ratio is also >>1 for both Helene and Polydeuces, showing that this dynamical mechanism could easily produce the observed relatively thick regolith cover on the co-orbital moons.

Implications: This simple toy model of 'co-orbital sweeping' of the E ring is intended for illustrative purposes to develop a physical intuition for the dynamical mechanisms likely responsible for the differing degrees of surface regolith coating and makes several approximations. Therefore, in addition to these preliminary estimates, we will discuss results from a more rigorous analysis of the stability of particle orbits acted upon by plasma drag near the L4 and L5 Lagrange points of Tethys and Dione. We will also show results from numerical integrations of particle trajectories in the outer E ring for particles originating on escape trajectories from the surface of Enceladus.

These preliminary calculations do show that the enhancement of regolith on most of the co-orbital moons could be primarily supplied by ambient E ring material instead of impact ejecta from moons in the co-orbital 'system', but not due to a concentration of ambient E ring material in the co-orbital resonance with Tethys or Dione. This scenario involving regolith deposition from the ambient E ring requires, however, that the ambient spatial density of E-ring particles needs to be fairly steady on timescales approaching the libration timescales of the co-orbitals. Current estimates of these libration periods are 1.82, 1.82, 2.08, and 2.17 years for Telesto, Calypso, Helene, and Polydeuces, respectively [5][6]. Given Enceladus' frequent cryovolcanic eruptions observed over the course of the Cassini mission [1][19], this implies that material from Enceladus is the likely source of the regolith on the co-orbitals. Impacts on the co-orbitals generating sufficient ejecta at speeds facilitating ejecta change with other moons would likely occur less often. From a more detailed analysis of the efficiency and time dependence of this 'co-orbital sweeping' process, in the future we plan to place constraints on the ephemeral nature of Enceladus' cryovolcanic activity and the sources of material to the E ring over a given timescale.

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