Influx of cometary volatiles to planetary moons: The atmospheres of 1000 possible Titans

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Abstract. We use a Monte Carlo model to simulate impact histories of possible Titans, Callistos, and Ganymedes. Comets create or erode satellite atmospheres, depending on their mass and velocity distributions: faster and bigger comets remove atmospheres; slower or smaller comets supply them. Mass distributions and the minimum total mass of comets passing through the Saturn system were derived from the crater records of Rhea and Iapetus. These were then scaled to give a minimum impact history for Titan. From this cometary population, of 1000 initially airless Titans, 16% acquired atmospheres larger than Titan's present atmosphere (9 × 10^{21} g), and more than half accumulated atmospheres larger than 10^{21} g. In contrast to the work of Zahnle et al. (1992), we find that, in most trials, Callisto acquires comet-based atmospheres. Atmospheres acquired by Callisto and, especially, Ganymede are sensitive to assumptions regarding energy partitioning into the ejecta plume. If we assume that only the normal velocity component heats the plume, the majority of Ganymedes and half of the Callistos accreted atmospheres smaller than 10^{20} g. If all the impactor's velocity heats the plume, Callisto's most likely atmosphere is 10^{17} g and Ganymede's is negligible. The true cometary flux was most likely larger than that derived from crater records, which raises the probability that Titan, Ganymede, and Callisto acquired substantial atmospheres. However, other loss processes (e.g., sputtering by ions swept up by the planetary magnetic field, solar UV photolysis of hydrocarbons) are potentially capable of eliminating small atmospheres over the age of the solar system. The dark material on Callisto's surface may be a remnant of an earlier, now vanished atmosphere.

1. Introduction

Saturn's largest satellite, Titan, the only moon with a thick atmosphere, is shrouded in 1 bar of N₂, CH₄ (0.1 bar), and the organic by-products of CH₄ photolysis [Broadfoot et al., 1981; Lindal et al., 1983; Lellouch et al., 1989]. Jupiter's satellites, Ganymede and Callisto, have essentially the same density and mass as Titan (Table 1), yet no atmospheres. Titan's existence presents two immediate questions. Where did its volatiles come from? Why don't the apparently similar Jovian satellites have atmospheres?

Two sources of volatiles are plausible: planetesimals that condensed within a Saturnian subnebula and eventually accreted to form Titan, and comets that condensed outside the Saturnian subnebula. These sources are expected to have been chemically and isotopically distinct [Owen, 1987; Owen and Gautier, 1989; Prinn and Fegley, 1989]. Comets are usually envisioned as directly condensing out of the solar nebula. Cometary carbon appears concentrated in the form of heavy organics, CO and CO₂, with only a small fraction as CH₄. (See Pollack et al. [1994] and Jessberger et al. [1989] for reviews on the composition of comets.) Cometary nitrogen may exist in both molecular form and in complex organic molecules. In contrast, the subnebula is, by definition, a region of higher temperatures and H₂ densities. Methane and ammonia are expected to have been the dominant C and N molecules in subnebular ices [Prinn and Fegley, 1989].

If Titan's atmosphere were supplied by comets, the N₂ may have come from a breakdown of complex organic material during impact. Deriving methane from comets is more problematical. Shocked comets, if water-rich, would have generated mostly CO and CO₂, although a dessicated comet when shocked might leave methane. If the atmosphere came from subnebula ices, CH₄ may have been supplied directly in the ices, and the NH₃ hydrate may have been shock heated during
accretion to form $N_2$ [Jones and Lewis, 1987; McKay et al., 1988]. UV-photolysis is another process that converts $NH_3$ into $N_2$ [Atreya et al., 1977]. Since $NH_3$ absorbs strongly throughout the infrared, its presence on a young Titan could have heated the lower atmosphere and surface dramatically and so altered the course of its evolution.

Titan's methane favors the subnebula model. However, cometary impacts are inevitable, capable of providing an atmosphere or chemically reprocessing an indigenous atmosphere. The D/H ratio in Titan's atmosphere favors an exogenous atmosphere. In the subnebula, where quench temperatures of ~800 K are predicted [Prinn and Fegley, 1989], the D/H ratio is expected to be cosmic. Instead, Titan's D/H ratio (~50 times larger) is enhanced like that of the Earth (~8 times larger), Mars (~45 times larger), carbonaceous comets and P/Halley (~15 times larger) [Geiss and Reeves, 1981; Owen et al., 1986; Owen et al., 1988; de Bergh et al., 1989; Coustenis et al., 1989; Balsiger et al., 1995; Eberhardt et al. 1995].

Comets can also erode atmospheres if they strike a planet with high enough energies [Melosh and Vickery, 1989]. Zahnle et al. [1992] suggested that cometary impact alone can explain both why Titan has an atmosphere and why Ganymede and Callisto have none. They argued that there are three important parameters that determine whether a satellite or planet acquires an atmosphere from impacts. Two of these, the volatile content of the impactors and the mass distribution of the impactors, are in all likelihood the same for cometary bombardment of Titan, Ganymede, and Callisto. The third is the probability that an individual impactor strikes slowly enough that its volatiles are accreted rather than lost. Zahnle et al. denoted the fraction of slow-moving impactors as $F_X$ (a notation we reintroduce here in order to facilitate comparison). The fraction $F_X$ depends on how the impact velocity compares to the escape velocity. As Ganymede, Titan, and Callisto have essentially the same escape velocity, the key difference between the three satellites is that impact velocities are larger on the Galilean satellites than on Titan. Systematically lower impact velocities on Titan allowed it to acquire an atmosphere while Ganymede and Callisto remained airless. The total incident mass remained a variable in these models; it determined the mass of the atmosphere that formed on Titan.

The calculations of Zahnle et al. [1992] approximate accretion, an inherently stochastic process, by continuous functions, where an atmosphere evolves in infinitesimal jumps. Yet real accretion proceeds by large discrete jumps. This is particularly important because the crater records on Rhea and Iapetus indicate that a large fraction of the cometary mass resides in the largest impactors (section 2). A second, related aspect of Zahnle et al.'s approach is that accretion is orderly. The time ordering of the largest impactors occurs by mass, with the largest bodies implicitly assumed to impact first. The contingent relationship between the stability of an atmosphere (through its mass) and the erosive effect of an impactor is effectively excluded. Zahnle et al. [1992] argued that if impact erosion gained an upper hand it would inevitably strip a planet or satellite of its atmosphere. Their formulation could not address the possibility that a single "late" large impactor can supply more air than all subsequent impacts could remove.

This study stresses the contingent relationship between a satellite's impact history and its final atmosphere. We simulate, using Monte Carlo techniques, 1000 impact histories for each satellite. From the results we deduce probabilities that a satellite acquires an atmosphere. These simulations allow us to treat large discrete impacts in a very natural way, and there is no artificial temporal order. We find that this is particularly significant when evaluating whether Ganymede and Callisto acquire atmospheres.

For each moon, we specify the mass and velocity distributions of the impactors. Parameters for each impact are chosen randomly from these distributions. The total mass of impactors that bombarded the Jovian and Saturnian systems is unknown; we use cratering records of other Saturnian moons to constrain the mass distribution and to derive a lower limit for the total mass. Because the simulations are stochastic it can often happen that in one history a satellite accretes a great deal more material than in another. Impact velocity distributions are derived from the dynamical models of Zahnle et al. [1992]. We ask the following questions: what is the chance that an initially airless Titan will acquire a comet-based atmosphere? How stable are atmospheres to impact erosion?

