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Chaotic dust dynamics and implications for the hemispherical color asymmetries of the Uranian satellites

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ABSTRACT

Dust grains generated by the Uranian irregular satellites will undergo chaotic large-amplitude eccentricity oscillations under the simultaneous action of radiation forces and the highly misaligned quadrupole potentials of the oblate planet and distant Sun. From a suite of orbital histories, we estimate collision probabilities of dust particles with the regular satellites and argue that this process may explain the observed hemispherical color asymmetries of the outermost four regular satellites of Uranus.

1. Introduction

Buratti and Mosher (1991) found that all five of the primary Uranian satellites, excluding the innermost Miranda, exhibit systematic leading-trailing color asymmetries of roughly 2–23% that increase with distance from the primary. In particular, the leading hemispheres of these tidally locked satellites (pointing in the direction of motion) are redder than their respective trailing hemispheres. Explaining the origin of this phenomenon is challenging. We briefly consider several exogenic possibilities, dismissing endogenic alternatives due to the difficulty of geological processes producing an effect coinciding with the satellite's apex of motion. Exogenic hypotheses can be divided into two categories: sources from within the Uranian system, and sources from beyond.

For explanations that rely on particles that come from beyond the Uranian system, we consider alteration by: (i) interplanetary dust particles (IDPs) (see for an analysis of the Saturnian system Cook and Franklin, 1970), (ii) interstellar dust particles (ISDPs) (Landgraf, 2000), (iii) solar radiation (Hodyss et al., 2009), and (iv) cosmic rays (Johnson, 1990). A tidally locked satellite on a circular orbit (like the primary Uranian satellites, to an excellent approximation) rotates on its axis once per orbit at a constant rate. For (iii) and (iv), the incoming particle velocity is large enough that the satellite's motion is negligible. Furthermore, the paths of these satellites over an orbital period ($\lesssim$2 weeks) are small compared to the distances over which the incoming particles travel. If one therefore ignores the moon's orbital motion and simply imagines it rotating in place, one can see that the leading and trailing sides will spend an equal amount of time facing each inertial direction. Thus, a distribution of fast incoming particles like solar photons and cosmic rays cannot generate a hemispherical leading/trailing asymmetry.

On the other hand, if the incoming particles have speeds comparable to a satellite's orbital speed ($\sim$5 km/s), the moon's motion introduces a detectable asymmetry. Like a car's windshield, the satellite's leading side will accumulate more material relative to its trailing side the faster it ploughs through the rain of particles. This is certainly the case for IDPs, whose speeds relative to the satellites is $v_{Rel} \sim 10$ km/s, and less so for ISDPs ($v_{Rel} \sim 30$ km/s). However, this argument predicts that inner satellites with faster orbital velocities should exhibit stronger asymmetries, which is opposite to the trend found by Buratti and Mosher (1991). Furthermore, gravitational focusing by Uranus would intensify the flux of IDPs and ISDPs nearer to the planet, which again runs counter to the observed pattern. Thus, (iii) and (iv) cannot produce leading/trailing asymmetries, and while (i) and (ii) in principle could, they would generate the opposite trend with semimajor axis to what is observed. It therefore seems unlikely that the source of the Uranian regular satellites' leading/trailing asymmetries lies beyond the Uranian system.

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Explanations from within the Uranian system include magnetospheric effects (see for a discussion in the Saturnian system Schenk et al., 2011), and the infall of dust that originates at the irregular satellites. Though resonant phenomena could in principle complicate the picture, magnetospheric effects would generally incorrectly predict a larger effect on inner moons, since all the satellites are beyond the co-rotation radius and the magnetic field strength falls off rapidly with semimajor axis (Buratti and Mosher, 1991). We are therefore left with the last hypothesis, dust from the irregular satellites, which we evaluate in the remainder of this paper. In fact, though the currently known Uranian irregular moons lay undiscovered at the time, Buratti and Mosher (1991) argued that such dust from unseen outer satellites could account for the observed hemispherical differences.

1.1. The irregular satellites

To date, nine irregular satellites have been found around Uranus, and many more around the other giant planets. In contrast to the large regular satellites nestled close to their planets, the irregular satellites are a separate population of distant, small moons. These bodies, rather than forming in a circumplanetary disk, are thought to have been captured by their respective planets' gravity (perhaps with the aid of drag forces) early in the Solar System's history (see and references therein Nicholson et al., 2008). As a result, the irregulars' orbits form a distant swarm of mutually inclined, highly elliptical, crossing orbits. This suggests an intense collisional history that would have generated much debris and dust, particularly at early times (Bottke et al., 2010). Furthermore, micrometeoroid bombardment of the irregular satellite surfaces would contribute further dust over the age of the Solar System.

