HYPERION AS A DUST SOURCE IN THE SATURNIAN SYSTEM

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Abstract. We argue that Hyperion may act as a reasonably effective source of dust in the Saturnian system. Hypervelocity impacts of interplanetary grains and of dust particles from the outermost moon Phoebe should produce impact ejecta from Hyperion's surface, an appreciable share of which would escape into the planetocentric orbits. Though the particles would initially be locked in a strong 4:3 mean motion resonance with Titan so that encounters with this satellite would be prohibited, the solar radiation pressure and especially plasma drag force destroy the resonant locking. Once the resonance is broken, the orbits become unstable and experience multiple close approaches to Titan. Using numerical integrations, we performed a statistical study of the grain trajectories and found that most of the grains larger than $\sim 5\,\mu$m will finally collide with Titan, smaller particles down to $\sim 1\,\mu$m will escape out of the system, and still smaller (submicrometer) particles will rapidly collide with Saturn. First order estimates of the dust influx to Titan are also made; they show that the upper limit of the income rate of the Hyperion particles is comparable with the direct influx of interplanetary grains.

1. Introduction

We suggest that Hyperion, a small icy satellite of Saturn, may play the role of a reasonably effective dust supplier to the Saturnian system. We discuss possible dust production mechanisms (Sect. 2), analyze the main features of the Hyperion ejecta dynamics (Sect. 3), present trajectory statistics ob-

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tained from numerical integrations (Sect. 4), estimate the dust influx from Hyperion to Titan (Sect. 5), and draw our conclusions in Sect. 6.

2. Dust Production Mechanisms

We found at least two mechanisms that would produce permanent dust ejections from Hyperion's surface. The first of them is quite common for bodies in the Solar system that lack an atmosphere. Continuous *impacts of interplanetary meteoroids on the Hyperion surface should eject the surface material.* The second mechanism is specific for Hyperion. Soter (1974) suggested that the dust material from the outermost Saturnian satellite Phoebe, when spiraling toward the primary because of the Poynting-Robertson effect, would be swept out by the inner moons, primarily Iapetus. Contamination of the leading hemisphere of Iapetus by the Phoebe dust is believed to be the cause of the observed brightness asymmetry of Iapetus (Cruikshank *et al.*, 1983, Buratti and Mosher, 1995). Some of the Phoebe material should drift past Iapetus and may reach Hyperion, the next satellite of Saturn (see Cruikshank *et al.*, 1983). Since the orbits of Phoebe particles are retrograde while that of Hyperion is prograde, the impact velocities would be roughly twice the Hyperion orbital velocity, $10\,\mathrm{km\,sec^{-1}}$. *The dust grains from Phoebe are therefore relatively energetic and may produce a considerable amount of ejecta from Hyperion's surface* as well.

A moderate share of the debris should be fast enough to overcome the Hyperion gravity (the mean escape velocity is $\sim 160\,\mathrm{m\,sec^{-1}}$) and get injected into the planetocentric orbits initially close to that of Hyperion.

3. Particle Dynamics

What is the fate of dusty ejecta which escape from Hyperion and begin to move in circum-Saturnian orbits?

We found three perturbing forces to be of importance for the dynamics: *Titan's gravity, solar radiation pressure, and the plasma drag force.* The interplay between these forces can be briefly characterized as follows.

At the beginning, the dust dynamics are dominated by a strong resonant influence of Titan's gravity. Hyperion is locked in a strong *4:3 mean motion resonance with Titan* in such a way that conjunctions of both satellites always occur near Hyperion's apocenter and, therefore, close approaches between the two moons are dynamically forbidden. Since the initial grain orbits are close to that of the parent satellite, the same conclusion should be true for the dust particles originating from Hyperion. As a result, the Hyperion ejecta would form a confined dust torus along the Hyperion orbit.

However, we found several mechanisms that will *destroy the resonant locking.* The particles moving in a complex magneto-plasmasphere of Sa-

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turn are influenced by a plasma drag force, with an estimated strength of several percent of the radiation pressure force. Despite such a small value, a tangential directionality and non-conservative nature of this perturbation inevitably leads to breaking down the resonance. It takes from 20–30 Saturnian years (s.y.) for 100 μm-sized to $\sim$ 1 s.y. for 10 μm-sized grains. Dynamics of smaller grains (with radii of several micrometers) is dominated by strong radiation pressure perturbations and a plasma drag force, and the resonant locking does not occur at all. Finally, for the grains of any size, the breaking of the resonance is facilitated if a particle is ejected with an appreciable speed, of the order of several tens m sec^{-1}, relative to the parent moon (Farinella *et al.*, 1983, 1990).