### 2. A Lower Limit for the Cometary Influx to Titan

Craters preserve the only record of the amount of rubble that visited the ancient satellite systems. The record is far from complete. Comets probably traveled to the Saturnian system in several stages, with many of the earliest arrivals unrecorded. Early bodies may have been captured by gas drag of the saturnian subnebula into planetocentric orbits and eventually accreted to form the satellites. Comets that remained in heliocentric orbits could have hit satellites before the moon's

### Table 1. Large Galilean and Saturnian Satellites

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Callisto</th>
<th>Ganymede</th>
<th>Titan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass, $10^{26}$ g</td>
<td>1.08</td>
<td>1.48</td>
<td>1.35</td>
</tr>
<tr>
<td>Radius, km</td>
<td>2400</td>
<td>2631</td>
<td>2575</td>
</tr>
<tr>
<td>$r$, km</td>
<td>$1.9 \times 10^6$</td>
<td>$1.1 \times 10^6$</td>
<td>$1.2 \times 10^6$</td>
</tr>
<tr>
<td>$v_{esc}$, km s$^{-1}$</td>
<td>2.45</td>
<td>2.74</td>
<td>2.64</td>
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<tr>
<td>$v_{esc}$, km s$^{-1}$</td>
<td>8.19</td>
<td>10.88</td>
<td>5.57</td>
</tr>
<tr>
<td>($v_{imp}$) (UN)$^b$</td>
<td>16.3</td>
<td>20.6</td>
<td>11.1</td>
</tr>
<tr>
<td>($v_{imp}$) (KB)$^b$</td>
<td>16.6</td>
<td>20.7</td>
<td>11.3</td>
</tr>
<tr>
<td>($v_{imp}$) (Oort)$^b$</td>
<td>26.0</td>
<td>27.5</td>
<td>19.1</td>
</tr>
<tr>
<td>$B$, Field, G</td>
<td>$2.3 \times 10^{-4}$</td>
<td>$1.3 \times 10^{-5}$</td>
<td>$2.6 \times 10^{-5}$</td>
</tr>
</tbody>
</table>

$^a$Orbital semimajor axis.

$^b$UN, Uranus-Neptune; KB, Kuiper Belt. Values from Zahnle et al. [1992].
last resurfacing events. In addition, the craters of early impactors could have been erased by later comets. Only the latest arrivals left records of their failure to pass through the Saturnian system.

The cratering record of Titan is presently unavailable. Titan’s thick atmosphere has so far prevented high-resolution imaging of its surface. In addition, up to 1 km of organic sediments may blanket Titan’s surface and bury ancient craters [Yung et al., 1984; Lunine et al., 1983; Sugar and Thompson, 1984]. We therefore use the crater records of Rhea and Iapetus to estimate a lower limit for the cometary volatiles that impacted Titan.

This study assumes that since planetocentric debris have short lifetimes ($10^{6}$-$10^{7}$ and $10^{3}$-$10^{4}$ years at Iapetus’ and Rhea’s orbital distances, respectively), extant craters were formed mostly by comets. Some small craters on Rhea could have formed from fragments of a catastrophic breakup of Hyperion [Farinella et al., 1990]. These smaller craters, however, do not affect the present analysis. (Section 2.6 discusses these points in more detail.) Based on the assumption that comets form the large craters, we determine, from the crater records of Rhea and Iapetus, a lower limit to the cometary mass that impacted Titan. It is a lower limit because it includes only the comets that hit after the last resurfacing events on these satellites, or those that struck after saturation was reached. We derive the minimum mass ($M$) that impacted Titan by summing the mass of comets that provided Rhea or Iapetus’ craters and scaling this sum to take into account the different impact probabilities on Rhea, Iapetus, and Titan:

$$M = 4\pi R^2 \times F_T \times \int m(D) \frac{dN(>D)}{dD} dD.$$  (1)

Here, $F_T$ is the ratio of the impact probability on Titan with respect to that on Rhea or Iapetus; $m(D)$ is the mass of the impactor that leaves a crater of diameter $D$; $N(>D)$ is the cumulative number of craters larger than diameter $D$ per surface area ($\text{km}^2$); and $R$ is Titan’s radius. The cometary composition, and the terms $N(>D)$, $m(D)$, and $F_T$ are discussed in the following sections.

2.1. Cratering Records of Rhea and Iapetus as Seen by Voyager 1

Voyager 1 imaged Rhea at spatial resolutions as high as 0.75 to 1.1 km/pixel, better than that of any of the other Saturnian satellites [Smith et al., 1981, 1982]. These high-resolution images cover only 19% of Rhea’s disk and were taken at only one lighting geometry. Iapetus was not imaged as well as Rhea. The highest resolution of the Iapetus images are 8.8 km/pixel. These covered 14% of Iapetus’ disk.

The impact records on the surfaces of Rhea and Iapetus were initially analyzed by Smith et al. [1981, 1982], in more detail by Plescia and Boyce [1982, 1983, 1985] and most recently by Lissauer et al. [1988] and Farinella et al. [1990]. Smith et al. found that the distribution of craters larger than ~20 km differed from the distribution of craters smaller than ~20 km (Figure 1). This discrepancy and the distribution of craters on the resurfaced areas of Enceladus, Tethys, and Dione [Farinella et al., 1990; Smith et al., 1981, 1982; Plescia and Boyce, 1982, 1983; Strom, 1987] suggest that the Saturnian system was bombarded by two distinct populations of impactors. The small craters are inferred to be formed from a younger population and may contain contributions due to fragments from a catastrophic breakup of Hyperion [Farinella et al., 1990]. The larger (Pop.1) craters may date to the early bombardment period. In addition, Plescia and Boyce noted that the crater density varied significantly across Rhea’s disk. They proposed several resurfacing processes to explain the nonuniformity of the large craters and, in other places, the low density of small craters.

Lissauer et al. [1988] challenged the evidence for resurfacing and for two crater populations. They found a strong correlation between the density of visible craters and the quality of lighting. The latter was quantified by a function of the incidence ($i$) and emission ($e$) angles, $\tan i \cos e$, which is proportional to the shadowed area. Lissauer et al. concluded that it was unnecessary to invoke resurfacing to explain the variation in the density of the small craters. They argued, in addition, that the nonuniform distribution of large craters did not require viscous relaxation. Instead, the inhomogeneous distribution of large craters was interpreted as the random placement of a small number of events. Lissauer et al. therefore suggested that the lack of uniformity for craters of $D > 64$ km indicates that saturation of Rhea’s present surface has not yet been reached. In contrast, the spatial distribution of craters smaller than 32-km diameter is nearly uniform, indicating that the crater distribution was approaching saturation. Lissauer et al. suggested that the deviation of the small craters from the large crater production curves (Figure 1) could be a result of saturation. Consistent with this interpretation, only the large craters reflect the production function, and Rhea provides little if any information about the distribution of small impactors.

2.2. Production Function

This study does not attempt to interpret further the distribution of crater populations on the Saturnian satellites. For simplicity, we consider two distributions. Our nominal distributions are the least squares fits calculated by Lissauer et al. [1988] for craters of $D > 64$ km (Figure 1). For Rhea and Iapetus, these are

$$\log_{10} N_R(>D) = -2.73 \log_{10} D - 0.064$$  (2)

and

$$\log_{10} N_I(>D) = -2.70 \log_{10} D + 0.109$$  (3)

respectively, where the crater diameter $D$ is in kilometers and $N$ is in craters $\text{km}^{-2}$. Since Lissauer et al. found no evidence of resurfacing, they simply counted the craters in the best illuminated areas of Rhea’s disk and extrapolated a crater size distribution for the entire
Figure 1. The crater distributions on (a) Rhea and (b) Iapetus' surfaces. \( N(>D) \) is the cumulative number of craters per unit surface area (km\(^2\)) larger than crater diameter \( D \). Lissauer et al. [1988] counted 17 craters on Rhea and 16 craters on Iapetus that were larger than 64 km. For craters larger than 32 km, a total of 93 and 56 were counted on Rhea and Iapetus, respectively. Error bars are based on \( n^{-1/2} \) where \( n \) is number of craters counted that are greater than each diameter. Figure from Lissauer et al. [1988]. The dashed line indicates Lissauer's least squares fit to the data, equations (2) and (3) in the text.

