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THE DISRUPTION OF HYPERION AND THE ORIGIN OF TITAN'S ATMOSPHERE

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ABSTRACT

Two peculiar features of the Saturnian satellite system, that is, the dense, N_2–dominated atmosphere of Titan, and the very irregular shape of Hyperion, are probably related to each other. Numerical integrations show that most fragments ejected after the catastrophic breakup of a presumably larger and nearly–spherical proto–Hyperion fell onto Titan over a time scale of 10^3 yr, at impact speeds <4 km/s. Such impacts resulted into accretion of the constituent volatile materials into Titan's atmosphere. If proto–Hyperion was ≈ 1000 km in diameter, the entire current atmosphere may have been generated by this impact shower. Even for a smaller total mass of the impactors, any pre–existing atmosphere must have been chemically reprocessed, producing large amounts of N_2 by shock effects. Impacts by proto–Hyperion fragments are also likely to have formed giant impact basins on Titan's surface. © *1997 American Astronomical Society.* [S0004-6256(97)01605-1]

1. INTRODUCTION

The Voyager probes have revealed two anomalies of the Saturnian satellite system. The former one concerns the atmosphere of Titan, originally discovered by Kuiper (1944), which has been found to be dense (≈ 1 bar surface pressure), optically thick and formed mainly by molecular nitrogen (Smith *et al.* 1981). The very existence of an atmosphere on Titan contrasts with the absence of similar atmospheres on Ganymede and Callisto, two Jovian moons with masses and sizes close to Titan's (Zahnle *et al.* 1992). The latter anomaly is the strongly irregular shape of Hyperion, a Saturnian moon ≈ 260 km in mean diameter which orbits just outside Titan, and is probably the biggest irregular body in the whole Solar System. The best–fit ellipsoid to Hyperion's shape, as observed by Voyager 2, has axes of 328, 260, and 214 km, but the residuals reach about 1/4 of the mean radius (132 km) (Thomas *et al.* 1995). Hyperion's properties provide strong evidence that the current satellite is just the remnant of the fragmentation of a larger, regularly shaped precursor body, which could not reaccrete due to the peculiar dynamical relationship of Hyperion to Titan (Farinella *et al.* 1983). According to the Voyager team (Smith *et al.* 1982), such catastrophic impacts by passing comets have probably affected all the Saturnian icy moons; only in Hyperion's case, the debris could not reaccrete into a comparatively large, nearly–spherical satellite.

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Here we show by a detailed numerical simulation that the fragments ejected from proto–Hyperion's breakup must have caused an intense shower of cratering impacts onto Titan, whose relatively low speeds resulted into accretion of volatiles rather than atmospheric erosion. Thus the origin of Titan's atmosphere, and possibly also some of its large–scale surface features, are likely to be related to the catastrophic impact which disrupted the Hyperion precursor.

2. THE TITAN–HYPERION RESONANCE

To understand the dynamics of the proto–Hyperion fragments it is important to recall that Titan and Hyperion are currently locked in a 4:3 mean–motion resonance: in the time Titan needs to make four revolutions around Saturn, Hyperion makes three (Greenberg 1973; Colombo *et al.* 1974; Bevilacqua *et al.* 1980). The orbit of Hyperion is fairly eccentric (eccentricity ≈ 0.1), but the resonance results into a protection mechanism which prevents close encounters (and collisions) with Titan. Actually, as a consequence of mutual perturbations, the line along which the two satellites are located when they are at conjunction (that is, aligned with and on the same side of Saturn) oscillates with an amplitude of about 36° around the direction of Hyperion's apocenter, and this dynamical configuration is stable.

