MICROMETEORITE ANNEALING OF OUTER PLANET ICY SATELLITE SURFACES.

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Introduction: Saturn, Uranus and Neptune play host to a menagerie of icy satellites. Ground-based observations of their near-infrared (NIR) reflectance spectra show the H_2O ice on these satellites' surfaces is predominantly crystalline [1-3]. This is fundamentally puzzling, because ice in these environments is exposed to Galactic cosmic rays (GCRs) and solar ultraviolet (UV) radiation, which should damage the internal structure of the ice and render it amorphous, on timescales much shorter than the age of the solar system. Ice at 40 AU from the Sun is amorphized to a depth of 350 μm (the depths probed by NIR observations) in ~ 1.5 Myr by GCRs, and in a time potentially as short as 50 kyr by solar UV [4]. Ice as cold as that on the icy satellites (40 K $\leq T \leq$ 120 K), in contrast, takes many Gyr to thermally anneal back to crystalline form. Some other process must therefore be either replenishing or recyrstallizing the ice on the surfaces of icy satellites. Cook et al. (2007) [4] reviewed several mechanisms that may act on Charon and concluded that the presence of crystalline ice on this body and other Kuiper Belt Objects (KBOs) is strongly suggestive of cryovolcanism. Cryovolcanism cannot explain the presence of crystalline water ice on all icy satellites, though; many are too small to support cryovolcanism, or are too heavily cratered to have been resurfaced. We hypothesize instead that the presence ice on icy satellites is annealed by the transient heating by micrometeorite impacts. In this abstract we compute the rate at which icy satellite surfaces are annealed by micrometeorites and predict the crystallinity of their surfaces.

Methodology: Cook et al. (2007) [4] calculated how heat deposited by a micrometeorite impact would thermally diffuse through ice. One third of the kinetic energy of impact is assumed to go into mechanical work, the remainder being deposited as heat. Initially, a small volume is heated to > 200 K, leading to rapid annealing within it; as the heat spreads, larger volumes are heated for longer times, but to lower temperatures. Eventually the heat is too diffuse to anneal the ice on the relevant timescales. For a reasonable range of ice thermal conductivities, the mass of ice that is annealed scales as a constant times the kinetic energy of the impact (about 10 times the mass of the impactor for an impact speed of 1.8 km/s). For the dust fluxes in the Kuiper Belt, derived from Pioneer 10 data [5], and the likely impact velocities, the annealing time was found to be > 3 Myr, making micrometeorite impacts ineffective ineffective (marginally) against amorphization by GCRs and potentially very ineffective against amorphization by solar UV [4]. The situation for micrometeorite annealing is much more favorable for icy satellites, though, as the impact speeds are higher and the planets' gravity focuses dust particles onto the satellites [6-7].

We assume that in the vicinity of a planet the micrometeorite densities correspond to those measured by Pioneer 10, which showed a near-constant dust flux between Saturn and Neptune [5]. We assumed a dust velocity relative to the planet $\approx \sqrt{e^2+i^2}V_{\rm p}$, with $e \approx i \approx 0.3$, $V_{\rm p}$ being the planet's orbital velocity. Within the satellite system the density of dust is increased (to $n_{\rm d}$) and its velocity is increased (to $V_{\rm d}$); we account for these effects using formulae from [8-9]. We then estimate the instantaneous kinetic energy flux onto the satellite surfaces as $F = n_{\rm d}\left[V_{\rm sat}^2 + V_{\rm d}^2\right]^{3/2}/8$, where $V_{\rm sat}$ is the orbital velocity of the satellite around its host planet. The kinetic energy flux is integrated over a complete satellite orbit, accounting for orbital eccentricity. Isotropy on the scale of the satellite is assumed. We then calculate the timescale for annealing as

$$t_{\rm anneal} \approx 1.1\,(F/1\,{\rm erg\,cm^{-2}\,s^{-1}})^{-1}\,{\rm yr}.$$

This is to be compared to the timescale for amorphization. For GCRs, we assume a constant $t_{\rm amor} = 1.5\,{\rm Myr}$, appropriate for 40 AU [4]. For solar UV, we assume a timescale $t_{\rm amor} = 50\,(r/30\,{\rm AU})^2\,{\rm kyr}$ based on [4]. The degree of crystallinity is then calculated as $t_{\rm amor}/(t_{\rm amor}+t_{\rm anneal})$.