2.3. Crater Scaling

An expression for the total mass that impacted the satellites' surfaces requires a relationship between the crater diameter \( (D) \) and the impactor mass \( (m) \). Recent experiments by Schmidt and Housen [1987] make use of a centrifuge to perform cratering experiments at elevated gravity. The results of these experiments can be scaled to much larger impactors for simple materials (substances whose properties are neither scale nor rate dependent). To a first approximation, we assume that the surfaces of Rhea and Iapetus behave like simple materials. For crater diameters larger than 1 km on Rhea and Iapetus, most of the energy goes into excavating material instead of overcoming material strength; the strength of the target and impactor are only of secondary importance in the formation of the crater [Chapman and McKinnon, 1986]. In this case, the strength of cohesion can be ignored, and the parameters that determine the crater diameter are the gravitational acceleration \( g \), the densities of the impactor and target (\( \delta \) and \( \rho \)), and the radius (\( a \)) and impact velocity (\( v \)) of the impactor. Scaling rules have been determined empirically for impacts in water, wet and dry sand [Schmidt and Housen, 1987]. The scaling law in the gravity scaling regime is written as

\[
\frac{D}{2} \left( \frac{\rho}{m} \right)^{1/3} = A(3.22ga^{-2})^\alpha
\]

The constants \( A \) and \( \alpha \) are determined empirically for each material. Wet sand is probably a better analog to Rhea's and Iapetus' surfaces than dry sand or water, since satellite surfaces are not porous (unlike dry sand) and have friction (unlike water). When material strength can be ignored, all nonporous materials exhibit the same power law dependence in (4), \( \alpha = 0.22 \pm 0.01 \) [Schmidt and Housen, 1987]. The friction of the material enters into the constant of proportionality, \( A \). If the target material is fluidized, the internal friction declines. In this case the constant of proportionality could approach that of water. \( A \) has been measured to be 0.8 for wet sand and 0.94 for water [Schmidt and Housen, 1987].

We rearrange (4) for an expression for the mass of the impactor that forms a crater of diameter \( D \):

\[
m = 0.3\rho^{1.28}g^{0.846}u^{-1.692}D^{3.846}
\]
Table 2. Input Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Rhea</th>
<th>Titan</th>
<th>Iapetus</th>
</tr>
</thead>
<tbody>
<tr>
<td>FT</td>
<td>0.8</td>
<td>1</td>
<td>1.3</td>
</tr>
<tr>
<td>(g), km s(^{-2})</td>
<td>(2.9 \times 10^{-4})</td>
<td>(1.4 \times 10^{-3})</td>
<td>(2.4 \times 10^{-4})</td>
</tr>
<tr>
<td>(r), km(^{b})</td>
<td>(5.27 \times 10^{5})</td>
<td>(1.22 \times 10^{6})</td>
<td>(3.56 \times 10^{6})</td>
</tr>
<tr>
<td>(v_{\text{sat}}), km s(^{-1})</td>
<td>8.5</td>
<td>5.6</td>
<td>3.3</td>
</tr>
<tr>
<td>(v_{\text{esc}}), km s(^{-1})</td>
<td>0.66</td>
<td>2.6</td>
<td>0.59</td>
</tr>
<tr>
<td>((v_{\text{esc}})) (UN)</td>
<td>4.8</td>
<td>4.8</td>
<td>4.8</td>
</tr>
<tr>
<td>((v_{\text{esc}})) (KB)</td>
<td>5.3</td>
<td>5.3</td>
<td>5.3</td>
</tr>
<tr>
<td>((v_{\text{esc}})) (Oort)</td>
<td>16</td>
<td>16</td>
<td>16</td>
</tr>
<tr>
<td>((v_{\text{imp}})) (UN)</td>
<td>16</td>
<td>11</td>
<td>7.4</td>
</tr>
<tr>
<td>((v_{\text{imp}})) (KB)</td>
<td>16</td>
<td>11</td>
<td>7.7</td>
</tr>
<tr>
<td>((v_{\text{imp}})) (Oort)</td>
<td>22</td>
<td>19</td>
<td>17</td>
</tr>
</tbody>
</table>

\(^{a}\)Ratio of the impact rate on Titan to that on Rhea or Iapetus.
\(^{b}\)Orbital semimajor axis.

Several processes enlarge craters, which would cause the scaling of (6) to overestimate the cometary masses. Floor uplift modifies the crater width only slightly. More important for craters in rock is rim failure (slumping) that leads to a larger final crater diameter \(D_F\), which is related to the transient diameter \(D_T\) (\(D\) in (5) and (6)) by

\[ D_F = k D_T^{1.13} D_T^{1.13}. \]

Here \(D_c\) is the transition diameter between simple and complex craters (~5 km [Chapman and McKinnon, 1986]) and \(k\) is adjusted so that, at \(D_c\), \(D_F\) is 17.5% larger than \(D_T\) [McKinnon et al., 1991]. However, the depth/diameter ratio of craters formed on the icy satellites suggests that \(D_F \propto D_T\), consistent with (4) and (6) [Schenk, 1989; McKinnon et al., 1991]. Therefore we will ignore slumping. Note, however, that (7) does provide an upper limit to the amount of crater widening [McKinnon et al., 1991]. If we were to use (7), our lower limit to the mass influx (section 2.6) would be reduced by a factor of 3.

The impactor's mass, derived from the crater diameter, depends on velocity. To obtain impactors' masses, we assume that in Saturn's rest frame the cometaw flux is isotropic. The comet's kinetic energy per unit mass when it crosses the satellite's orbit is then \(\frac{1}{2}(v_{\text{sat}}^2 + 2v_{\text{esc}}^2)\), and the mean impact velocity \((v_{\text{imp}})\) can be approximated by:

\[ v_{\text{imp}} \approx v_{\infty}^2 + 3v_{\text{sat}}^2 + v_{\text{esc}}^2. \]

where \(v_{\text{sat}}\) is the orbital velocity of the satellite and \(v_{\text{esc}}\) is the surface escape speed from the satellite [Zahnle et al., 1992]. For Titan, Zahnle et al. [1992] calculated \((v_{\text{imp}}) = 11.1\) km/s for Uranus-Neptune (U-N) planetesimals and 11.3 km/s for Kuiper Belt comets. Thus \((v_{\text{imp}}) = 4.80\) km/s and 5.25 km/s respectively (Table 2, Figure 2). The median velocity expected of Öort

![Figure 2](https://example.com/figure2.png)

**Figure 2.** Cumulative impact velocities of (a) Uranus-Neptune planetesimals and (b) Oort comets on Ganymede, Callisto, and Titan. Impact velocities of Kuiper Belt comets are similar to U-N planetesimals. From Zahnle et al. [1992].
comets is higher, \(v_{\infty, Oort} = 16 \text{ km/s}\), since Oort comets are isotropic and inclined. Kuiper Belt and U-N objects are strongly prograde; therefore \(v_{\infty}\) is relatively small at Saturn; impact velocities are dominated by the satellite’s orbital velocity. The velocity of the impactor becomes important when considering whether volatiles are retained upon impact or whether cometary erosion of atmospheres is predominant (section 3).

