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Note

Impact-driven ice loss in outer Solar System satellites: Consequences for the Late Heavy Bombardment

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ABSTRACT

We use recent hydrodynamical results (Kraus, R.G., Senft, L.G., Stewart, S.S. [2011]. Icarus, 214, 724–738) for the production of water vapor by hypervelocity impacts on ice targets to assess which present-day major satellites of Jupiter, Saturn, and Uranus would have lost mass due to impact vaporization during an era of massive bombardment similar to the Late Heavy Bombardment in the inner Solar System. Using impactor populations suggested by recent work (Charnoz, S., Morbidelli, A., Dones, L., Salmon, J. [2009]. Icarus, 199, 413–428; Barr, A.C., Canup, R.M. [2010]. Nat. Geosci., 3, 164–167), we find that several satellites would have lost all their H_2O; we suggest that the most likely resolution of this paradox is that either the LHB delivered ≈10 times less mass to the outer Solar System than predicted by the standard Nice Model, or that the inner satellites formed after the LHB.

1. Introduction

The location of satellites deep in the gravity well of a large planet poses a potential threat to their long-term survival. Smith et al. (1982) recognized that the innermost saturnian satellites likely suffered multiple disruptive collisions, owing to the large impact velocities caused by gravitational focusing. On the other hand, velocities at the locations of the outer satellites are much lower, and the resulting impact energies correspondingly small. As a result, bodies such as Callisto and Titan can potentially undergo accretion and experience a Late Heavy bombardment without necessarily melting and differentiating fully (Barr and Canup, 2010; Barr et al., 2010). The aim of this study is to employ an approach similar to that of Barr and Canup (2010) but to apply it to the high-velocity case relevant to the inner satellites of Jupiter, Saturn and Uranus. Rather than focusing on melting, we focus on vapor production, and the resulting changes to the bulk ice:silicate ratio of the satellites. We conclude that, in the cases of Mimas, Enceladus and Miranda, removal of ice by this process during the Late Heavy Bombardment (Gomes et al., 2005) should have been extremely effective. This result is hard to reconcile with the apparently ice-rich natures of both Mimas and Miranda. One possible explanation is that the LHB delivered at least an order of magnitude less mass to the outer Solar System than has previously been assumed; alternatively, the inner satellites may have formed after the LHB.

The Jovian satellites show a steady decrease in density (and increase in ice:silicate ratio) as a function of semi-major axis. This simple pattern may be due to variations in tidal heating, proto-satellite disk temperatures (Canup and Ward, 2009) or, as we suggest below, impact-driven vapor loss. The pattern in the saturnian and uranian systems is more complicated: the mean value is roughly 50:50 rock:ice, but there is no obvious trend (e.g. Mosqueira and Estrada, 2003; Sekine and Genda, 2011). For most of these satellites (except perhaps Enceladus) tidal heating is unlikely to be important, while the existence of low-density, ice-rich inner bodies such as Miranda and Tethys argue against high temperatures in the inner proto-satellite disk.

Accretion of satellites from the proto-satellite disk typically involves relatively low collision velocities (of the order of $v_K e$, where e is the eccentricity and v_K is the Kepler velocity), and thus little melting or vapor production (Lunine and Stevenson, 1982; Canup and Ward, 2006). If migration due to the presence of gas is important (Mosqueira and Estrada, 2003; Canup and Ward, 2006), collisions between proto-satellite embryos may occur (Sekine and Genda, 2011). Such collisions have the potential to generate stochastic variations in rock mass fraction between neighboring satellites.

In contrast to the accretion stage, more recent satellite impactors are typically on heliocentric orbits, which together with gravitational focusing by the primary can result in significantly higher impact velocities (up to roughly 30 km s^{-1}; e.g. Zahnle et al., 2003). Whether such impacts have significant effects on the global volatile budget or differentiation state of the body in question thus depends on the total mass delivered. The most likely period during which significant mass was delivered is the putative Late Heavy Bombardment (LHB). The LHB was originally proposed to explain the cluster of large lunar basins around 3.9 Ga (e.g. Cohen et al., 2000), but probably applies at least to all the terrestrial planets (Strom et al., 2005). Dynamical explanations for the LHB typically appeal to consequences of planetary migration in the outer Solar System (e.g. Fernandez and Ip, 1984; Hahn and Malhotra, 1999; Levison et al., 2001), with the so-called Nice Model (Tsiganis et al., 2005; Gomes et al., 2005) invoking a crossing of the 2:1 mean motion resonance between Jupiter and Saturn. If these scenarios are correct, the outer Solar System would also have suffered a LHB (Charnoz et al., 2009; Barr and Canup, 2010). On the other hand, scenarios invoking an inner Solar System origin (such as a fifth terrestrial planet; cf. Chambers, 2007) would not imply an outer Solar System LHB. Below, we will examine the consequences of the Nice Model LHB on satellite ice:silicate ratios.