On the other hand, any fragments ejected from proto–

Hyperion after its presumed breakup must have had substantial velocity increments (say, 0.1–1 km/s) with respect to both the parent body and the current Hyperion, and this destroyed the stabilizing resonance locking. Therefore, the fragments ended up into chaotic orbits, and could undergo close encounters and even collisions with Titan or the other satellites. Farinella *et al.* (1990) modelled this process in an approximate way by using Öpik's (1976) theory, that is an analytical, statistical theory for the diffusion-like evolution of the orbital elements of minor bodies undergoing a sequence of close encounters or collisions with massive objects, with each encounter treated according to a two-body approximation. The results showed that Titan, due to its proximity and larger cross-section, played a dominant role in sweeping the chaotic fragments up, with most collisions occurring within $\approx 10^3$ yr from the original breakup event. Only a small percentage of the chaotic fragments ended up into unbound orbits escaping from Saturn's system or hit the other satellites. According to this scenario, those fragments which remained in the ''stable island'' of the orbital element space associated with the resonance gradually reaccreted and formed a remnant body, that is the current Hyperion.

The idea that some reaccumulation of fragments occurred on the current Hyperion is not necessarily at odds with its irregular shape. For low-velocity impacts (in the case of Hyperion, reaccretion occurred at speeds lower than the escape speed of the parent body, say 10–100 m/s) the final shape of the body depends on the size distribution of the reaccreting fragments, which in turn depends on the mass-speed relationship among ejecta. In other words, if (as it is likely) the largest proto-Hyperion fragments were ejected at lower speeds and preferentially reaccreted, an irregular final shape is to be expected. Such a mechanism has been recently invoked to explain the ''lumpy'' shape of several asteroids imaged by both the *Galileo* spacecraft and radar (Thomas *et al.* 1993, 1996; Hudson & Ostro 1994; Davis *et al.* 1996). Alternatively, a reaccreted Hyperion may have had its shape modified by subsequent impacts.

3. BREAKUP SIMULATIONS

The conclusions summarized above from the approximate Öpik model suggest that the catastrophic collision originating Hyperion may have produced a very intense and short pulse of impacts onto Titan, possibly affecting its surface and/or atmosphere. To obtain a more quantitative assessment of this process, we decided to simulate in a realistic way both the proto-Hyperion breakup and the subsequent dynamical evolution of the ejecta, in order to derive reliable statistical estimates on how many fragments impacted Titan, escaped to unbound orbits, or reaccreted. To reproduce the initial breakup event, we used a collisional algorithm recently developed to predict the size and orbital distribution of the fragments generated from the collisional disruption of asteroids (Petit & Farinella 1993; Marzari *et al.* 1995).

In our ''nominal'' simulated impact event, we assumed a proto-Hyperion 380 km in diameter that was hit by a 180-km projectile (possibly a passing Chiron-like comet) at a relative velocity of 5 km/s. The largest fragment produced by the model was somewhat smaller than the present Hyperion (80% of its mass), to take into account the subsequent reaccumulation of some minor fragments onto the largest one. The orbital elements of the fictitious fragments were calculated assuming an isotropic distribution of the ejection velocities in three-dimensional space. We assumed that fragment speeds matched a Maxwellian distribution whose mean is inversely related to the square root of fragment size, in agreement with the results of laboratory experiments on hypervelocity impacts (Nakamura & Fujiwara 1991; Nakamura *et al.* 1992); speeds were normalized in such a way that 20% of the original impact energy was partitioned into ejecta kinetic energy, based on the dispersion of orbital elements observed in the asteroid families (Marzari *et al.* 1995; Davis *et al.* 1989). The average ejection velocity was about 400 m/s, with a few fragments escaping with speeds up to 1 km/s.

