

Electron bombardment of Europa

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Abstract. Energetic electrons trapped in Jupiter's magnetic field are a principal source of energy for driving chemistry on the surface of Europa. Here we show that energetic (10 keV–10 MeV) electrons precipitate primarily on the trailing hemisphere, and we give the spatial distribution of the dose-rate deposited in Europa's surface. Based on this we propose that energetic electrons are a primary agent in determining the hemispherical differences in Europa's albedo, which have been attributed to differences in the incident ion flux. We compare the spatial distribution in the dose-rate deposited by the energetic electrons to the spatial distribution in the hydrate (likely frozen, hydrated sulfuric acid) determined by Galileo's near-infrared mapping spectrometer. This comparison supports the idea that radiolysis by the energetic electrons contributes significantly to producing the hydrate.

1. Introduction

Europa is located inside Jupiter's radiation belt. It is bombarded continuously by ions and electrons trapped in Jupiter's giant, rotating magnetic field. Particles that impact the moon alter its reflectance properties by sputtering and chemically modifying the optical surface. Because electrons are a principal carrier of energy to Europa's surface and deposit most of their energy in an optically thick layer near the surface [Paranicas *et al.*, 1999; Cooper *et al.*, 2000], they play a role in determining its optical properties. We generated a map of the dose-rate across Europa's surface due to energetic electrons [Paranicas *et al.*, 1999] using Voyager 1 LECP and Galileo EPD data. This map is compared with a Galileo near-infrared (IR) spectral map showing that energetic electron bombardment plays an important role in the radiolysis (chemical alteration due to incident particle radiation) of Europa's surface.

The spectral data used here are from the Galileo Near-Infrared Mapping Spectrometer (NIMS) [Carlson *et al.*, 1992]. These data were used to show that a principal radiolysis product of ice, hydrogen peroxide, exists in Europa's optical surface [Carlson *et al.*, 1999a]. That result indicated that Europa's surface is affected by high-energy particle impact. Europa is also exciting because its surface is relatively young, particularly in the regions called the "chaos regions." These appear to be indicative of an active surface and, possibly, an underground

ocean [see Pappalardo *et al.*, 1999, for a review]. NIMS spectra of the chaos regions were shown to be consistent with the radiolytic production of hydrated sulfuric acid, sulfur, and sulfur dioxide [Carlson *et al.*, 1999b]. We evaluate the possible role of energetic electrons as chemical alteration agents by comparing the spatial distribution of the electron dose deposited in Europa's surface with the spatial distribution of the hydrate.

Paranicas *et al.* [1999] and Cooper *et al.* [2000] have used Galileo data and a model of trapped flux levels [Divine and Garrett, 1983] to estimate dose vs. depth into Europa's surface due to the energetic ions and electrons. Whereas the energetic ions dominate the energy deposition rate in the top ~10 mm at unit density, the energetic electrons appear to dominate at lower depths, from ~50 mm to ~10 cm. Hence, the energetic electrons are likely to be important in determining the IR absorption features. We first describe the spatial distribution of energetic electron dose and then compare this to the spatial distribution of the IR feature associated with hydrated material.

2. Electron Bombardment of Europa's Surface

In Figure 1, we show 20-min averages of electron data taken near Europa's orbit by Voyager 1. In addition, we present intensities from three Galileo near encounters with

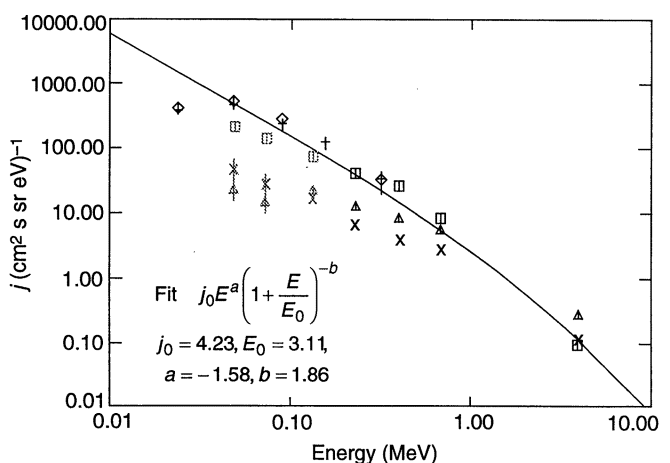


Figure 1. Electron energy spectrum at Europa's orbital radius. Data are from Voyager 1 as it crossed Europa's orbit inbound (+) and outbound (diamonds) to Jupiter. Galileo data are from E12 (triangles), E14 (squares), and E26 (×). A subset of the data (black points) are fit as shown.