2. Model and results

The production of melt and vapor during impacts is usually calculated using hydrodynamic codes together with the relevant equation of state (Pierazzo et al., 1997), although semi-analytical techniques have also been used (Croft, 1982). For water, a significant difficulty is the complexity of the H_2O phase diagram. Two recent studies (Barr and Citron, 2011; Kraus et al., 2011) both found that the Pierazzo et al. results overestimated the volume of melt and vapor production in H_2O. Barr and Citron (2011) used the ANEOS coefficients for water ice from Turtle and Pierazzo (2001), while Kraus et al. (2011) used the 5-phase EOS from Senft and Stewart (2008).

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Here we calculate the ratio of the vapor mass (M_{vap}) to the impactor mass (M_i) using Eq. (13) of Kraus et al. (2011). We assume ice–ice impacts, with zero porosity (appropriate for satellite-scale bodies) and assume a temperature of 150 K to obtain conservative estimates of mass loss. We take the specific energy of melting E_M to be 8.2×10^5J kg^{-1}. We carried out a Monte Carlo calculation, based on procedures described by Zahnle et al. (2001) and Zahnle et al. (2003) assuming heliocentric impactors. Impactor radii (and hence masses) are chosen from a size distribution scaled to match the crater record on Iapetus (Charnoz et al., 2009). The cumulative size distribution $N(>r)$ consists of power-laws with break points at radii $r_1 = 7.5$ km and $r_2 = 100$ km; the corresponding differential power-law indices are $\beta_1 = 2.5$, $\beta_2 = 3.5$, and $\beta_3 = 4.5$ (Charnoz et al., 2009). We assume that the mass delivered to Callisto by the LHB was 3×10^{20} kg (Barr and Canup, 2010) and scale the mass delivered to the other bodies by using the probabilities given in Table 1 of Zahnle et al. (2003). Each Monte Carlo run was ended when the total mass delivered to a particular satellite exceeded the corresponding scaled value. Assuming an impactor density of 920 kg m^{-3}, Fig. 1a plots the total mass M_{imp} delivered to each body compared to the satellite mass M_{sat}. For some of the inner satellites (Umbriel, Ariel, Miranda, Enceladus and Mimas) this ratio exceeds ten percent, suggesting the importance of the LHB in these bodies' evolution.

The total mass delivery corresponds to a $\sim$20 $M_\oplus$ outer-system planetesimal disk at the time of the LHB (Barr and Canup, 2010), derived from a disk with an initial mass of $\sim 35 M_\oplus$ (Levison et al., 2001; Gomes et al., 2005; Charnoz et al., 2009). Impactor velocities are derived assuming a velocity at infinity v_∞ and an orbital inclination uniformly distributed $-30° < i < 30°$. The eccentricity e and periapse q are given by $e = \left[1 + xU_\infty^2\left(U_\infty^2 + 2\right)\right]^{1/2}$, $q = (e-1)/U_\infty^2$, where $U_\infty = v_\infty/v_s$, x is a random variable uniformly distributed $0 < x < 1$, and the satellite orbital velocity $v_s = (GM_p/a)^{1/2}$. The scaled impact velocity is given by $U = [3 - (1-e)/q - 2[q(1+e)]^{1/2}\cos i]^{1/2}$ with the physical impact velocity $v_i = v_s U$ (Zahnle et al., 2001; Zahnle et al., 2003). For v_∞ we used $v_\infty = 4.4$ km s^{-1} as given by Zahnle et al. (2003). (Using $v_\infty = 7$ km s^{-1} (Barr and Canup, 2010) gives insignificantly different results.) Collision impact angles θ (as distinct from the orbit inclinations i of the impactors) are isotropic $0 < \theta < \pi/2$, yielding the usual $\sin 2\theta$ probability distribution (Zahnle et al., 2001). We neglect the effects of satellite escape velocities, either for additional focusing or vapor retention (see below).

Real impactors are likely to be mixtures of rock and ice, so that the resulting density (and thus the peak shock pressure) will be higher than the value we implicitly assume. On the other hand, the target material will also be a rock:ice mix, so that our estimate of mass loss will be too high (impact velocities are generally too small to produce significant rock silicate vapor). To first order, these two effects will likely cancel each other out. Each effect individually will introduce an uncertainty – determined by the ice mass fraction – which at worst will be a factor of ≈ 2; this will not significantly affect our conclusions.