4. NUMERICAL INTEGRATIONS AND RESULTS

As a dynamical model for integrating the fragment orbits, we used the elliptical three-body problem Saturn-Titan-fragment, which contains all the basic features of the resonant and chaotic motions present in the real case. The number of fictitious fragments used in our integrations for the nominal breakup model was 438, fixed by the lower limit (20 km) in the diameter of the fragments included in our computations. The numerical integrations, over a time span of 5000 years ($\approx 10^5$ revolutions), were performed with a modified version of the RADAU15 code developed by Everhart (1974). Note that this program is suitable for orbits undergoing close encounters and strong perturbations, owing to its automated step-size control, and for this reason it has been widely used in the last two decades to study the chaotic orbits of comets and planet-crossing asteroids. We modified the integration code by adding a subroutine which detects and records the collisions of fragments with Titan. This is not trivial, as the discrete time steps require an interpolation algorithm to find out whether the numerically integrated orbit intersects a sphere corresponding to the real size of Titan. Cubic splines were used to interpolate the relative fragment-Titan position during each close encounter (that is, whenever the relative distance was less than twice the radius of the gravitational sphere of influence of Titan, about 9×10^4 km). Then the minimum distance between the two bodies, computed by interpolation, was compared to the radius of Titan to check whether a collision had occurred. If so, the impact velocity on the surface of Titan was determined by conservation of energy. A number of tests showed that this procedure is fairly accurate in handling even the low-velocity encounters, which often result into strongly non-hyperbolic titanocentric trajectories and even into temporary captures of the fragments about Titan (yielding impact velocities somewhat smaller than Titan's escape velocity).

We performed several different integrations, corresponding to variations of the nominal breakup model and of the initial position of the fragments along proto-Hyperion's orbit (assumed to coincide with the current orbit of Hyperion). The main conclusions obtained from these simulations can be summarized as follows:

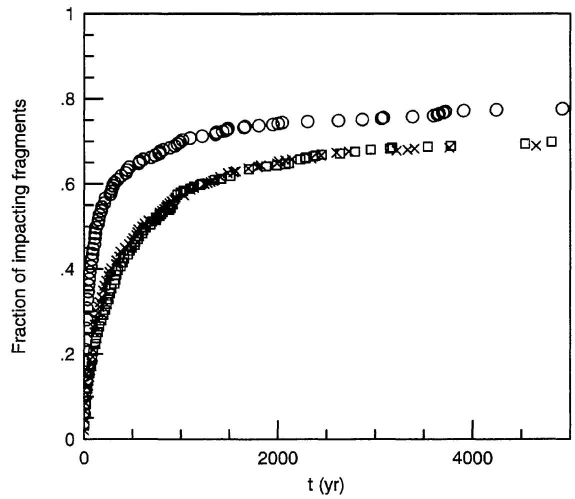

FIG. 1. The cumulative percentage of proto–Hyperion fragments having hit Titan versus time for three numerical integrations, with proto–Hyperion at three different positions in its orbit at the instant of breakup (mean anomaly 0°, 90°, and 180°, corresponding to circles, squares, and crosses, respectively). Fragments starting near pericentre hit Titan sooner and in a somewhat larger percentage.

TABLE 1. Statistics of the eventual fates of proto–Hyperion fragments in three numerical integrations corresponding to the same fragmentation model, but with three different mean anomalies of the parent body at the instant of breakup (M_0). The second to sixth columns give the percentages of fragments which at the end of the 5000–yr integration time span are still locked in a mean–motion resonance, have collided with Titan, have been ejected on a hyperbolic Saturnocentric orbit, have high–eccentricity orbits reaching at pericentre the orbital radius of Rhea and at apocentre the orbital radius of Iapetus. For the Titan–hitting fragments, the last two columns give the average collision velocity ($\langle V\rangle$) and the observed collision velocity range.

M_0 (deg)	% res.	% imp.	% esc.	% Rhea	% Iap.	$\langle V\rangle$ (km/s)	V range (km/s)
0°	7.7	77.6	0.2	0.2	10.0	2.69	2.58–3.10
90°	8.7	69.9	2.7	2.7	9.8	2.95	2.60–3.52
180°	3.7	68.9	2.3	1.8	12.0	2.94	2.58–3.63

(1) The time span over which a significant collisional flux affects Titan ranges from a few hundred to a few thousand years (see Fig. 1). After this time, almost all the surviving fragments are either locked into stable mean–motion resonances with Titan (1:1, 2:3, 3:4, and 3:5), or have escaped from Saturn's system (see Table 1 and Fig. 2). The eventual fate of the surviving resonant fragments is uncertain: they may have been later reaccreted by Hyperion, or have left the resonance locking to hit Titan, or—an intriguing possibility—they may still be there without having been detected so far owing to their small size.