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Europa, just upstream of the moon. All data were averaged over instrument look direction. We use a single fit to these data to approximate the long-time average effects of the radiation environment. Only those data that could be corrected for instrument saturation were included in the fit.

Saur *et al.* [1998] performed an MHD simulation showing how plasma is diverted around Europa and how extensively field lines connect to the moon. They found the radial dimension of Europa's wake to be smaller than the moon's diameter. Our analysis [Paranicas *et al.*, 2000] showed decreases of electron fluxes to the instrument background in Europa's wake, suggesting losses to the moon. We found the radial extent of Europa's wake was comparable to its diameter, and that dimension is used below.

Before estimating the spatial distribution of the dose-rate, we mention some recent results. Induced magnetic fields [Kivelson *et al.*, 1999] are not included here because we consider effects averaged over very long electron bombardment times ($>>10^7$'s of years). No attempt is made to calculate exact electron trajectories based on MHD simulation results as Thorne *et al.* [1999] did for Io. Those investigators illustrated the guiding-center drift paths of equatorially trapped electrons showing how electron trajectories become influenced by $B = \text{constant}$ contours at high energies. This is relevant because of the increase in magnetic field measured just upstream of Europa [Kivelson *et al.*, 1999]. Trajectory calculations may improve the relation between the measured and predicted wakes. These points illustrate areas of potential disagreement between the predicted bombardment pattern and the IR observations.

We assume a 65–70 km/s plasma drags magnetic flux across Europa, allowing trapped electrons to be lost to the satellite's surface. Since electron bounce times are smaller than the transit time of plasma across Europa, flux tubes are emptied of electrons as soon as they come into contact with the satellite. A 1-MeV electron with equatorial pitch angle, $\alpha_{\text{eq}} = 45^\circ$ has a total bounce time of ~ 8 s, whereas the guiding center transit time across the moon's diameter is ~ 48 s. This means the vast majority of LECP electrons are lost preferentially on Europa's trailing hemisphere, a fact ignored to date in interpreting Europa's albedo. At the lowest end of this energy range, electrons have the longest bounce times, are distributed to higher latitudes, but have the smallest penetration depths.

To estimate where electrons deposit their energy, we sum over contributions from 10 keV to 10 MeV and all pitch angles (assumed isotropic). The power per unit area at a surface location \mathbf{r} is

$$\Pi(\mathbf{r}) = \sum_{\text{energy}} \sum_{\text{pitch angle}} \cos \alpha \sin \alpha \Delta \alpha \int E j(E) \Delta E s(\mathbf{r}, E, \alpha) \quad (1)$$

At each \mathbf{r} , we associate a contact time, representing how long that particle's guiding center field line would have been in con-

tact with Europa before reaching \mathbf{r} . If that time is less than the half bounce time, it is assumed that the flux tube contains trapped particles and $s \equiv 1$; it is 0 otherwise. The contact time is (v/d) , where v is the speed of the guiding center magnetic field line with respect to Europa. If the point \mathbf{r} is projected onto Europa's equatorial plane, d is the distance from the edge of Europa to the projected point, along an equipotential of the flow.

Figure 2 illustrates the results of this calculation. It is seen that most energetic electrons impact Europa's trailing hemisphere, primarily at low latitudes. Peak intensities are shifted from the nominal corotation direction by 15° following Saur's picture of the equipotentials. The preferential bombardment of the trailing hemisphere would appear to be similar to the ram bombardment of the trailing hemisphere by low-energy, corotating ions if they have unimpeded access to the surface. However, these ions would have a much broader latitudinal distribution. Furthermore, they have very small penetration depths ($\leq 0.1 \mu\text{m}$), much less than the optical depth for IR photons. The spatial distribution in Figure 2 also differs from that for energetic ions [Pospieszalska and Johnson, 1989]. In addition to being partially deflected around Europa's trailing hemisphere, energetic ions have very long bounce times and large gyroradii, precipitating from high Jovian latitudes and neighboring field lines to all locations on Europa's surface.