Dust particles of radius 10 μm will then slowly migrate inward through Poynting–Robertson (P–R) drag on a timescale of 5 myr, with the timescale for larger particles scaling linearly with grain radius (Burns et al., 1979). Upon reaching the inner Uranian system, this dust will coat the regular satellites. We evaluate the dust grains' ability to generate leading/trailing asymmetries below. Fig. 1 shows this process schematically. Note that the irregular satellites, which are dominantly affected by solar perturbations, lie (very roughly) symmetrically about the planet's orbital plane, while the regular satellites lie in the planet's equatorial plane, which, due to Uranus' extreme obliquity, is 98° away! The diagram also displays a chaotic range in semimajor axis that is more fully described below.

We pause to caution that several important aspects of these processes are poorly constrained. For example, the lifetimes of dust particles orbiting planets in the outer Solar System are very uncertain. The main mechanisms for grain destruction are sputtering, shattering by micrometeoroids, and sublimation. The last of these is not thought to be important at Uranus and Neptune, and Burns et al. (2001) give sputtering and shattering timescales of $\sim 10^{5\pm2}$ and $\sim 10^{6\pm2}$ yrs for 1-μm particles orbiting Uranus in its magnetosphere, respectively. However, dust from the irregular satellites lives out its life in a very different environment to typically-considered circumplanetary grains. Because the irregular satellites ($\sim$200–800 Uranian radii, R_p) reside far beyond the magnetopause ($\sim 20R_p$), sputtering should be much less important. Also, far out in the Uranian gravity well, IDPs and ISDPs are not as gravitationally focused and have reduced orbital speeds, resulting in longer collision timescales. However, depending on the optical depth of the generated dust cloud, one may have to consider mutual collisions between grains (Tamayo et al., 2011). Given our crude knowledge, it is not clear whether lifetimes of such particles can be very long ($\sim$100 Myr), or whether large particles will be eroded into smaller particles that evolve inward faster and have longer collisional lifetimes (Burns et al., 2001).

A second uncertainty is the total supply of dust available from the irregular satellites. If this quantity is much smaller than the mass of IDPs striking the regular satellites, it would seem dubious to suppose that the irregulars could be responsible for the color asymmetries. Cuzzi and Estrada (1998) estimate an IDP mass flux $\sim 5 \times 10^{-16}$ kg m^{-2} s^{-1} of IDPs in the outer Solar System. This corresponds to $\sim 10^{14}$ kg on each of the regular satellites over 5 Gyr. As for the irregulars, Bottke et al. (2010) estimate that, over the Solar System's history, these satellites would produce $\sim 10^{20}$ kg of dust solely through mutual collisions (this number would be enhanced by micrometeoroid bombardment). This value, however, is very uncertain since it assumes a number and distribution of primordial irregular satellites that is poorly constrained (it draws initial conditions from models of irregular satellite capture during a Nice-model reshuffling of the planets). Furthermore, as discussed above, it is then not clear what fraction of this dust will survive on its way inward. Nevertheless, we find below that the vast majority of surviving grains will strike one of the regular satellites; it therefore seems plausible that irregular satellite debris represents the dominant source of micrometeoroids impacting the regular satellites.

Finally, the precise mechanism through which incoming dust particles alters the satellites' surface color is unclear. Does the altered color represent a contribution from the dust material? Is the satellite's regolith mineralogy altered by the micrometeoroid impacts due to vaporization and/or melting? Or is it something else? Presumably the answer involves all three.

In the end, we take the view that the above considerations are unfortunately too uncertain to be of much guidance. Yet if, as we have argued, other sources are unable to account for the hemispheric asymmetries and if, as we will try to show, irregular

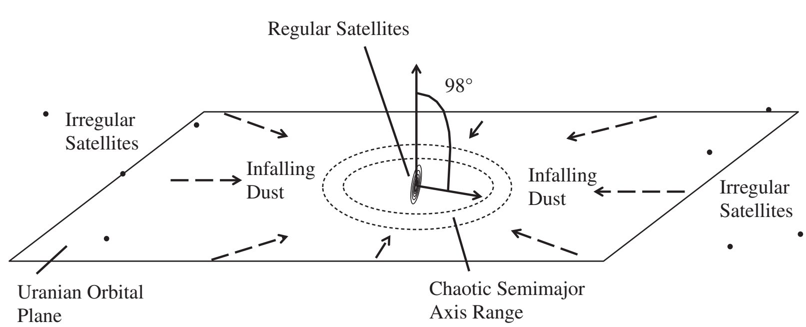

Fig. 1. Schematic diagram showing the geometry of the Uranian system. The regular satellite orbits lie in the planet's equatorial plane, which is inclined by 98° to the planet's orbital plane, shown by the surrounding rectangle. The irregular satellites (black dots) lie at large distance from the planet on inclined orbits to the planet's orbital plane. They have only been drawn on the left and right for clarity, but there would also be moons at phases in their orbit such that they lie at the bottom and top edges of the plane pictured. Dust from these satellites will spiral inward over millions of years through P–R drag, eventually entering a chaotic semimajor axis range schematically depicted by two concentric, dashed rings. Upon doing so, the dust orbits will undergo chaotic large-amplitude oscillations in eccentricity and inclination. See Section 1.2 for details.