2.4. Cratering Rates for Rhea, Iapetus and Titan

For isotropically distributed heliocentric comets, the impact rate \(n_{\text{sat}}\) varies among the Saturnian satellites as a result of the gravitational focusing by Saturn:

\[
n_{\text{sat}} \approx 1 + \frac{GM_s}{r v_{\infty}^2}, \tag{9}
\]

where \(M_s\) is Saturn’s mass and \(r\) is the distance from the satellite to Saturn [Moffett et al., 1983]. Processes of less importance include gravitational focusing by the satellite and interception of comets by Saturn [Lissauer et al., 1988]. Using the formalism of Lissauer et al., the cratering rate at Titan is a fraction \(F_T\) of that at Rhea and Iapetus, as shown in Table 2. The fraction \(F_T\) is defined equal to \(n_{\text{Titan}}/n_{\text{Rhea}}\) and \(n_{\text{Titan}}/n_{\text{Iapetus}}\) for Rhea and Iapetus, respectively.

2.5. Mass Spectrum of Impactors

The mass spectrum of the impactors is conveniently described by a power law,

\[
n(m) dm \propto m^{-q} dm, \tag{10}
\]

where \(q\) has a value on the order of 1.5-2.0. The term \(n(m)\) is defined by separating the total mass striking a planet into a velocity distribution, \(f(v)\), and the mass distribution of comets, \(n(m)\):

\[
M = \int f(v) dv \int m n(m) dm. \tag{11}
\]

This implicitly assumes the orbital distributions are the same, regardless of the impactor mass. This assumption is applicable only when one comet population is considered at a time, since different populations may have different typical velocities and masses.

Based on the crater distributions on both Rhea and Iapetus and the scaling relation for wet sand, we find that \(q = 1.7 \pm 0.1\). This is consistent with the extremely uncertain values obtained from studies of cometary magnitudes for short \((q \sim 1.5)\) and long period \((q \sim 1.7)\) comets [Hughes, 1988; Donnison, 1986]. Estimates from cometary observations depend on a derivation of the cometary mass from its luminosity, a relationship that is difficult to determine. A value of \(q = 1.54\) is derived from the lunar crater record using the Schmidt and Housen [1987] scaling law assuming slumping [Chyba, 1990], while the value derived without slumping is \(q = 1.47\) [Melosh and Vickery, 1989].

2.6. Cometary Mass Influx

We combine the production function \(N(> D)\), (2) and (3), crater scaling \(m_{R/J}/(6)\), and estimated impact velocities (Table 2) to determine the least total mass of comets that impacted Iapetus and Rhea:

\[
M = 5 \times 10^{17}[D_{\text{large}}^{1.15} - D_{\text{small}}^{1.15}] + 3 \times 10^9 D_{\text{large}}^{3.846} \tag{12a}
\]

\[
M = 1 \times 10^{17}[D_{\text{large}}^{1.12} - D_{\text{small}}^{1.12}] + 8 \times 10^9 D_{\text{large}}^{3.846} \tag{12b}
\]

respectively, where \(M\) is in grams and the diameter is in kilometers. Here we have integrated the mass influx (1) from the smallest impactor \(m(D_{\text{small}})\) to the largest impactor \(m(D_{\text{large}})\) that hit Iapetus and Rhea, respectively. The first term sums the mass of the impactors that produce craters of diameters \(D_{\text{small}} < D < D_{\text{large}}\). The second term adds the mass of the largest impactor, \(m(D_{\text{large}})\).

These impact records correspond to \(2 \times 10^{20}\) and \(10^{21}\) g of impacted comets for Rhea and Iapetus respectively, suggesting that more comets hit Iapetus than Rhea. There are several possible explanations for this discrepancy. For example, Iapetus’ surface might be older than Rhea’s. Alternatively, Iapetus might be recording the presence of planetocentric bodies. Since Iapetus is farther from Saturn than is Rhea, planetocentric debris survive longer at Iapetus’ distance, 10⁶-10⁷ years, than at Rhea’s distance, 10⁴ years [Horedt and Neukum, 1994]. Whether the bodies that impacted Iapetus were planetocentric or heliocentric could be resolved by examining the distribution of the craters across the satellite’s disk. Heliocentric bodies most likely impact the satellite at the leading point. The relative probabilities of impacting the leading or trailing points depend on the velocity of the impactors, the orbital velocity, and the escape speed of the satellite. For encounter speeds of 8 km s⁻¹ and 17 km s⁻¹ the ratio of the cometary flux at leading to trailing points is 11 and 3, respectively, for Iapetus (following the formalism of Shoemaker and Wolfe [1982]). Therefore, as long as no resurfacing processes depend on the distance from the leading point, craters from heliocentric impactors would appear distributed asymmetrically between the apex and antapex. The Cassini mission, by imaging the surfaces of Rhea and Iapetus at high spatial resolution, may improve determinations of the crater distributions on these satellites, and possibly establish regions of old surfaces with greater crater populations. The craters considered in such an observation must be those least likely to be saturated, having a more random distribution than uniform.

Another explanation for the great difference in the cometary mass that hit Rhea and Iapetus is suggested by direct quantitative comparison of Rhea’s and Iapetus’ crater distributions: they are extremely alike (Figure 1; equations (2) and (3)). It is only the lower impact velocities on Iapetus that causes us to deduce a larger mass of comets. In addition, Callisto’s crater record has a smaller density of large craters than does
Rhea's; however, differences in these records may be due to endogenic processes [McKinnon et al., 1991]. A similarity in crater records may be a result of achieving equilibrium. If the entire distribution is in equilibrium (including large craters), we may then be strongly underestimating the mass of the cometary influx.

Lower limits to the cometary mass that hit Titan are obtained by multiplying (12a) and (12b) (for Iapetus and Rhea, respectively) by the the relative cratering rates ($F_T$) and the square of the ratio of the satellite radii (Table 2):

$$M = 8 \times 10^{18} [D_{\text{large}}^{1.15} - D_{\text{small}}^{1.15}] + 3 \times 10^{10} D_{\text{large}}^{3.846}$$  \hspace{1cm} (13a)

$$M = 1 \times 10^{18} [D_{\text{large}}^{1.12} - D_{\text{small}}^{1.12}] + 8 \times 10^{9} D_{\text{large}}^{3.846}$$  \hspace{1cm} (13b)

The mass, $M$, depends strongly on the largest impactor (13). The diameter of the largest crater observed on Rhea so far is 355 km. Considering only impactors small enough that $D_{\text{Rhea}} < 355$ km, the mass that impacted Titan is estimated to be $10^{21}$ g. However, Titan is larger and therefore intercepted more and larger comets. A better upper limit for the impact crater size is that for which there is a 50% chance for the existence of a crater of diameter $> D_{\text{MAX}}$ on Titan's surface. We approximate $D_{\text{MAX}}$ by equating the number of craters with $D > D_{\text{MAX}}$ estimated for Titan's surface to 0.5:

$$0.5 = F_T \times N(D_{\text{MAX}}) \times 4\pi R^2.$$  \hspace{1cm} (14)

Extrapolating from Rhea's crater record, $D_{\text{MAX}} = 900$ km (Table 3). Using this new upper limit for the crater size (equivalently, the impactor size), a mass of $\sim 4 \times 10^{21}$ g impacted Titan. The equivalent total mass calculated from Iapetus' crater record is $\sim 6 \times 10^{22}$ g. This is shown in Table 3, along with the mass of cometary material that would be deposited in an impact with no chemical reprocessing (discussed in section 2.7). For comparison, the volatile contents of Titan's atmosphere and surface are given in Table 4. The largest impactor supplies roughly 50% of the total mass (Table 3). For a mass spectrum of $q = 1.7$, the ratio of the largest and second largest impactor masses to the mass spectrum is roughly 34% water ice, 31% rock, 23% nitrogen, 1% carbon, and 1% oxygen.