Once the resonance is broken or, for smaller particles, immediately after ejection, the particle motion becomes, in a sense, stochastic and shows fast, unpredictable changes due to repeated *encounters with Titan*. This leads, finally, to collisions with Titan or Saturn or to escapes from the system.

4. Trajectory Statistics

We integrated numerically the equations of motion to follow a large number of grain trajectories. The calculations have been performed for grain sizes from 1 to 100 μm over the interval of 10 s.y. The main findings are as follows.

In the size range 10 μm $\lesssim r_g \lesssim$ 100 μm, about 30 to 60% of the Hyperion ejecta collide with Titan, the remaining particles exhibit mostly clear trajectories, except for rare collisions with the parent moon Hyperion. It suggests that *the common fate for grains larger than* $\sim$ 5 μm *is collision with Titan.*

The dust grains with $r_g = 5\,\mu$m show, somewhat unexpectedly, a very large share of clear trajectories (about 90%), a relatively low number of collisions with Titan (5 to 10%), and of escapes (1 to 2%). This effect can be explained by the fact that the particles of that size rapidly develop substantial orbital inclinations (a result of radiation pressure perturbations), that allow them to avoid multiple approaches to Titan in the considered time interval.

The smallest dust grains ($r_g = 2\,\mu$m) also show some unusual behavior. Instead of the expected dominant collisions with Saturn (due to strong radiation pressure perturbations), we observed that almost all the particles escape from the Saturnian system. The explanation is not so simple and will be published elsewhere.

In Figure 1, we show the histograms that depict radial and vertical distributions of different-sized grains in relative numbers. The histograms particularly show the changes in dust concentrations in the vicinities of the orbits of both satellites. Near Hyperion's orbit there is an excess of

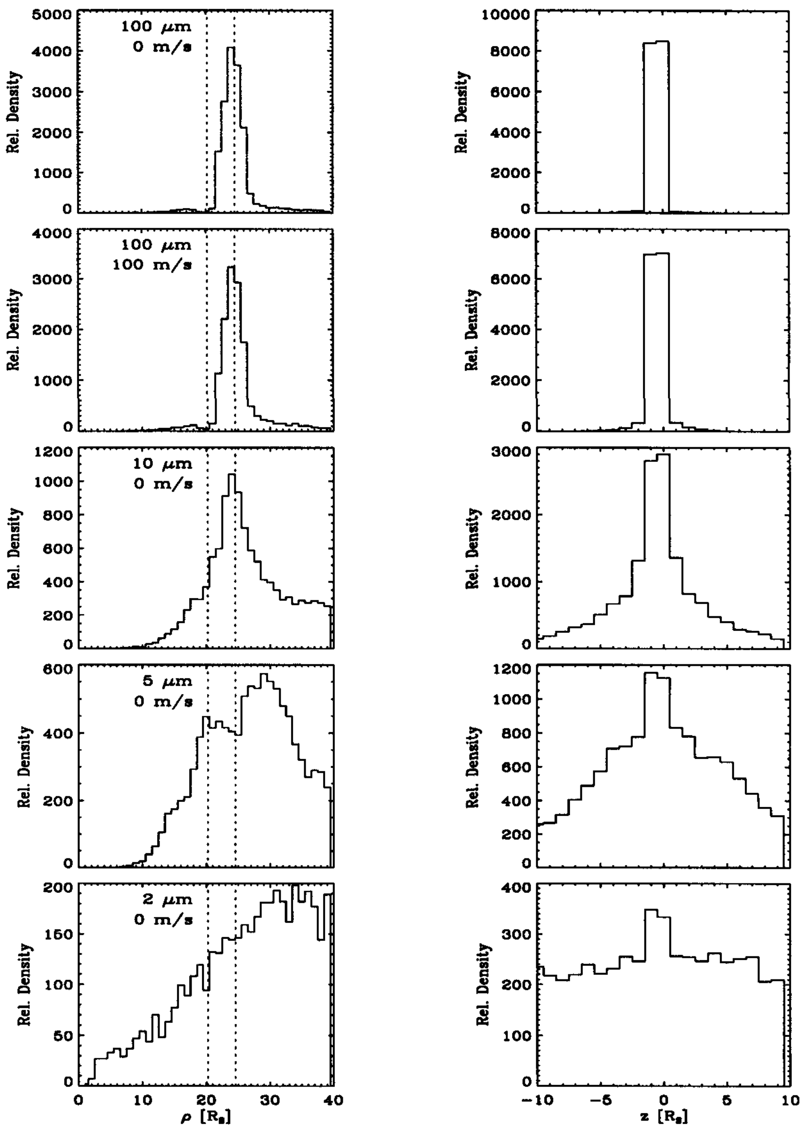

Figure 1. Relative densities of dust particles as functions of the distance from Saturn (left panels) and from the Saturnian equatorial plane (right panels). The data set includes the trajectories of 228 dust grains whose positions were marked after each 0.1 Saturnian year in a 10-year long particle motion. The sizes and the initial speeds of particles (the latter being measured at the boundary of Hyperion's sphere of influence) are shown in the left panels.