(2) The percentage of proto–Hyperion fragments eventually hitting Titan ranges from about 70% to 80%, mainly

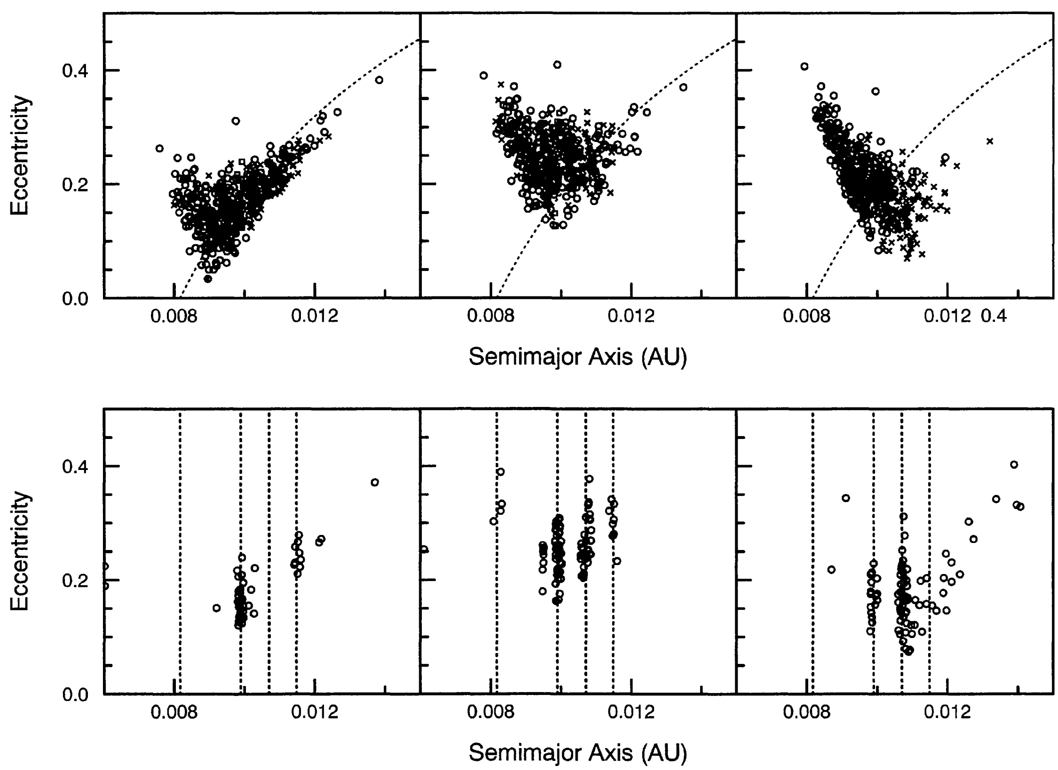

FIG. 2. The upper plots show the initial distributions of proto–Hyperion fragments in the orbital eccentricity versus semimajor axis plane for the three different numerical integrations (proto–Hyperion's mean anomaly 0°, 90°, and 180° from left to right). The dashed curves correspond to orbits tangent to that of Titan at pericentre. Crosses correspond to orbits of bodies surviving over the 5000 yr integration time span, circles to orbits hitting Titan. The lower plots show the corresponding orbital parameters of the remaining fragments after 5000 years, with the vertical dashed lines corresponding to mean–motion resonances with Titan (1:1, 3:4, 2:3, and 3:5 from left to right). Note that most of the surviving fragments are ''protected'' by a resonance locking from encounters and collisions with Titan.