### Table 3. Cometary Influx of Volatiles to Titan

<table>
<thead>
<tr>
<th>Based on Cratering Record of</th>
<th>Rhea</th>
<th>Iapetus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total mass*, g</td>
<td>1.2 - $4.2 \times 10^{21}$</td>
<td>0.5 - $1.8 \times 10^{23}$</td>
</tr>
<tr>
<td>N mass*</td>
<td>0.5 - $1.7 \times 10^{20}$</td>
<td>2.0 - $7.3 \times 10^{21}$</td>
</tr>
<tr>
<td>CO mass*</td>
<td>1.1 - $3.8 \times 10^{19}$</td>
<td>0.5 - $1.6 \times 10^{22}$</td>
</tr>
<tr>
<td>CH$_4$ mass*</td>
<td>1.2 - $4.2 \times 10^{19}$</td>
<td>0.5 - $1.8 \times 10^{21}$</td>
</tr>
<tr>
<td>Total carbon*</td>
<td>2.8 - $9.7 \times 10^{20}$</td>
<td>1.1 - $4.2 \times 10^{22}$</td>
</tr>
<tr>
<td>Largest impactor:</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Crater diameter</td>
<td>900 km</td>
<td>1300 km</td>
</tr>
<tr>
<td>Total mass, %</td>
<td>48</td>
<td>53</td>
</tr>
</tbody>
</table>

*The uncertainty in scaling determines range of masses.

### Table 4. Titan’s Surface and Atmospheric Volatiles

<table>
<thead>
<tr>
<th></th>
<th>25% CH$_4$</th>
<th>65% CH$_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>N$_2$ atmospheric mass</td>
<td>$9.0 \times 10^{21}$</td>
<td>$9.0 \times 10^{21}$</td>
</tr>
<tr>
<td>+ ocean</td>
<td>$1.2 \times 10^{22}$</td>
<td>$1.8 \times 10^{22}$</td>
</tr>
<tr>
<td>CO atmospheric mass</td>
<td>$5.4 \times 10^{17}$</td>
<td>$5.4 \times 10^{17}$</td>
</tr>
<tr>
<td>+ ocean + surface deposits*</td>
<td>$2.7 \times 10^{20}$</td>
<td>$8.1 \times 10^{20}$</td>
</tr>
<tr>
<td>CH$_4$ atmospheric mass</td>
<td>$3.7 \times 10^{22}$</td>
<td>$5.8 \times 10^{22}$</td>
</tr>
</tbody>
</table>

Titan’s present methane abundance is uncertain. Therefore, two possible atmospheric and oceanic abundances are considered [Lunine and Risk, 1989]. N$_2$, CH$_4$, and CO abundances come from Lindal et al. [1983], Lellouch et al. [1989] and Marten et al. [1988].

2.7. Volatile Content in Comets

The influx of volatiles to Titan depends on the composition of the comets and the chemistry that follows impact. In a high-velocity collision, the shock of impact vaporizes the impactor and a comparable mass of the target material [Melosh and Vickery, 1989]. Fast chemical reactions in the hot vapor produce a suite of molecules that are favored by high temperatures. Cooling freezes the chemistry so that the characteristic high temperature species persist in the quenched gas [Zel'dovich and Raizer, 1967]. This process has been shown as a way of converting NH$_3$ into N$_2$ [McKay et al., 1988]. As a rule of thumb, strongly shocked oxygen-rich vapor (O/C) will produce CO, H$_2$O, and N$_2$, regardless of the form in which C, H, O, and N are supplied, while carbon-rich vapor (C>O>N) will produce CO, C$_2$H$_2$, HCN and more complicated unsaturated hydrocarbons and nitriles (i.e., tholins). In addition, Titan's atmosphere might have been chemically processed by a shower of as much as $10^{23}$ g of material coming from Hyperion's breakup [Farinella et al., 1990; P. Farinella and P. Paolicchi, manuscript in preparation, 1995]. We will explore the chemistry in more detail in a future paper. Here we address the more limited question of how much cometary nitrogen and carbon impacted Titan and were subsequently retained.

Based on the composition of Comet Halley [Jesselberger et al., 1989] and solar elemental abundances [Anders and Grevesse, 1989], Zahnle et al. construct a model of comets that is roughly 34% water ice, 31% rock, 23% CHON and 9% CO. CHONs are chemically complex molecules composed of carbon, hydrogen, oxygen, and...
nitrogen in the ratios $1 : 1 : 0.5 : 0.12$. In addition, if comets carry nitrogen in cosmic abundances, molecular nitrogen is predicted to be present at the percent level [Engel et al. 1990]. Methane has been possibly detected at the 3-sigma level with a CH$_4$/H$_2$O mixing ratio of 0.014-0.045 [Larson et al., 1989]. From these considerations, we assume 4% of the mass of the comet is made up of nitrogen; methane makes up 1%; and 23% of the cometary mass is made up of carbon in various molecular forms. Based on this cometary composition, the population of comets that caused Rhea's and Iapetus' craters impacted Titan with 20-60% of Titan's present atmospheric abundance of nitrogen (Table 3). In addition, these comets brought in up to 100 times Titan's present atmospheric inventory of carbon, which is close to the total amount of carbon needed to supply Titan with CH$_4$ over its lifetime (Tables 3 and 4).

### 2.8. Retention of Cometary Mass

The sum of the mass of cometary volatiles implied by Iapetus' crater record is very close to the mass of gases in Titan's present atmosphere. However, comets not only supply volatiles to planets and satellites; if they are big enough and fast enough, impacts can erode atmospheres. Melosh and Vickery [1989] suggest that if the vapor plume created upon impact exceeds the air mass above the horizon, and if the plume is hot enough to expand at velocities exceeding the escape velocity ($v_{esc}$), both the plume and the air it intercepts escape to space. Also lost are the atmospheres in the impactor itself. Note that Melosh and Vickery's criteria apply less to individual impacts than to the integration over a distribution of impactors spanning a range of impact velocities and a wide range of masses.

The fraction of an atmosphere above the horizon is $H/2R$, where $H$ is the scale height and $R$ the planet's radius. For Titan's present atmosphere, this is $3.5 \times 10^{19}$ g. The minimum impact velocity needed for escape is

$$v \cos \theta > \frac{2}{\sqrt{\eta}} \sqrt{v_{esc}^2 + 2H_{vap}}$$

(15)

where $H_{vap}$ is the vaporization energy and $\eta$ is the fraction of the total internal energy deposited in the shock that is available as thermal energy to drive the expansion of the vapor plume [Zahnle et al., 1992]. Equation (15) assumes that only the vertical component of the impact velocity contributes to the thermal energy of the ejecta plume; this is consistent with crater volumes measured in laboratory-scale impact experiments [see Figure 7.5; Melosh, 1989; Gault and Wedekind, 1979].

For wet sand, $\eta = 0.33$ [Zahnle et al., 1992], for which the critical velocity at normal incidence would be $\sim 12.6$ km/s or, if material condenses releasing $H_{vap}$ to heat the vapor plume, $\sim 9.4$ km/s. These velocities are below the mean impact velocities estimated for Oort cloud comets, suggesting that Oort comets should be highly erosive (Tables 1 and 2). However, the critical velocities are comparable to the median impact velocity of 11 km/s [Zahnle et al., 1992; Zahnle and Dones, 1993] expected for Uranus-Neptune or Kuiper Belt comets, making it unclear whether these slower comets would have supplied or eroded Titan's atmosphere.