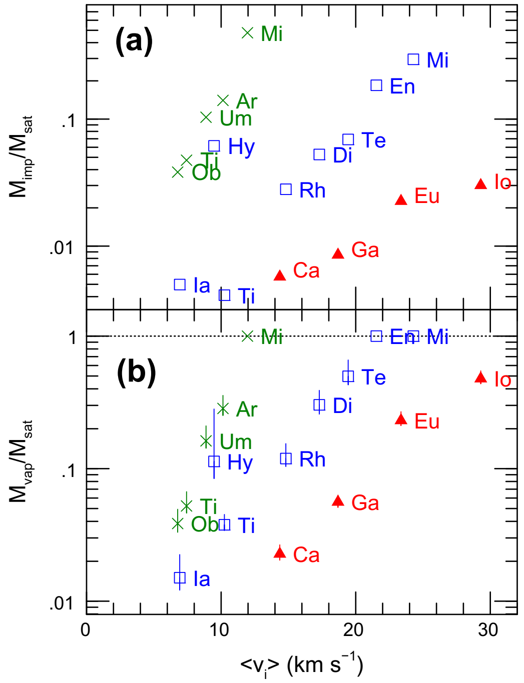

Fig. 1. Top: Mass of impacting material as fraction of satellite mass for satellites of Jupiter (filled triangles), Saturn (open squares), and Uranus (crosses), plotted versus median impact velocity. Individual satellites are indicated by the first two letters of their names. Impacting masses are derived from collision probabilities (Zahnle et al., 2003) scaled to 3×10^{20} kg at Callisto (Barr and Canup, 2010). Bottom: Mass of impact-produced vapor as fraction of satellite mass versus median impact velocity. The symbols are the median mass fractions from 1000 Monte Carlo trials. Error bars indicate the range from 10th to 90th percentile results (at bottom/left and top/right ends). Mimas, Enceladus, and Miranda are completely vaporized in every trial, so lack vertical error bars.

Because of the impactor size-frequency distribution adopted, most of the mass is contained in the intermediate size range bodies (7.5–100 km). Roughly 10^2 bodies of radius 100 km would be required to provide the mass delivered to Callisto by the LHB. Thus, the stochastic nature of the impact process is likely to cause only small variations in the total impactor mass delivered (Fig. 1a). The total impactor mass in turn largely determines the total vapor mass produced (Kraus et al., 2011).

One caveat is that the Kraus et al. (2011) equations assume that the impactor is small compared to the target; impacts between comparably-sized bodies will yield different answers (Louzada and Stewart, 2009). However, in the case of the LHB the mass of individual impactors on each satellite is of order 1% of the target mass, so that the assumption of that the impactors are small is probably satisfied. In Monte Carlo simulations, rare high-mass impacts can violate this assumption. We take this into account in a simple way by imposing an upper limit of $M_{vap} = M_{sat}$ for a single simulation run. We also note that the Kraus et al. (2011) equations break down at impact velocities less than about 8 km s^{-1}; but as will become evident below, bodies experiencing such low impact velocities are unlikely to experience significant vapor loss irrespective of the calculation details. (Our lowest median velocity (for Oberon) was $\langle v_i \rangle = 8.9$ km s^{-1}.)

We assume that any vapor produced is lost from the satellite, the logic for which is as follows. The root mean square thermal velocity of water vapor at 273 K is about 0.6 km s^{-1}. For comparison, the escape velocity of an ice-rich (2000 kg m^{-3}) satellite of radius R is approximately $0.5(R/500\text{ km})$ km s^{-1}. Thus, most of the vapor produced will escape the immediate vicinity of an impacted satellite. Once it condenses, it will be rapidly removed (e.g. by sputtering or Poynting–Robertson drag). Enceladus is a present-day example of vapor removal, where the thermal velocity of the vapor produced by geysers (300–500 m s^{-1}; Tian et al., 2007) exceeds the escape velocity of the object (240 m s^{-1}), and the resulting E-ring material has a lifetime of only a few hundred years (Horanyi et al., 2008).