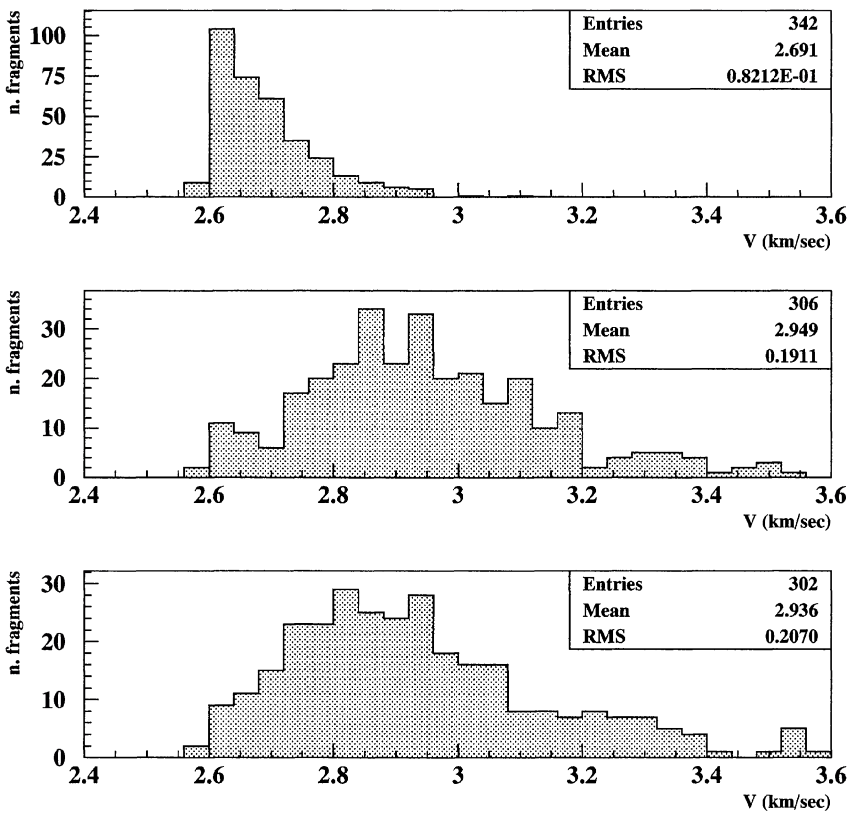

FIG. 3. Distributions of the impact velocity on Titan in the three cases illustrated in Figs. 1 and 2. In most cases the impact velocity is in the range from 2.6 to 3.2 km/s, well below the threshold corresponding to collisional erosion of an existing atmosphere. Note that when the fragments start near pericentre (upper plot) they tend to hit Titan soon (see Fig. 1) and from nearly-tangent orbits corresponding to relatively low impact speeds, whereas in the other two cases the fragment orbits are "randomized" by repeated encounters before hitting, and therefore yield higher typical impact velocities.

depending on the position of the target along its orbit at the time of breakup (Table 1, Figs. 1 and 2). The largest projectiles were bodies exceeding 100 km in diameter, and therefore must have formed large impact basins onto Titan's surface.

(3) Impact velocities range from 2.6 km/s (slightly less than Titan's escape velocity) to about 3.6 km/s (Table 1), with a somewhat asymmetric distribution (Fig. 3). Impact velocities exceeding 4 km/s were never observed.

(4) The fraction of fragments escaping onto hyperbolic Saturnocentric orbits is typically a few percent. We did not try to record collisions with the other satellites, but from their cross-section ratio to Titan's it is easy to estimate that the corresponding percentages were $<1\%$, in agreement with the results reported by Farinella *et al.* (1990).

(5) The statistical results listed above are not sensitive to the detailed initial conditions of the fragments (apart from the initial position of proto-Hyperion along its orbit), nor to the starting time step of the integration. Of course, the orbits of individual fragments are typically very chaotic, and this may have resulted into a strongly stochastic collisional flux onto Titan if the distribution of fragment masses was such that the largest bodies accounted for most of the total mass.