### 3. The 1000 Titans

We investigate the balance between impact erosion and supply of atmospheres with a Monte Carlo program that simulates the bombardment history of a satellite as a random sequence of $\sim 10^8$ impacts. The total mass of comets is statistically determined from the cometary mass distribution such that there is a 50% chance that the largest body is greater than $(9.6 \times 10^{22}$ g, the mass of the largest impactor inferred from Iapetus' crater record, (13a) and (14). A single model consists of 1000 satellites built using the same cometary parameters. We then ask what percentage of these satellites lost atmospheres if they previously had any, and what percentage acquired atmospheres if they previously had none.

Most of the mass arrives in the largest impactors, although most of the impactors are small. To facilitate the analysis, we have weighted the mass of the small impactors so that we could use correspondingly fewer small impactors, consistent with the cometary distribution. This method is a computational short-cut only, which does not change the results. We proceeded by dividing the distribution into bins. The first bin of large impactors is not weighted and carries 4 orders of magnitude more mass than the other weighted bins of smaller impactors. This method insures that we integrate the distribution function to low enough masses to cover the distribution.

For each impact, the mass is picked randomly from the cometary mass distribution obtained from the crater records of Rhea and Iapetus (Figure 1). The impact velocity is chosen from one of two velocity distributions, the Oort and the Kuiper Belt comets (Figure 2). The latter is effectively equivalent to any low inclination distribution of short period comets. We assume a fixed volatile composition for the comets. The incidence angle $\theta$ is chosen randomly from the isotropic distribution. For comparison, we also show in Table 5 (Models 16-18) the results of models with $\theta$ fixed at normal incidence. In the latter case, the temperature of the plume is independent of the incidence angle, and all of the impactor's kinetic energy goes into heating the plume. The former case follows (15) where only the vertical component of the impactor's incident momentum heats the plume. In this case a greater percentage of grazing impacts contribute their volatiles to the atmosphere. Hence the former assumption leads to much thicker atmospheres than does the latter assumption. Our intention is that the two assumptions should bracket the plausible range of possibilities.

Each impact is tested to determine whether it supplies volatiles or erodes the atmosphere. Following Melosh and Vickery [1989], the impact is erosive if the impactor mass and velocity exceed the mass of the satellite's current atmosphere above the tangent plane and the critical velocity (15), respectively. If both these cri-
teria are met, the atmosphere above the tangent plane is expelled. We subtract the volatiles above the tangent plane from the atmosphere. If these criteria are not met, we add the mass of the cometary volatiles to the atmosphere.

4. Aftermath

4.1. The Formation of One Titan Atmosphere

The growth of an impact-generated atmosphere is illustrated by Plate 1a, which shows the histories of five arbitrarily selected simulations, two of which happen to develop Titan-like atmospheres. The different total masses accreted are a matter of chance; all five cases are equally consistent with the craters counted on Iapetus. Shown in the background are corresponding evolutionary trajectories calculated according to the method of Zahnle et al. for \( F_x = 0.44 \), the value derived for Titan using Kuiper Belt comets and (15) with isotropic \( \theta \).

Consider a specific example that is denoted with red open circles in Plate 1a; this Titan begins airless by assumption. It gains atmosphere steadily until a long series of fast \( 10^{14} \) g and \( 10^{16} \) g impactors cause a noticeable erosive event, visible as a kink in Plate 1a. Two slow and massive \( (\sim 10^{23} \) g) impactors are mostly responsible for this Titan accumulating a thick atmosphere. Most of the erosion is done by impactors near the lower mass threshold. Hence the role of chance is played mostly on the supply side.

The general behavior of these simulations is that all five Titans accumulate atmospheres. This is because impact velocities are slow enough that accumulation of cometary material is predominant; that is, the effective value of \( F_x (0.44) \) is much higher than the threshold value of \( F_x = 0.25 \) needed to accumulate an atmosphere from a population of impactors with \( q = 1.7 \) and volatile content 4%. (The threshold value is calculated from (47) by Zahnle et al.)

4.2. Formation of 1000 Atmospheres

The atmosphere that remains after cometary bombardment depends on the initial atmosphere, the velocity distribution of the impactors, and the total mass flux of the impactors. The balance of these effects becomes apparent when a statistically significant number of atmospheres are calculated. A list of models and relevant parameters is given in Table 5. Of 1000 initially airless Titans bombarded by an “Iapetus” flux of Kuiper Belt comets (model 2, Table 5; results shown in Plate 1b), over half (63%) acquire atmospheres 10% or larger than Titan’s present atmosphere, and 16% acquire atmospheres at least as massive as Titan’s present atmosphere. The wide spread in final and incident masses illustrates the enormous variance inherent in the power law distribution with \( q < 2 \). This uncertainty is larger than those introduced from, say, crater scaling.

The final atmosphere also depends on the partitioning of the impactors’ kinetic energy, uncertainties in the mass spectrum of the impactors, and their volatile content (Figure 3). We therefore choose conservative values for these parameters, unless otherwise stated, and leave them fixed throughout the study (Table 5).

A higher comet flux gives Titan-like Titans more often. For example, if the flux were 7 times greater than the lower limit implicit in the Iapetus crater record, over half of the Titans acquire atmospheres \( > 9 \times 10^{21} \) g (Figure 4). Note that amplifying the comet flux by 7 implicitly extrapolates the cometary mass distribution to include comets that are 7 times more massive; i.e., the largest objects inflate to roughly \( 2 \times 10^{22} \) g, according to (14) and subsequent discussion. Ancient comets this massive are plausible; comets as large as \( 10^{22} \) g exist today in Saturn-crossing orbits (e.g., Chiron), and Pluto has a mass of order \( 10^{25} \) g.

4.3. Formation of Atmospheres on Ganymede and Callisto

Impact velocities of comets are larger on the Jovian satellites than on Titan. This is a consequence of the higher orbital velocities of Ganymede and Callisto or, equivalently, Jupiter’s impressive gravity. Cometary impacts are therefore on average more erosive on the Jovian satellites [Zahnle et al., 1992]. The role of comets in the evolution of Ganymede and Callisto is investigated here by simply changing the impact velocities to those estimated for comets hitting the Jovian satellites (Figure 2), and making the small adjustments for Ganymede’s and Callisto’s different radii and masses. We assume for comparison that the Jovian satellites were subjected to the same mass flux of comets. Crater records on Callisto indicate, however, a slight paucity of very large craters compared to the records on Saturnian satellites, suggesting a different bombardment history for the Jovian satellites [McKinnon et al., 1991; Shoemaker et al., 1982; Passey and Shoemaker, 1982; Woronow and Strom, 1982; Chapman and McKinnon, 1986]. Alternatively, the crater records of Callisto and Rhea might be considered very similar, with differences explained by endogenic processes such as viscous relaxation on Callisto [McKinnon et al., 1991].

The evolution of 5 selected comet-based atmospheres on Callisto are shown in Plate 1c. This figure is directly comparable to Plate 1a depicting five Titans. Again, time increases to the right. Immature atmospheres of Callisto fluctuate more dramatically than Titan’s atmosphere. This is a result of the higher impact velocities on Callisto. Numerous, small impactors \( (\sim 10^{14} \) g), which were usually too slow to significantly affect Titan’s atmosphere, are erosive on Callisto.

