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Magnetospheric considerations for solar system ice state

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ABSTRACT

The current lattice configuration of the water ice on the surfaces of the inner satellites of Jupiter and Saturn is likely shaped by many factors. But laboratory experiments have found that energetic proton irradiation can cause a transition in the structure of pure water ice from crystalline to amorphous. It is not known to what extent this process is competitive with other processes in solar system contexts. For example, surface regions that are rich in water ice may be too warm for this effect to be important, even if the energetic proton bombardment rate is very high. In this paper, we make predictions, based on particle flux levels and other considerations, about where in the magnetospheres of Jupiter and Saturn the ~MeV proton irradiation mechanism should be most relevant. Our results support the conclusions of Hansen and McCord (2004), who related relative level of radiation on the three outer Galilean satellites to the amorphous ice content within the top 1 mm of surface. We argue here that if magnetospheric effects are considered more carefully, the correlation is even more compelling. Crystalline ice is by far the dominant ice state detected on the inner Saturnian satellites and, as we show here, the flux of bombarding energetic protons onto these bodies is much smaller than at the inner Jovian satellites. Therefore, the ice on the Saturnian satellites also corroborates the correlation.

1. Introduction

The magnetospheres of Jupiter and Saturn contain the most intense fluxes of energetic charged particles close to the planet and near the magnetic equator. Icy satellites are present deep in these magnetospheres and their surfaces are continuously weathered by charged particles. These interactions can modify the ice in a number of ways including by sputtering it (e.g., Cassidy et al., 2013), destroying its crystallinity (e.g., Moore and Hudson, 1992), altering its thermal properties through the deposition of energy (e.g., Howett et al., 2011), and creating new molecules, such as peroxide (e.g., Carlson et al., 1999; Moore and Hudson, 2000; Hand and Carlson, 2011). In this paper, we will focus on predicting which satellites in the inner to middle magnetospheres of Jupiter and Saturn will likely be most affected by energetic protons that can modify the ice lattice.

Previously, several researchers have documented surface characteristics resulting from bombardment by magnetospheric particles. Hansen and McCord (2004) carried out analyses of reflectance spectra of the surfaces of the three outer Galilean satellites using data from the Galileo Near-Infrared Mapping Spectrometer (NIMS). They concluded that among them, the one that is closest to the Jovian radiation belts (Europa, $r \sim 9.4\ R_J$, where $R_J = 71{,}492$ km) and subject to the most radiation, also has the most amorphous ice. This was based on the nature of the 3.1 µm Fresnel reflection peak in ice that probes the upper microns of the grains in the regolith. The percentage of amorphous ice in the outer portion of the grains decreases for Ganymede ($r \sim 14.9\ R_J$). For Callisto ($r \sim 26.3\ R_J$), only crystalline ice is detected. Hansen and McCord (2004) further found through the analysis of the 1.65 µm water ice feature, that ice grains are crystalline in their interiors such that amorphous ice, when present, is limited to the very top surface. At a depth of 1 mm and deeper, all water ice on these three satellites is crys-

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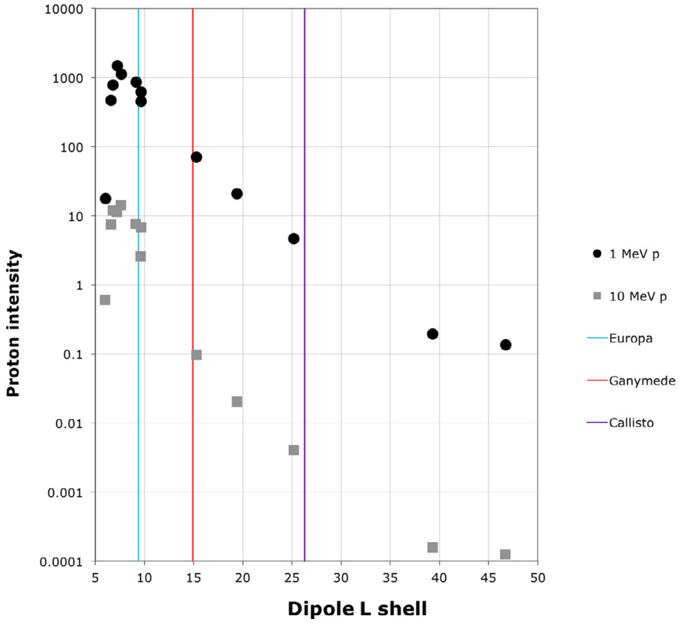

Fig. 1. Proton intensities versus dipole L shell for 1 MeV and 10 MeV protons. These points are derived from fit functions to the Galileo EPD data created by Mauk et al. (2004). Units are protons per cm^2-s-sr-keV.

talline. This interpretation of only crystalline water ice (at depth) is also supported by Earth based telescopic observations (Ligier et al., 2016).