5. COLLISIONAL EVOLUTION OF TITAN'S ATMOSPHERE

Which were the consequences of this short but intense impact flux onto Titan? Collisions may have either an accretionary or an erosive influence on the atmosphere of the target body (Cameron 1983; Melosh & Vickery 1989; Zahnle *et al.* 1992). A collision is erosive—that is, the atmospheric mass blown away is larger than the projectile's mass—if: (i) the impact velocity exceeds a minimum threshold depending on the material, in the case of Titan ≈ 7 and 11 km/s for icy and silicate projectiles, respectively; and (ii) the projectile's mass exceeds a significant fraction of the total mass of the atmosphere. According to our results, the former condition was never fulfilled for proto-Hyperion fragments hitting Titan, so the corresponding collisions always built up the atmosphere rather than eroding it away.

To estimate the influx of volatiles into Titan's atmosphere, one should know the mass and composition of the impactors, and also model the complex chemistry that follows impact. We note that the relatively low impact velocities derived above for the colliding fragments are somewhat less than the minimum value required to completely vaporize the impactors, for the simple reason that the heat of vaporization of water ice (3×10^{10} erg/g) is of the same order as the specific kinetic energy of the projectiles (see Zahnle *et al.* 1992, Eq. (56) and Fig. 7). On the other hand, in such collisions the shock of impact typically vaporizes also a mass of target material comparable to that of the impactor itself (Melosh & Vickery 1989). To derive an order-of-magnitude estimate, we shall follow the previous workers quoted above in simply assuming that the amount of volatiles supplied to the atmosphere coincided with the mass of the impactors, and that the corresponding nitrogen content was entirely converted into atmospheric N_2.

Of course, the total mass of proto-Hyperion—hence, of its fragments hitting Titan—is unknown. A plausible lower bound, close to that used in our nominal breakup simulation, can be derived by assuming that the disrupted body had a nearly-spherical shape of diameter equal to the longest axis of the current Hyperion, about 350 km (Thomas *et al.* 1995). This yields about twice the mass of the current Hyperion (1.5×10^{22} g for a mean density of 1.5 g/cm^3). An upper bound is probably the mass of a satellite as big as some of the other icy satellites of Saturn, such as Rhea or Iapetus, and this is several tens of Hyperion masses. Thus we can conclude that a total fragment mass between $\approx 10^{22}$ and several times 10^{23} g did hit Titan. This should be compared to the mass of Titan's atmosphere, about 9×10^{21} g. The abundance of nitrogen—the dominant constituent of Titan's atmosphere—in typical icy Solar System materials (including those forming the nuclei of comets) does not exceed a few percent (Owen & Bar-Nun 1995), so the above estimates imply that the entire atmosphere may have been generated by proto-Hyperion impacts only if the original mass was close to the upper limit given above. Otherwise, collisions by proto-Hyperion fragments may have chemically reprocessed a pre-existing ammonia-rich atmosphere, producing large amounts of N_2 by shock-induced effects (Jones & Lewis 1987).

The scenario described above does not exclude other, more complex sequences of events. For instance, an impact origin for Titan's atmosphere has been recently proposed also by Griffith & Zahnle (1995), but these authors considered comets as the main source of impactors onto Titan. As typical comet impact velocities are ≈ 10 km/s, such collisions are often erosive, and the eventual outcome of the process cannot be predicted with certainty. Also, comets did hit the Galilean satellites at a somewhat higher average speed than Titan, but it is not straightforward to explain why Ganymede and Callisto did not accrete an atmosphere too. Even if the cometary influx of volatiles had been responsible for the formation of Titan's atmosphere, the results reported above show that such a primordial atmosphere was probably reprocessed to a great extent by the proto-Hyperion "impact shower."

The surface morphology of Titan is still little known, due to the opaque atmospheric haze. However, recent observations suggest that it is heterogeneous, with highlands and/or disconnected liquid seas (or lakes) of methane and ethane (Lorenz 1993; Griffith 1993; Smith *et al.* 1996). If such seas do exist, they may have filled a number of giant impact basins. Since the largest proto-Hyperion fragments were probably 50–100 km in diameter, they may well have produced lunar-type *maria* several hundred km across (with the name *maria* more closely resembling reality in this case!). Hopefully, the forthcoming *Cassini/Huygens* mission will lead to a better knowledge of Titan's surface and atmosphere in the next decade, and the scenario described here will be tested against actual data.

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