Results: The degrees of crystallinity for selected satellites are presented in Table 1. The key geometric factor in determining the gravitational focusing of dust is the ratio of the satellite's semi-major axis to the planet radius [7-8]. Generally speaking, annealing rates are much higher for satellites orbiting close to their host planets, and tend to be somewhat higher at Saturn than at Neptune. An

	Saturn			Uranus		Neptune	
	Phoebe	**Iapetus**	**Mimas**	**Oberon**	**Miranda**	**Nereid**	**Proteus**
$a_{satellite}/R_{planet}$	215	59.4	3.09	23.3	5.18	221	4.71
$e_{satellite}$	0.156	0.0286	0.0202	0.00140	0.00130	0.751	0.00053
V_{dust} (km/s)	4.10	4.10	4.10	2.90	2.90	2.30	2.30
t_{anneal} (kyr)	600	154	0.493	116	6.01	1290	1.83
$t_{amorph,UV}$ (kyr)	2.95	2.95	2.95	11.8	11.8	29.0	29.0
$t_{amorph,GCR}$ (kyr)	1500	1500	1500	1500	1500	1500	1500
% Annealed (UV)	0.5%	1.9%	86%	9.3%	66%	2.2%	94%
% Annealed (GCR)	84 %	95%	100%	96%	100%	71 %	100%

eccentric orbit can also enhance the kinetic energy flux onto a satellite because although the satellite spends a small fraction of its time near the planet at high velocity, the flux scales as velocity cubed. Nereid's eccentricity of $e = 0.75$ enhances the kinetic energy flux impacting it by a factor of 2 (over the flux if Nereid had a circular orbit). The range of orbital parameters leads to a range of annealing times. Phoebe's slow orbit and weak focusing lead to an annealing timescale ~ 0.6 Myr, whereas the ice on Mimas can be annealed by micrometeorite impacts on timescales as short as 500 years. In all cases, annealing is competetive with the amorphization due to GCRs but is not, generally, competetive with the maximum possible amorphization by solar UV.

Discussion: We have shown that the thermal annealing of water ice due to deposition of kinetic energy by micrometeorite impacts is potentially competetive with amorphization by GCRs. **Annealing by micrometeorites may therefore explain why the water ice on satellites is generally crystalline.** However, many factors complicate our analysis. Amorphization by solar UV potentially may be effective on $\sim 10^4$ yr timescales [4], and if it is then it will dominate over micrometeorite annealing. Energetic particles trapped in planetary magnetospheres may amorphize ice more quickly than we have calculated. On the other hand, our analysis has assumed impacts by interplanetary dust particles only, but the production of Saturn's E-Ring by Enceladus [9] creates a dust cloud through which Dione, Tethys, and Mimas must orbit [10]. Particles may also be ejected from the other planets' satellites and considerably enhance the micrometeorite flux onto their icy satellites, more rapidly annealing their ice. Finally, GCRs will be stopped by solar wind and planetary magnetospheres, and should take > 1.5 Myr to amorphize ice on satellites. Further study is needed to assess the net effect of these many factors.

Most of these factors are absent for KBOs, simplifying the discussion. Micrometeorite annealing is marginally unable to compete with GCR amorphization, and solar UV amorphization would be faster. The presence of crystalline water ice on KBO surfaces is likely diagnostic of some other replenishing or recrystallizing process, such as cryovolcanism, unless the dust fluxes are higher than measured by Pioneer 10, by about an order of magnitude. A test of micrometeorite annealing on KBOs should be possible by obtaining an improved NIR spectrum of the satellite of 2003 EL_{61}. 2003 EL_{61} itself has a crystalline water ice surface [11], and while its satellite is known to be predominantly water ice [11], its crystallinity is unknown. If this satellite is found to have amorphous water ice, this would argue strongly against annealing by micrometeorites. The presence of crystalline wate ice on this satellite, however, would suggest annealing by micrometeorites, since it is too small to suport cryovolcanism. Spectra of other KBOs could be similarly analyzed to test the micrometeorite annealing hypothesis.

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