These simulations are equivalent to the continuous calculations of Zahnle et al. where \( F_x = 0.20 \). The relatively high value of \( F_x \) compared to similar models presented by Zahnle et al. derives from the different way high angle (grazing) impacts are treated in the simulations presented in Plate 1. Here, the incidence angle is specified randomly from an isotropic distribution, and only the vertical component of the velocity contributes energy to heat the plume. By contrast, Zahnle et al.
Plate 1. The growth of (a) five atmospheres on Titan and (c) six atmospheres on Callisto from Monte Carlo simulations of bombardment by Kuiper Belt comets (models 2 and 7, Table 5). The x axis is the total mass of the cometary population minus that which already has impacted the satellite. Time goes to the right. At the end of the bombardment, this is zero. Yellow lines are solutions to the continuous formulation by Zahnle et al. [1992] for the comparable calculation ($F_X = 0.44$ for Titan, and $F_X = 0.20$ for Callisto). (b and d) The atmospheres acquired by 1000 initially airless Titans and Callistos impacted with Kuiper Belt comets. The total incoming mass was determined by the Iapetus population, (13a) and (14), where 50% of the simulations have an impactor larger than the $9.6 \times 10^{21}$ g.
neglected the effect of impact angle (i.e., all impacts are at normal incidence), and allow all the kinetic energy of the impactor to heat the plume. Table 5 (Models 16-18) provide results of normal incidence impacts that are equivalent to the calculations of Zahnle et al. [1992]. As discussed below, the mass of the post bombardment atmosphere is sensitive to the partitioning of the kinetic energy; smaller atmospheres result when a greater fraction of the initial energy is available to expand the plume.

Evolutionary tracks of Zahnle et al.’s model for \( F_x = 0.20 \) appear faintly in the background of Plate 1c as dashed yellow curves. An atmosphere above the upper solid yellow line is stable against impact erosion because there are not enough impactors left to remove it. An atmosphere below this line (in the continuous formulation) is doomed to disappear. The lower line is the equilibrium between impact erosion and impact supply. The effective value of \( F_x \) for these simulations (0.20) is slightly below the critical value of 0.25, above which Callisto is expected to accrete an atmosphere. Zahnle et al.’s evolutionary tracks for Callisto and Ganymede remain below this lower line (Plate 1c); these satellites end up airless.

Here we find that Callisto and Ganymede most often do acquire atmospheres (Plate 1d). Of the five Callistos shown in Plate 1c, the three satellites marked with solid lines all eventually ended with stable atmospheres; one is quite considerable. The two dashed Callistos are still in grave danger of ending with only a small atmosphere at the end of the simulation. The evolutionary tracks of these atmospheres appear at first to jitter along the equilibrium track. However, eventually one discrete large and slow impact can cause an atmosphere to cross the boundary between the erosive and accumulative regimes. The satellite has then acquired an atmosphere that is too massive for subsequent impacts to remove (Plate 1c). This possibility to “parachute” (upwards) from the erosive regime to the stable regime is briefly mentioned by Zahnle et al. [1992] but not pursued. We see here that parachuters are the norm rather than the exception. Evidently, accumulation is not very well approximated by continuous functions.

We do not see evolutionary tracks that parachute downwards from the accumulative to the erosive regime. This is because no single erosive event ever removes more than \( H/2R < 0.01 \) of the atmosphere. Impact erosion is the sum of many events. It is therefore well described by a continuous function.

The more numerous small impactors do not affect the accumulation of mass (if \( q < 2 \)), only the erosion of atmospheres. We estimate the effect of the uncertainty in the distribution of impactors by calculating models with a distribution that is depleted in the small impactors compared to our nominal distribution; it literally follows the kink in Rhea’s crater counts (Figure

---

### Table 5. Description of Monte Carlo Calculations

<table>
<thead>
<tr>
<th>Model</th>
<th>Mass Impact</th>
<th>Initial Atmosphere</th>
<th>Volatiles in Comets</th>
<th>Final Atmospheres</th>
<th>( F_x )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Iapetus</td>
<td>KB/Titan</td>
<td>0</td>
<td>2</td>
<td>9</td>
</tr>
<tr>
<td>2</td>
<td>Iapetus</td>
<td>KB/Titan</td>
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<td>16</td>
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<td>0</td>
<td>10</td>
<td>53</td>
</tr>
<tr>
<td>4</td>
<td>7 \times Iap</td>
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<td>0</td>
<td>4</td>
<td>5</td>
</tr>
<tr>
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<td>Iapetus</td>
<td>KB/Ganymede</td>
<td>0</td>
<td>4</td>
<td>5</td>
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<td>Iapetus</td>
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<td>9</td>
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</tr>
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<td>Iapetus</td>
<td>Oo/Titan</td>
<td>10^{21}</td>
<td>4</td>
<td>10</td>
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<tr>
<td>12</td>
<td>Iapetus</td>
<td>Oo/Titan</td>
<td>9\times10^{21}</td>
<td>4</td>
<td>100^{d}</td>
</tr>
<tr>
<td>13</td>
<td>Iapetus</td>
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<td>4</td>
<td>4</td>
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<tr>
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<td>9\times10^{21}</td>
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<td>15</td>
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<td>3</td>
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</table>

KB, Kuiper Belt; Oo, Oort; C, Callisto; G, Ganymede.

\( * \) Mass fluxes are derived from Iapetus’ crater record. The mass spectrum is specified by \( q = 1.7 \).

\( ^{b} \) Unless otherwise noted, \( \eta = 1 \).

\( ^{c} F_x \) = fraction of impactors that strike too slowly to erode atmospheres

\( ^{d} \) Final atmospheres > 5 \times 10^{21}.

\( ^{e} \) All the impactor’s kinetic energy contributes to heating the plume (\( \cos \theta = 1 \), from (15)).

\( ^{f} \) One third of the impactor’s kinetic energy heats the plume (\( \cos \theta = 1 \) and \( \eta = 0.33 \), from (15)).
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Figure 3. Final atmospheres of 1000 Titans that were impacted with Kuiper Belt comets. (a) Value of 4% refers to N$_2$ and effectively 10% refers to CO. The peak to the left of the diagram includes the Titans that are off the graph (models 2 and 3, Table 5). (b) Two values of $\eta$, the fraction of impact energy available to power the explosion (volatile abundances kept at 4%). (c) Two different cometary mass spectra power laws, $q$ (volatile abundance 4%, $\eta = 1$). In all calculations, Titan began with no initial atmosphere.

Figure 4. The 1000 Titans impacted with Kuiper Belt comets for two different cometary mass fluxes. The solid line corresponds to an incident mass calibrated to Iapetus. This provides a lower limit to the influx (model 2, Table 5). The dashed line corresponds to a mass influx that is 7 times the nominal value (model 4, Table 5).

1) Changing the distribution does not significantly affect results for Titan, where impact erosion is relatively unimportant. In addition, we find that most Callistos and Ganymedes are not strongly affected. The exception is the Ganymedes that accrued very thin atmospheres (< 10$^{19}$ g).

The sizes of the atmospheres most likely acquired by Ganymede and Callisto are sensitive to the way that the impactor’s kinetic energy is partitioned upon impact, which is not well constrained. We try to bracket the possibilities with two approaches. We calculate bombardment histories where only the vertical component of the impactor’s velocity contributes to heating the plume (Plate 1; Figures 3-5). Here, oblique events...
produce relatively cold, low-energy plumes. This approach yields results that are similar to the case where the total kinetic energy is available to heat the plume and \( \eta = \frac{3}{5} \), (15). For these cold plume calculations, Callisto and Ganymede acquire significant atmospheres from comets, although these atmospheres are generally smaller than that amassed by Titan (Plate 1d, Figure 5). The majority of the satellites bombarded by an "Iapetus-like" comet flux (50% of Callistos and 70% of Ganymedes) accreted atmospheres smaller than 1% of Titan's present atmosphere. Moreover, there is a small (5% and 7%) but finite probability that Callisto or Ganymede could have acquired a massive Titan-like atmosphere.