Cooper *et al.* [2000] calculated an energy flux to the surface [$4\pi \int jE dE$] and found the electron integral to be larger than the ion integral. We evaluated this integral from 0.02 to 100 MeV using the Figure 1 fit and a proton fit [Paranicas *et al.*, 1999] and found $\sim 10^{11}$ keV/cm²s for both species. Both results, combined with the spatial distribution of the dose-rate, indicate the importance of the energetic electron dose for radiation chemistry on Europa's trailing hemisphere.

Finally we note that the picture for Europa differs dramatically from that at Ganymede. There the presence of an internal magnetic field changes the way electrons are lost to the surface. Flux tubes in contact with Ganymede only lose electrons when they diffuse into the loss cone created by that moon. This process takes ~ 10 bounces [Williams *et al.*, 1998], so electrons are distributed more uniformly over Ganymede's polar region, possibly accounting for the bright polar "cap" [Johnson, 1997].

3. Observations by NIMS

Surface mapping of Europa by NIMS showed that the major surface species are water ice and a hydrated compound. The latter was interpreted as radiolytically produced sulfuric acid hydrate [Carlson *et al.*, 1999b] or a mixture of hydrated, non-radiolytic evaporite salts [McCord *et al.*, 1998, 1999]. We next present the spatial distribution of the hydrate for comparison with electron impact fluxes.

Table 1. NIMS Global Observations of Europa

Observation	Range (km)	Resolution (km) (sub-spacecraft)	Sub-spacecraft longitude, latitude	Phase angle
GIENNHLAT01	156,000	78	236°, 20°	31°
E6ENTERINC01	99,000	50	209°, -1°	35°
15ENSUCOMP03	27,000	14	55°, 2°	103°
17ENGLOBAL02	116,000	58	75°, 0°	101°

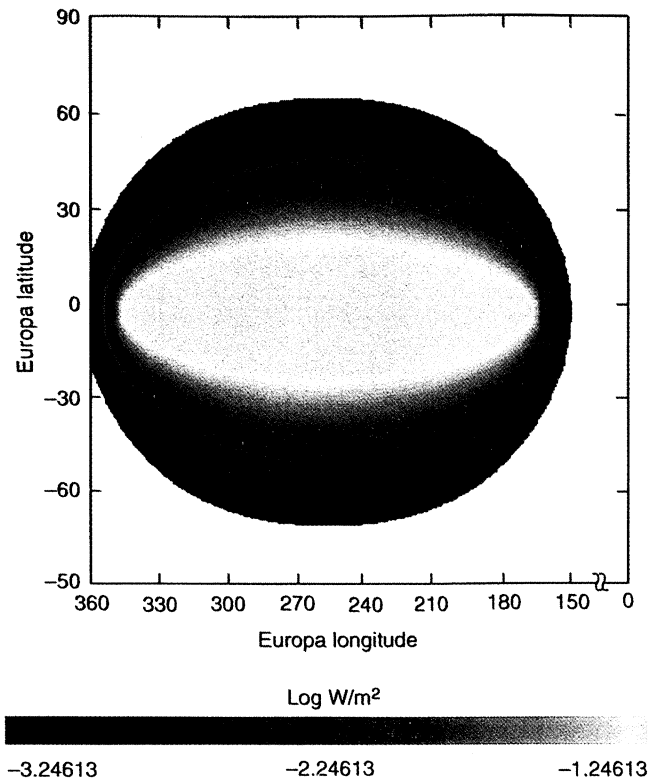


Figure 2. Energetic electron bombardment of Europa. Dose-rate is based on the Figure 1 fit. Coordinates are as in Saur [1998], with the polar axis anti-parallel to the undisturbed magnetic field and the 90° meridian in the nominal corotation direction.