While Hansen and McCord (2004) pointed out that energetic ion bombardment is only one mechanism for transforming crystalline ice to amorphous ice, the increasing crystallinity of surface ice correlating with the satellites' Jovian distance makes this mechanism a very likely explanation. Furthermore, the crystalline-to-amorphous transition has been demonstrated in laboratory experiments in which water ice is bombarded with protons (Moore and Hudson, 1992; Mastrapa and Brown, 2006; Fama et al., 2010). This is a useful piece of the puzzle even though the laboratory data are not all completely consistent with each other. Finally, the penetration depth of energetic protons and heavy ions in ice is very shallow, as is the amorphous ice feature. A depth of 20 µm, for instance, is sensed by the 3 µm feature.

2. Charged particle bombardment of the three outer Galilean satellites

The fall-off of energetic ion flux from the orbit of Europa to that of Callisto correlates with the percentage of amorphous ice on the surface, as measured by the 3.05 µm Fresnel reflection peak in the ice. In this section, we will take a more comprehensive look at the relevant satellite environments.

In Fig. 1, we show the behavior of the intensity of 1 and 10 MeV protons at dipole L shells between 5 and 50 R_J. In a dipole model of the magnetic field, L (expressed in planetary radii) is the distance at which magnetic field lines associated with that L shell cross the magnetic equator. This plot uses the energy spectra determined by Mauk et al. (2004), who based their fits on time-of-flight and other measurements from the Galileo Energetic Particles Detector (EPD) instrument at a limited number of Jovian distances. The data show the peak intensity is located close to the orbit of Europa, falling both inward toward Jupiter and outward toward Callisto. While there is a level of variation near Europa's orbital distance, the plot shows the intensities at Callisto are at least an order of magnitude lower.

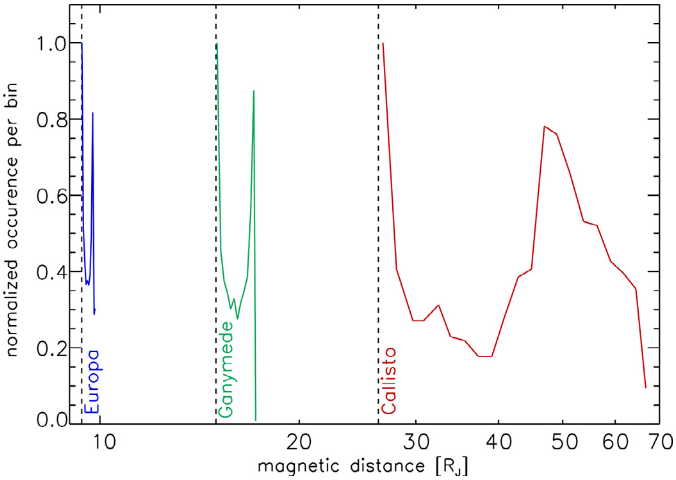

Fig. 2. Histogram of magnetic distances covered by Europa, Ganymede, and Callisto during their orbits around Jupiter. Each moon location is traced in the Khurana magnetic field model to the minimum B point. The radial distances of these magnetic equator points are shown on the x-axis. The occurrence of the distances is sampled in logarithmic bins, normalized to the maximum, and shown on the y-axis.

A complication of displaying proton flux as a function of dipole L shell is the planetary ring current. This current flows in the azimuthal direction and effectively stretches the magnetic field lines out of their dipolar configuration. Connerney et al. (1981) showed, using a model of the magnetic field near the current sheet, that the equatorial crossing point of the field lines can be significantly different from a dipole at equatorial distances greater 15 R_J (see their Fig. 10). Therefore Fig. 1 provides a reasonable approximation to the intensities out to about Ganymede's orbit only.

Since we are interested in comparing the charged particle weathering of Europa and Callisto, we have improved upon the dipole picture in the following way. We used representative points along the moon orbits to determine the corresponding radial distance to the point of the minimum magnetic field intensity on the field line occupied by the satellite. Because the dipolar L value is the radial distance to the minimum B point on the field line, the minimum B point in a non-dipolar magnetic field is a way to associate each magnetic field line with a radial distance. Magnetic field lines with a larger minimum B distance would, for example, be less likely to sustain high fluxes of trapped charged particles. We computed minimum B points in the Khurana magnetic field model (Khurana, 1997), which includes non-dipolar terms of Jupiter's intrinsic field and accounts for time-varying ring and other current systems. We sampled positions along the orbits of Europa, Ganymede, and Callisto, and traced these points along the model magnetic field line to its minimum B distance. By doing so, we found the following range of distances at which the minimum B point is located: Europa (9.3 to 10.0 R_J), Ganymede (15.0 to 17.4 R_J) and Callisto (26 to 69 R_J). A histogram of the time spent at each distance is shown in Fig. 2.

In a dipolar magnetic field, the nearly 10° tilt between the magnetic equator and the orbital plane of the satellites means the moons occupy a range of dipole L shells during their orbits. As noted, for very stretched magnetic field lines this range can dramatically increase. At the same time, trapped flux tends to become less intense with increasing distance from Jupiter. In addition, some of the flux on stretched field lines will be confined to the region near the magnetic equator and never reach the satellite. Therefore, in addition to the fall-off of flux that would be approximated using the dipole L in Fig. 1, these factors suggest that the weathering rate of Callisto by energetic charged particles is likely orders of magnitude smaller than the rate at Europa.