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particles with $100\,\mu m \lesssim r_g \lesssim 10\,\mu m$ and a gap for $5\,\mu m$. Near Titan's orbit, the picture is nearly the opposite: a moderate gap is seen for 100 down to $\sim 20\,\mu m$-grains, and an excess appears for $5\,\mu m$ particles. The particles with $r_g = 2\,\mu m$ reveal an almost uniform radial distribution.

5. Dust Influx to Titan

Now we *compare two dust populations at Titan: the flux of Hyperion ejecta and the interplanetary flux.* Their ratio is determined by a number of factors

$$F_{\rm HT}/F_{\rm IT} = \eta_{\rm geom}\,\eta_{\rm yield}\,\eta_{\rm esc}\,\eta_{\rm size}\,\eta_{\rm coll}. \tag{1}$$

The first term is the ratio of surface areas of Hyperion and Titan:

$$\eta_{\rm geom} = S_{\rm H}/S_{\rm T} \approx 2.5 \times 10^{-3}. \tag{2}$$

The second factor is the characteristic yield, defined as the ratio of the ejected mass to the impacting mass. For icy targets and impacts at speeds $\approx 10\,{\rm km\,sec^{-1}}$, we have a plausible estimate

$$\eta_{yield} \approx 1 \times 10^3 \quad \text{to} \quad 5 \times 10^4. \tag{3}$$

The third factor, the fraction of ejected particles that overcomes the gravitational field of Hyperion, $\eta_{\rm esc}$, was estimated to be

$$\eta_{\rm esc} \sim 1 \times 10^{-3} \quad \text{to} \quad 2 \times 10^{-2}. \tag{4}$$

The fourth factor, $\eta_{\rm size}$, represents the fraction of the dust material that falls in the size regime $2\,\mu m \lesssim r_g \lesssim 100\,\mu m$ (the smaller grains are unlikely to reach Titan, and the larger ones are few). We have modeled an ejecta size distribution to get an estimate

$$\eta_{\rm size} = 0.4 \quad \text{to} \quad 0.8. \tag{5}$$

The last factor, $\eta_{\rm coll}$, defines the portion of particles which, if they leave the Hyperion action sphere, eventually collide with Titan. As follows from the numerical integrations, we can assume for $2\,\mu m \lesssim r_g \lesssim 100\,\mu m$ that

$$\eta_{\rm coll} \approx 1. \tag{6}$$

Combining the above values, we finally obtain:

$$F_{\rm HT}/F_{\rm IT} = 1 \times 10^{-3} \quad \text{to} \quad 2 \times 10^{0}, \tag{7}$$

which *is less than (but in the upper limit may be comparable with) unity.*

Unfortunately, it is hardly possible to narrow the interval (7). A principal problem is our lack of knowledge concerning the ejecta yield from the Hyperion surface, which follows from uncertainties in the quantitative assessment of all the processes controling the dust production. First, a source flux of impactors at the Hyperion surface (except for the interplanetary ones) is vaguely known. We give only a "pessimistic" estimate based on the interplanetary impactor population, but Phoebe, and possibly other, yet unknown, retrograde moons of Saturn could provide another, more effective, impactor population. Second, the data in the literature on hypervelocity impact experiments with low-temperature ices does not allow one to provide definite estimates of the characteristic yield and ejecta size and velocity distributions. That is why we cannot obtain, with an accuracy better than 1–2 orders of magnitude, the total ejecta yield from the Hyperion surface, what share of the ejected grains would overcome the Hyperion gravity, and what will be the actual size distribution of the debris.

6. Conclusions

1. There exist at least two mechanisms that should eject dust material from Hyperion's surface: impacts of interplanetary grains and those of particles coming from Phoebe.
2. Most of the particles larger than $\sim 5\,\mu$m in size, which escape from Hyperion, would eventually collide with Titan.
3. The dust influx from Hyperion to Titan may be comparable with the income rate of interplanetary particles to Titan.

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