NIMS has observed about 75% of Europa’s longitudes during the Galileo mission. We combine three global-scale and one regional-scale observation to produce a global view of Europa (see Table 1). Each individual observation consists of a spatial-spectral data cube, forming spectral images of Europa with a complete spectrum for each spatial pixel. The combined observations span the longitude range from ~90°W to ~300°W and provide equatorial and mid-latitude coverage of the trailing hemisphere and partial coverage of the leading hemisphere.

The 1.5- μm H₂O absorption band is useful for estimating the abundance of the hydrate. In regions having relatively pure water ice, this band is quite deep and extends to ~1.7 μm . A plateau occurs between 1.7 μm and 1.85 μm , where absorption from the 2- μm H₂O band begins. In contrast, Europa’s hydrated compound exhibits a skewed 1.5- μm H₂O band with no distinct minimum, resembling instead a step. The radiance at 1.5 μm is higher or lower than the radiance at 1.8 μm , depending upon the relative concentrations of hydrate and ice. The radiance ratio $\rho = I(1.5\mu)/I(1.8\mu)$ varies between $\rho(0) \approx 0.4$ for a surface that is mostly ice, with little hydrate, to $\rho(1) \approx 1.1$ for a predominately hydrated surface. In a simple linear mixing model, the fractional hydrate concentration is $[\rho - \rho(0)]/[\rho(1) - \rho(0)]$. This expression was used to derive the hydrate concentration shown in Figure 3.

Although the hydrate map in Figure 3 is incomplete, it indicates a dramatic leading/trailing (*l/t*) asymmetry for the hydrated species that is similar to the electron flux (Figure 2). The hydrate concentration may be affected by local geology and may require a supply of material to the surface. Spectra of the leading side indicate the presence of nearly pure H₂O, with hydrate concentrations <10% compared to the ~100% hydrate concentration in portions of the trailing hemisphere. Figures 2

