

CONSTRAINTS ON CRATER FORMATION AGES ON DIONE FROM CASSINI VIMS AND ISS.

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Introduction: During a hypervelocity impact onto an icy moon, a shallow melt region is produced [1,2]. Crystalline ice then forms from the flash heating and cooling of the exposed melt [3]. During the subsequent years, bombardment by ions and micrometeorites disrupt the crystalline structure resulting in amorphousization [3]. Several of the Saturnian mid-sized moons (MSMs) orbit within Saturn's magnetosphere. Because the magnetosphere revolves much faster than these MSMs orbit Saturn, their trailing hemispheres are preferentially exposed to such ion bombardment; this flux has been measured by Cassini [4]. The rate of transition from crystalline to amorphous ice depends on the ion bombardment flux; therefore, the amorphous ice fraction can be used to constrain the timing of heating events, such as those related with crater formation [5].

Here we follow the work by [5] for Rhea and apply it to Dione. We make use of newly developed ice phase maps for Dione, using new techniques from [6] in order to provide new constraints on the formation ages of several of Dione's young craters.

Ice Phase Distribution: H₂O ice phase can be determined based on a few key differences in the spectral signature. The most obvious and commonly adopted is the depth of the 1.65-μm band. In the case for the presented data, we are precluded from using this band as it corresponds to one of the Cassini instrument filter junctions. Furthermore, the band is highly biased by the presence of even traces of crystalline H₂O ice [3] and so does not yield a precise measure of ice phase. We therefore adopt the 2.0-μm band whose shape is affected by phase changes [7] in a consistent way. The techniques by [5,6], are then applied, using 600 cubes to measure the amorphous water ice fraction on Dione.

Crater Aging: In order to find candidate craters for ice phase inferred aging, we compared the amorphous water ice fraction map with crater counts on Dione [8]. We used several criteria to select candidate craters: (1) The crater should lie on the trailing hemisphere, where charged particles preferentially impact; (2) There should exist a correlation between the ice phase distribution and the crater's morphology; (3) Sufficient data within and surrounding the crater is required in order to conduct the aging study.

We searched for craters whose morphology was correlated with water ice crystallinity by using a two-sample z test following

$$z = \frac{|\bar{\varphi}_i - \bar{\varphi}_o|}{\sqrt{\left(\frac{\sigma_i}{n_i}\right)^2 + \left(\frac{\sigma_o}{n_o}\right)^2}}$$

where $\bar{\varphi}$ is the average amorphous ice fraction, σ is the standard deviation, n is the number of pixels, and the indices i and o represent the values for inside and outside of the crater, respectively. The test is conducted to a 99% confidence. Because confident amorphous ice fractions were not found for some regions on Dione due to noisy spectra (blank spaces in Figure 1), we only considered craters that have data on $\geq 50\%$ of both their floor and surrounding ejecta blanket. In Figure 1, craters that pass the 3 criteria are shown in green, while craters that pass criteria 2 and 3 but are on the leading hemisphere are shown in magenta. All craters with diameters > 30 km are shown in cyan.

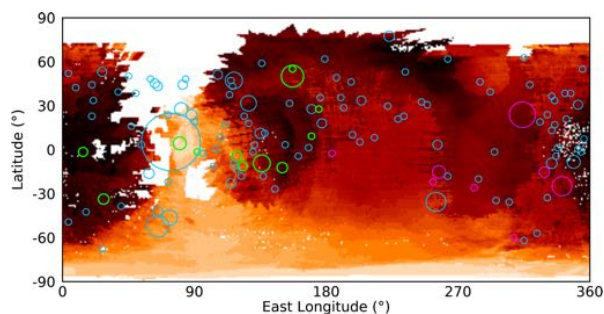


Figure 1. Global amorphous water ice fraction map of Dione, based on 39 spectral clusters, with light colors representing low values and dark colors representing high values.

Eleven craters on the trailing hemisphere are used for ice-inferred aging. For each of these, we obtain the average amorphous ice fraction inside the crater and in their respective ejecta blanket as well as the range of φ values. To derive formation age (t), we used the formulation by [9] that describes the transformation of crystalline to amorphous ice due to charged particle irradiation fluence (F) following

$$t = -\ln\left(1 - \frac{\varphi_A}{\varphi_{Amax}}\right) * k^{-1} F^{-1},$$

where k is a fitting parameter strongly dependent on the surface temperature, φ_A is the typical amorphous ice fraction related to the crater, and φ_{Amax} is the crater's maximum amorphous ice fraction. Because the selected craters are in the trailing hemisphere, we can assume they are predominantly bombarded by protons [10].