Fig. 1b shows the total mass of ice removed, relative to the present-day mass of the satellite, as a function of median impact velocity for the Jovian, saturnian and uranian satellites. The distributions of impact velocity and (especially) vapor mass are highly non-Gaussian and asymmetric; to give an idea of the spread of those quantities, we draw "error bars" on the plot that span the 10–90th percentile values. The most striking results are obtained for Mimas, Enceladus and Miranda: in each case, the predicted mass loss equals (or exceeds) the mass of the satellite. This is clearly unlikely in practice, but strongly suggests that these inner bodies should have been most susceptible to ice loss during the LHB. Io, Europa, Tethys, Dione, Rhea, Hyperion, Ariel, and Umbriel should also have lost significant fractions (>10%) of their water–ice inventory.

3. Discussion

As one might expect, the innermost satellites (Mimas, Miranda and Enceladus) are most susceptible to vapor loss during the LHB. This result is also consistent with the calculations of Charnoz et al. (2009), who concluded that the effects of the LHB would likely involve the total disruption of Mimas.

Although Enceladus is dense and rock-rich, Mimas, with a density of 1150 kg m^{-3} (Thomas et al., 2007) has the second lowest density of the major saturnian satellites (only Tethys is less dense), while Miranda has the lowest density of the uranian satellites, at 1200 ± 140 kg m^{-3} (Jacobson et al., 1992). The corresponding estimated ice mass fractions are 82% and 77%, respectively (Hussmann et al., 2010). Thus, neither Mimas nor Miranda appears to be notably depleted in volatiles, in contrast to the predictions of Fig. 1b.

One possible explanation of this paradox is that water was added after the LHB. However, integrating the total mass delivery over 4 Gyr based on impactor flux curve A from Zahnle et al. (2003) does not result in a significant amount of material being added. Another possible explanation is that the mean impact velocities we assumed are too high. However, these velocities are mainly a consequence gravitational focusing by the primary, and are unlikely to be in error by enough to matter. The median impact velocities plotted in Fig. 1 are close to those used by Charnoz et al. (2009), where the impact velocities were taken to be $v_i = (3GM_p/a + v_\infty^2)^{1/2}$, with $v_\infty = 4.7$ km s^{-1} derived from a Nice Model simulation by Gomes et al. (2005). Taking $v_\infty = 7$ km s^{-1} increases mean values of v_i by only 0.5–1 km s^{-1}.

A third possible explanation is that the mass delivered during the LHB consisted of relatively few, large bodies, in which case stochastic effects will have come strongly into play (cf. Sekine and Genda, 2011), so that – for instance – Miranda never suffered a large, vapor-removing impact. A similar argument has been made for the Earth–Moon system (Bottke et al., 2010). However, this scenario would require a size-distribution very different from that used by Charnoz et al. (2009) and adopted here. Furthermore, in this model both Miranda and Mimas must have avoided large impacts, while Enceladus experienced loss of ice but not catastrophic disruption. Further work exploring the likelihood of such a scenario is required.

A fourth potential explanation is that the inner moons formed after the LHB, and were thus not denuded of volatiles by it. One possible mechanism for delayed satellite formation, based on the expansion of a massive primordial Saturn ring, has recently been proposed (Canup, 2010; Charnoz et al., 2011). Other mechanisms, such as a giant impact on Uranus (Morbidelli et al., 2011), might also have played a role. If the inner satellites are indeed younger than the LHB, then interpretations of their surface ages and evolution based on crater counts (Zahnle et al., 2003) will likely have to be significantly revised.

A perhaps more likely explanation appears to be that the mass of the LHB we have invoked is too large. Assuming that no more than few tens of percent (at most) of the masses of Mimas and Miranda could have been lost, Fig. 1b suggests that a reduction in LHB mass by a factor of ≈10 or more would solve the problem. This would also make it easier to explain the apparently undifferentiated natures of Titan and Callisto (cf. Barr and Canup, 2010; Barr et al., 2010) and would reduce the likelihood of collisional disruption of Mimas and other satellites identified by Charnoz et al. (2009) and Korycansky and Nimmo (2011). The corresponding upper bound on the mass delivered to Callisto is $\approx 3 \times 10^{19}$ kg. This upper bound implies that Ganymede would not have undergone differentiation during the LHB (cf. Barr and Canup, 2010); however, other mechanisms for Ganymede undergoing late-stage differentiation have been proposed (Showman and Malhotra, 1997).

Although we have focused on the Nice model, the argument presented here applies to any LHB mechanism which affects the outer Solar System. We emphasize that the argument does not depend on how the satellites initially formed, unless some are younger than the LHB. It is not yet clear whether the Nice Model LHB is compatible with the new mass constraints that we have deduced; a future investigation of this question would be desirable.

Note added in proof

It has also been argued that the Earth's present-day noble gas inventory is too small to be consistent with the standard LHB model (Marty and Meibom, 2007). This argument is in agreement with our findings.

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