We also consider the possibility that all of the impactor's kinetic energy heats the plume. These hot plume simulations are more erosive, particularly for Ganymede and Callisto, and yield results for Ganymede that are radically different from those for Callisto. Most Ganymedes acquired insignificant atmospheres (< 10^{11} g). Most Callistos gained considerably more massive atmospheres, greater than 6 \times 10^{16} g, with the most probable atmospheres having a size of 10^{17} g (Figure 6).

Why do we not see thin atmospheres on Ganymede and particularly Callisto? There are processes other than impact erosion that can destabilize a thin atmosphere. The likeliest for Callisto and Ganymede are solar UV and Jupiter's magnetic field. UV photolysis is expected to convert methane into H2, which escapes, and complex refractory organics, which precipitate to the surface. This process depletes 10^{21} g of methane in 10^{8} years at Titan [Yung et al., 1984] and would be \( \sim 4 \) times faster for Callisto and Ganymede. The net effect is that an initially small CH4 inventory can be lost in a relatively short time, leaving behind a dark surface mantling that may or may not have mixed with the regolith. Callisto's dirty surface may be a remnant of a past atmosphere.

Magnetospheric electrons have been suggested as particularly potent at driving escape. Strobel et al. [1992] place an upper limit of 10^{25} atoms/s on nitrogen atom escape from Titan today, most of which is due to magnetospheric electrons. Over 4.5 b.y., this upper limit corresponds to 3 \times 10^{19} g, roughly 0.3% of its present N2. Callisto and Ganymede experience magnetic fields that are 10 to 50 times larger than Titan's, and thus magnetic fields may be more effective at sweeping away atmospheres on these Galilean satellites.

### 4.4. Where is the Carbon Monoxide?

P/Halley observations suggest a 10% mass fraction of CO in comets. Therefore, in addition to supplying nitrogen, comets are expected to have provided even greater quantities of CO. If we assume a 10% CO abundance, comets may have provided Ganymede and Callisto with as much as 10^{20.7} g of CO. The CO inventory acquired by Titan would be expected to be \( \sim 10 \) times higher (Figure 3). CO also is expected to form when any mixture of water and hydrocarbons is shocked to high temperature, as would happen during impacts.

The fate of CO is debatable. It would not be expected to survive if water were present in the atmosphere, since photochemistry would convert it to CO2. In Titan's present atmosphere, CO2 would have precipitated to the surface to form a veneer, possibly tens of meters thick. Micrometeorites have been suggested as a source of water [Samuelson et al., 1983]. In addition, (explored in a later paper) the energy released during accretion could have created massive steam atmospheres on young icy satellites. Titan's present tropopause has a CO/N2 mixing ratio of 6 \times 10^{-5} [Lutz et al., 1983]. Whether the CO is supplied continuously from reactions with H2O and methane-produced radicals or whether it constitutes our only evidence of a surface veneer of CO2 is unclear.

Infrared observations of the Galilean and Saturnian satellites [Clark et al., 1986; Griffith, 1993; Lemmon et al., 1995] have failed to find spectral features of CO2. However, H2O is probably more abundant than CO on the icy satellites, and H2O has strong absorption features that swamp those of CO2 even when only 0.1 weight fraction of H2O is present in a course-grained H2O-CO2 mixture [Kieffer, 1970]. Therefore the null CO2 observation for these icy satellites cannot rule out its presence.

### 4.5. Oort Comets and the Stability of Atmospheres Against Cometary Impact

Oort comets impact satellites at much higher velocities than do Kuiper Belt comets. They do not provide an efficient way of building an atmosphere on any satellite. From an "Iapetus" population of Oort comets, 22% of the Titans acquired atmospheres greater than 10% that of Titan's present atmosphere (Figure 7). Only 9% of the Callistos and 11% of the Ganymedes acquired such atmospheres from bombardment by Oort comets (Figure 7).
Titan's present atmosphere

Figure 7. The atmospheres acquired by 1000 Titans and Ganymedes impacted with Oort comets for the "Iapetus" comet population, (models 10 and 13, Table 5).

We tested the stability of atmospheres by impacting satellites that have nonzero initial atmospheres with Oort comets. Monte Carlo calculations indicate that a cometary bombardment does not strongly affect an atmosphere if cometary mass fluxes are smaller than or equal to the initial atmospheric mass (Figure 8). The cometary mass influx suggested by Iapetus' record is comparable to the mass of Titan's present atmosphere and therefore would have little effect at eroding such an atmosphere (Plate 1d). Oort comets are only slightly more effective at eroding equally massive atmospheres on Ganymede and Callisto (Table 5, Models 12 and 14). Therefore if the three satellites began with similar primordial atmospheres, erosion would have affected the atmospheres similarly, unless cometary invasions were vastly different in the Galilean and Saturnian systems. This is consistent with the idea that if Titan's atmosphere were derived from subnebula volatiles, the Jovian satellites did not acquire the same volatiles as did Titan [Lunine and Stevenson, 1982; Prinn and Fegley, 1989].

5. Discussion

The probability of forming a comet-based atmosphere on a satellite depends on the moon's context in a solar system. The impact velocity distribution is determined mostly from the orbital velocity of a satellite around its planet ($v_{\text{sat}}$ in (8)) and, to a lesser extent, by the planet's propinquity to the sun and by the orbital elements (chiefly the inclination distribution) of the comets ($v_{\infty}$ in (8)). Titan's low orbital velocity makes Titan most likely to acquire a significant atmosphere. However, both Ganymede and Callisto are likely to have had non-negligible atmospheres while young. The mass of these vanished atmospheres is difficult to predict; thin atmospheres appear to be extremely sensitive to luck.

There are several regions in our solar system that would allow for a "low energy impact" environment, that is, regions that are as safe or safer than Titan's. Since Jupiter's mass is roughly 4 times that of Saturn, a satellite would have to have accreted at 4 times the Titan-Saturn orbital semimajor axis to have enjoyed calm conditions with Titan-like impact velocities. At this distance from Jupiter, no large satellites presently exist. Neptune and Uranus, which are 5 to 7 times less massive than Saturn, allow low-impact velocities much closer to the planet than does Saturn. Typical impact velocities on Triton are significantly lower than impact velocities on Titan. Leaving aside for the moment the question of whether Triton and Pluto actually are comets, these bodies would appear to have a larger probability of retaining incident cometary volatiles than does Titan. Pluto and Triton are too cold to raise massive atmospheres [Tryka et al., 1993; Stansberry et al., 1994]. But nitrogen is present on Pluto and widespread on Triton [Brown et al., 1991; Cruikshank et al., 1993; Owen et al., 1993]. The quantity and nature of these ice deposits are as yet unconstrained; however, an upper limit of ~100 m has been derived from models of the viscous flow of N$_2$ ice [Brown and Kirk, 1994]. This quantity of N$_2$ ice is comparable to the inventory of N$_2$ in Titan's atmosphere.

It is difficult to quantify the amount of cometary mass that passed through the satellite systems. However, if we assume that the craters on the Saturnian satellites were formed from Kuiper Belt comets, and recognize that these records are incomplete, we estimate an order of magnitude mass flux for the Kuiper Belt comets as greater than $10^{23}$ gm.

Based on this lower limit, our Monte Carlo simulations indicate that the typical Titan would have acquired at least 10% of its volatile mass from countable comets, with a 16% chance of acquiring all its N$_2$ from comets. Because the cratering records set only a lower limit on the mass flux, it is relatively easy to imagine Titan acquiring its full complement of atmospheric nitrogen exogenously. The Jovian satellites would also be expected to have acquired atmospheres, however ones that were too small to have survived until the present era.

Figure 8. Final atmospheres following impact by Oort comets for 1000 Titans of several different initial atmospheres (models 10-12, Table 5).
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