Results: The ages of the analyzed craters are presented in Table 1. Error is found as the standard deviation of the calculated ages over the variation of amorphous ice fraction associated with the studied crater; however, it does not account for error associated with F or k and thus is only an approximation to the true error of the crater's formation age.

The named craters are *Latinus*, *Allecto*, *Amata*, *Silvius*, *Pegasus*, *Entellus*, *Amastrus*, *Ilia*, and *Coras*. Two studied craters are unnamed and so we designated them as *LR1* and *LR2*. Of note, because the amorphous ice fraction associated with older craters may be degraded by repeated and overlapping impacts, our statistical test for criteria 2 has a selection bias against older craters. The studied craters have ages ranging from the last few Myrs to potentially 1.4 Ga (within error); however, all studied craters are much younger than the proposed Late Heavy Bombardment (LHB) ($\sim 3.9 - 4.1$ Ga).

Table 1. Formation ages for studied craters

Name	Diameter (km)	Latitude (°)	East longitude (°)	Age (Ma)
Latinus	133	52.5	157.3	500 ± 260
Allecto	101	-7.6	135.8	340 ± 150
Amata	70.06	5.7	80.5	110 ± 110
Silvius	62.78	-32.6	28.19	490 ± 190
Pegasus	61.78	-3.07	119.3	170 ± 270
Entellus	59.55	-11.03	149.7	600 ± 240
Amastrus	57.81	-10.09	123.4	260 ± 100
Ilia	50.72	-0.29	13.8	740 ± 110
Coras	41.36	0.47	92.0	210 ± 100
LR1	37.28	57.8	157.1	880 ± 390
LR2	32.15	10.97	169.9	990 ± 420

Discussion & Conclusions: Recently, [5] found that the surface amorphous water ice fraction can be inferred for the Saturnian satellites using Cassini data. Furthermore, [5] found that the local amorphous water ice fraction associated with craters can be used to date their formation. Applying this technique to Dione, we investigated the formation age of craters on its trailing hemisphere, which is thought to be predominantly bombarded by energetic particles.

Ice inferred ages ranged from very recent to potentially as old as 1.4 Ga. Crater counts for *Allecto* suggested it to be younger than the LHB [8]; our ice inferred formation age for *Allecto* agrees, giving confidence to the technique. Visual inspection of the amorphous ice phase map (Figure 1), though, suggests an association between Dione's chasmata and crystalline ice. Several of the chasmata cross cut craters aged in this study, and thus could potentially alter their ice inferred age.

Figure 2 shows several of our selected craters, *Amata*, *Pegasus*, and *Amastrus* being cross-cut by the chasmata. Furthermore, as seen in Figure 1, several other craters (*Coras* and *Amata*) are within the high crystalline region associated with the chasmata. These

craters, whose amorphous ice fraction may be affected by Dione's wispy terrain, appear to have younger ages (Table 1) than would be expected given their degradation state and superposed crater count.

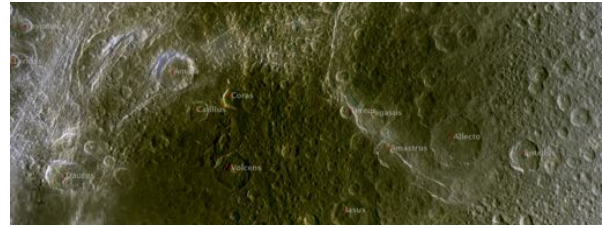


Figure 2. Image of Dione's wispy terrain obtained from JMARS tool. *Amata*, *Pegasus*, and *Amastrus* are cross cut by the chasmata.

Here, we restrict our investigation to craters outside of the potential effects of Dione's wispy terrain; specifically, to *Latinus*, *Allecto*, *Entellus*, *Ilia*, *LR1*, and *LR2*. These craters formed between 200 Ma to 1.4 Ga (within error), younger than the proposed Late Heavy Bombardment. The superposed crater density on *Latinus* and *Allecto* are $N(D > 10 \text{ km}) = 1430$ and $\leq 252 \text{ km}^2$, respectively [11]. Indeed, our inferred ages suggest *Latinus* may be about twice as old as *Allecto*. Though our ages agree within error for crater model ages of *Allecto*, they significantly disagree with crater model ages for *Latinus*; however, *Latinus*' ice inferred age may be impacted by the significant number of superposed small young craters.

The youngest of our studied craters, within error, would suggest Dione must have formed at least >200 Ma, which disagrees with a late formation for Dione, as suggested by some numerical simulations [12]; however, recent simulations that account for an evolving tidal quality factor for Saturn suggest Dione is primordial [13]. Our derived ages would support such results.

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