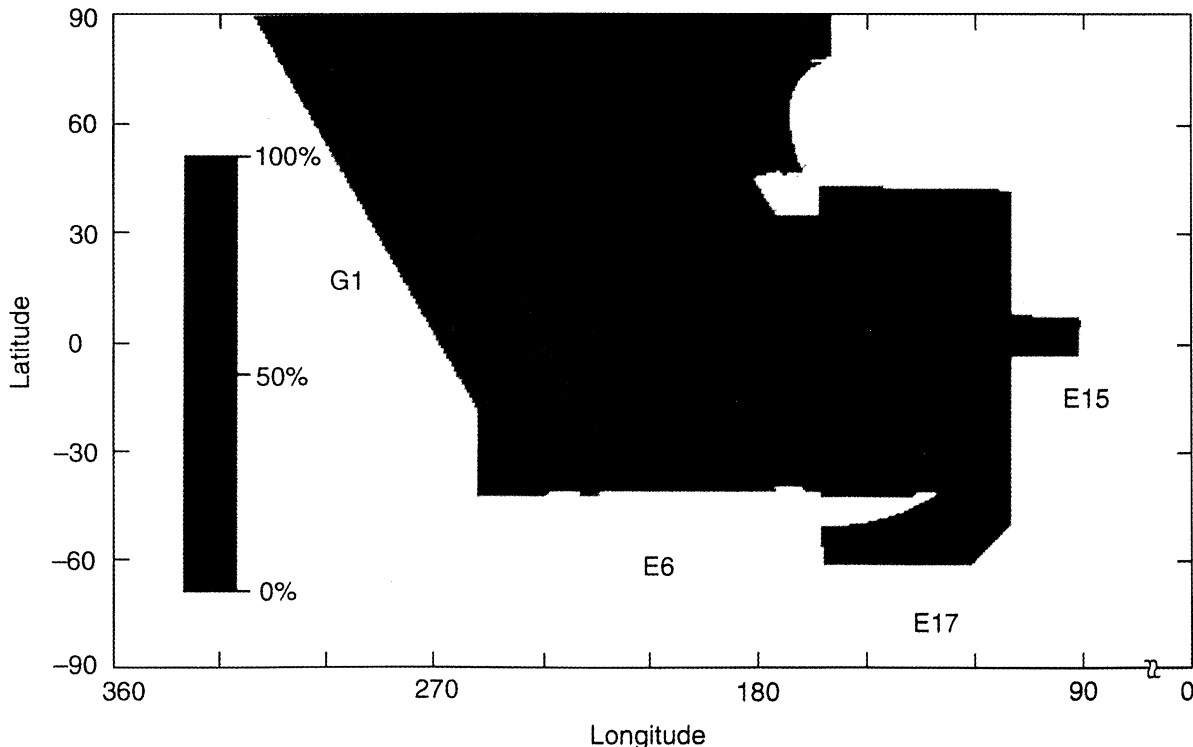


Figure 3. Europa’s hydrate distribution from Galileo NIMS spectral mapping. Note the enhancement and steep latitudinal gradients on the trailing side, similar to the Figure 2 profile.

and 3 indicate distributions more confined in latitude than longitude, with gradients at about $\pm 30^\circ$ latitude. Corotating flux tubes first contact Europa at low latitudes and deposit the majority of their energetic electrons there, producing a latitudinally confined distribution. This correlation suggests that the hydrate is produced radiolytically, as proposed by Carlson *et al.* [1999b]. Here we show that energetic electrons are likely a principal radiolytic agent. Reproducing the actual longitudinal hydrate distribution may require including the effect of radiolysis by protons and implantation of sulfur.

4. Discussion

Early observations of Europa's reflectance in the visible and near UV [e.g., Morrison and Burns, 1976] indicated a distinct *lt* asymmetry in Europa's albedo. These observations were reinforced by the Voyager images of Europa in four color filters [Johnson *et al.*, 1983]. This asymmetry has long been thought to be due to bombardment by trapped Jovian plasma. Initially, it was assumed to be principally a result of sputtering by corotating plasma ions (<10 keV) because they preferentially bombard the trailing hemisphere. Indeed, sulfur implantation may still play an important role. However, the energetic (10 keV to 10 MeV) ion bombardment was also shown to exhibit a significant *lt* difference [Pospieszalska and Johnson, 1989]. Combining the low-energy and energetic ions, a reasonable correlation was found between the ion flux to Europa's surface and the observed latitudinal variation in the Voyager UV filter data, after removing effects of the local geology [Johnson *et al.*, 1988, Fig. 5]. Although the effect on the leading hemisphere was overestimated, this paradigm has been in place for over a decade.

Recently, it was shown that energetic ion and electron energy depositions are comparable. This suggested to us that the long-ignored electron component is likely to be a principal chemical agent for Europa surface material. Here we show that the hemispherical difference in energy deposition is largest for energetic electrons, which combined with their energy flux implies they are the principal radiolytic agent on the trailing hemisphere.

We have presented maps of dose-rate and hydrate concentration. From Figure 2 it is clear that the map of the energetic electron dose-rate differs from the spatial profiles calculated earlier for both the plasma and the energetic ions [Pospieszalska and Johnson, 1989]. Although the corotating plasma ions and the energetic electrons are both affected by any deflection of the field lines, the former have a much broader distribution in latitude and a broader distribution in longitude. This is because electrons precipitate in times short compared with the encounter time and because their gyroradii tend to be smaller than spatial scales of interest. Therefore, the map of the electron dose-rate shows the most dramatic spatial asymmetry, suggesting that the energetic electrons and not ions may be the most important agent in causing the observed *lt* asymmetries.

When the hydrate concentration map is compared to the dose-rate map, a strong correlation is seen both in the latitudinal and longitudinal distribution. Although these distributions are not identical and ions certainly play a role, the similar asymmetries in the electron and hydrate distributions suggest that radiolytic processing by the energetic electrons is important. This supports the suggestion that the hydrate is associated with radiolytic processing of Europa's surface materials [Carlson *et al.*, 1999b]. Radiolytic processing and sputtering of

Europa's surface by the incident plasma needs to be re-evaluated using Galileo spectral and plasma data.

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