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Chaotic dust orbits at Uranus may explain hemispherical color asymmetries on its regular satellites

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Abstract

When [1] noticed that Uranus' four largest moons had leading-trailing hemispherical color asymmetries, they conjectured that infalling dust from yet-to-be discovered, retrograde irregular satellites might be responsible. Eight such retrograde moons have since been found, and the recent detection of Phoebe's ring at Saturn [6] suggests that large dust rings generated by irregular satellites might be common around the giant planets. We therefore investigate whether infalling dust in the Uranian system might explain the color dichotomies among its regular satellites. In particular, we aim to understand why dust seems to have been distributed among them all rather than concentrated almost exclusively on the outermost moon, Oberon, as in the Saturnian case of Iapetus. When studying the orbits of evolving dust grains, we find that Uranus' unique, extreme obliquity ($\approx 98°$) results in chaotic, large-amplitude variations in orbital eccentricity and inclination due to the wide misalignment between perturbations from the planet's oblateness and tidal perturbations from the Sun. These rapid orbital variations allow dust to access all the regular satellites simultaneously (rather than in sequence from outermost inward). This can explain the fact that all four moons exhibit leading-trailing hemispherical color asymmetries.

1. Introduction

Radiation pressure and Poynting-Robertson drag can transfer dust generated at the irregular-satellite populations of the Jovian planets onto the surfaces of each system's outermost regular satellites. The most striking example of this process is Iapetus at Saturn, whose yin and yang albedo pattern most likely results from thermal ice migration [3] modifying an initial pattern of dust deposition [4]. Less obvious hemispherical color dichotomies have also been discovered, both on Iapetus [2] and on the largest Uranian regular satellites, where the magnitude of the asymmetry increases with distance from Uranus [1].

In Saturn's case, dust orbits decay through Poynting-Robertson drag on timescales of millions of years, slowly bringing grains within range of progressively closer-in satellites. Collision timescales of dust with large regular satellites are comparable, though generally shorter, than the fastest decay timescales. Hence dust is predominantly deposited on the outermost satellite Iapetus, leaving little left over for moons further in [4]. Thus, it is somewhat surprising that color asymmetries are detected on all four of Uranus' outermost regular satellites.

To understand these observations, we have numerically investigated the evolution of dust-particle orbits falling in toward Uranus. We find that Uranus' high obliquity induces chaotic and strong fluctuations in the orbital eccentricities and inclinations of particles. This results in a more equal distribution of dust among the regular satellites of Uranus, perhaps explaining the fact that all exhibit leading-trailing color asymmetries.

We will elucidate the basic physics involved, present our numerical orbit integrations, and discuss our calculated probabilities of collision for each Uranian satellite.

2. Methods

The orbital history of a circumplanetary particle acted on by both a planet and the Sun has long been studied. When the particle's orbital axis lies between the planetary spin pole and the planet's orbital axis, the grain orbit experiences opposing torques from the planet's zonal harmonics and the Sun's tidal gravity. Consequently, for every distance from the planet (which determines the relative strength of the two torques), one can find an orientation of the particle's orbit-pole at which the two torques exactly balance. This direction specifies the local Laplace plane, and orbits in this plane do not precess. In the classical case (i.e., for low planetary obliquities) perturbations away from the local Laplace plane are stable—orbits simply precess around the equilibrium orientation.

Tremaine et al. [5] study the stability of Laplace equilibria across a broader range of obliquities than previously considered. They reproduce the classical behavior at low obliquities, but surprisingly find that within certain radial ranges for obliquities $\gtrsim 70°$, orbits are unstable to small perturbations in the eccentricity vector. Furthermore, they identify a class of Laplace equilibria at inclinations $> 90°$ to the planetary spin axis that is unstable to both perturbations in the eccentricity and angular momentum vectors.

Our numerical integrations (Fig. 1) at Uranus (obliquity $\approx 98°$) illustrate such instabilitiy, which leads to chaotic, large-amplitude variations in the orbital eccentricities and inclinations of particles.

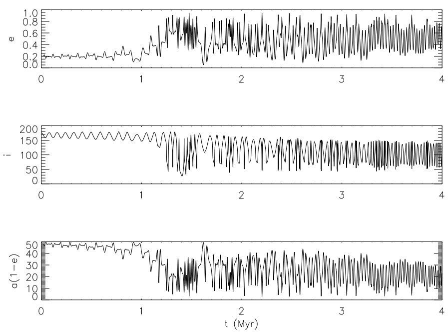

Figure 1: Orbital eccentricity (top panel), inclination (middle, in degrees) and pericenter distance (bottom, in planetary radii), plotted vs. time in Myr. The dust particle is slowly evolving inward, but then its dynamics become unstable and the orbital eccentricity and inclination vary chaotically. Note that this integration does not include the gravity of the inner regular satellites which would enhance Uranus' effective J2 and push the onset of instability farther out from Uranus.

As can be seen from the bottom panel plotting pericenter distance, particle paths oscillate from being beyond the regular-satellite orbits ($\gtrsim 21R_U$) to crossing all moon orbits almost simultaneously ($5R_U \lesssim a(1-e) \lesssim 21R_U$).

To quantify the distribution of dust among the satellites, we undertake collision-probability calculations using previous methods [4]. Preliminary results show distribution among all the regular satellites. We are performing additional integrations to bolster the statistical robustness of our calculations.

3. Summary and Conclusions

Uranus' extreme obliquity renders it a unique system with rich orbital dynamics. We find that orbits of infalling dust particles from the irregular satellites become chaotic, and undergo large eccentricity and inclination variations on timescales much faster than the slow Poynting-Robertson decay one would naively expect. This simultaneously distributes dust among all the large regular satellites of Uranus, perhaps explaining the observation that they all display leading-trailing hemispherical color asymmetries as reported by [1].

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