Europa's Radiation Environment and Its Effects on the Surface

1. INTRODUCTION

Charged particles trapped in Jupiter's rotating magnetosphere continuously overtake Europa in its orbit. At sufficiently high energies, these particles are relatively unaffected by the tenuous atmosphere of the satellite and instead bore directly into the ice before losing much energy. For example, energetic electrons and their bremsstrahlung photon products can directly affect the top meter of the icy regolith, which is also processed by meteoritic impact gardening (Cooper et al., 2001; Chyba and Phillips, 2001). Charged particle irradiation of ice produces a number of new species as described in the chapter by Carlson et al. Those that are volatile at the ambient temperature, such as O₂, populate the atmosphere, whereas those that are more refractory, such as H₂O₂, can be detected as trace species in the ice. In addition to the chemical weathering of Europa's surface, the bombarding energetic particle flux drives species into the gas phase, a process called "sputtering." This produces a thin atmosphere above Europa's surface as described in the chapters by Johnson et al. and McGrath et al. Extrapolation from laboratory data to the quantification of radiation effects on Europa's surface and atmospheric environment requires modeling of the longitudinal and latitudinal distributions of energy deposited per unit volume vs. depth into the surface. It is also useful to characterize ranges of temporal variation caused by jovian magnetospheric activity and other effects. Therefore a central goal of this chapter is to provide estimates of the average energy vs. depth distributions at representative locations on the surface and to describe variations one might expect. We will also estimate the principal effects produced for different radiation types.

In section 2 of this chapter, we will discuss the jovian radiation environment to provide a context for Europa. In particular, we note the relative levels of radiation among the inner satellites as potentially important for differences in surface weathering. We also point out that Europa's orbit coexists with a cold neutral gas torus. This gas influences all ions up to the few-MeV range because of charge-exchange collisions that create energetic neutral atoms (ENAs) with energies reflective of their parent ion. In section 3, we turn our attention to the environment close to the satellite itself. We provide recent fits to the electron and ion data that describe the intensity of these trapped particles near Europa's orbit. We cover the energy range from about 1 keV to tens of MeV. We will also elaborate on the asymmetric bombardment of Europa by electrons, which has consequences for surface processing.

In section 4 of this chapter, we describe some of the effects of the radiation environment on the surface itself. A good recent summary of the consequences of charged particle weathering of Europa's surface can be found in Johnson et al. (2004) and references therein. Cooper et al. (2001) provide a table (their Table II) of surface irradiation parameters for the icy satellites. It is not our intention to repeat that material here but to mention highlights and updates since some of the earlier publications. In particular, we will extend some of our previous ideas on the non-uniformity of the surface bombardment. A central reason for improved modeling of space weathering effects on exposed surfaces in space is to determine the chemical compo-
of the magnetic field of the planet. In their fits to the various datasets, >10-MeV ion intensities also show a peak close to the planet but fall off rapidly with increasing radial distance. Near Europa’s orbit, R ≈ 9.4 R$_J$ (here R$_J$ = 71,492 km), and keeping in mind the different lower-energy MeV ion backgrounds are already substantially reduced from their peak, whereas the MeV electrons are somewhat lower than their peak but still significant. The DG83 model electron fluxes have been compared to Galileo orbiter measurements near Europa, Ganymede, and Callisto (Cooper et al., 2001). The model and Energetic Particle Detector (EPD) fluxes in the 1-MeV range were found to agree well on the decrease in flux with increasing distance from Jupiter. At higher energies the electron data model of Cooper et al. (2000) was derived only from DG83. The DG83 modeling for electrons has been superseded by the Galileo Interim Radiation Electron (GIRE) model (Garrett et al., 2002, 2005). Model integral fluxes from GIRE/DG83 are presented in Fig. 1.

The work of Jan et al. (2005) displayed Galileo EPD data, comparing the electron count rates and fluxes for energies ≥1.5, 2.20, and ≥11 MeV, for orbits over the whole mission. They found an approximately 2-order-of-magnitude increase in tens of MeV electron densities of Ganymede (R = 15 R$_J$) to that of Europa, DG83, its GIRE update, and Jan et al. (2005) also report a more or less steady-state structure in the energetic electron belt. This suggests that the population is persistent every time we sample it. Furthermore, from the work of Jan et al. (their Fig. 3), it is possible to estimate the variability of this population. Near Europa’s orbital distance, the 1st level of the ≥11-MeV electron flux is about a factor of 2-3 times the mean and the 2nd level is a factor of 10. These data include nearly all the Galileo orbits and are ordered in dipole L shell and angular intensity data to 10$^3$ cm$^{-2}$ s$^{-1}$ sr keV$^{-1}$. In a dipole model, the L shell can be calculated from L = r/cos$\theta$, where r is the distance from the center of the dipole and $\theta$ is the magnetic latitude of the point in question.)

Probably an upper limit on the variability of that population since, for example, Jan and his colleagues did not separate the data by pitch angle.

Coexisting with the MeV particles, there is dense, cold plasma (see, for example, the chapter by Kivelson et al.) and medium-energy particles in the keV energy range. Mauk et al. (2004) have generated fit functions for the tens of keV to tens of MeV ion data obtained by Galileo. Mauk et al. (2004) present various moments of the distributions function by radial distance from Jupiter. In Fig. 2, we have used the fits from Mauk et al. (2004) to create plots of particle intensity by species and L shell specific energies. Each panel shows a separate ion in the radial range from Io’s orbit to about 20 R$_J$. In large gaps in coverage are due to the fact that Mauk et al. were only able to compute fits at specific locations in the magnetosphere. Typically we would expect such curves to rise inward toward the planet because as particles are transported inward they are energized and there are typically more charged particles at lower energies. It is notable in Fig. 2 that ions above about 500 keV continue to increase inward across Europa’s orbit. On the other hand, lower-energy ions have dramatic changes at or near Europa’s orbital distance.

The ion density increases (moving radially inward in L in Fig. 2) in the ion densities below about 500 keV is likely caused by their loss to the neutral gas torus at Europa’s orbit (Lagg et al., 2003; chapter by Johnson et al.). Magnetospheric ions can undergo charge-exchange reactions with neutrals in the gas torus and leave the system. Charge exchange across sections are large at low energies but begin to fall off rapidly for protons above about 100 keV and for O$^+$ above several hundred keV (e.g., Lindsley and Slavin, 2003). If charge exchange is the dominant process for ions below about 500 keV near Europa’s orbit, then these ions are not principally lost to the satellite’s surface. It is likely then that the surface is not heavily weathered by these ions, as was believed prior to Galileo. This is not the case for MeV ions or electrons. Their mean intensities continue to rise radially inward to the planet, relatively unaffected by the gas.

One mechanism for populating such a neutral torus is collisions between corotating magnetospheric ions and neutrals in Europa’s atmosphere. Neutral modeling by Smyth and Encre Golf (2006) shows high column densities of O and H$_2$ that peak in the radial dimension at Europa’s orbit (see chapter by McGrath et al.). To further support the presence of neutral gas near Europa, Mauk et al. (2003) found evidence of ENA emissions from the region of the gas torus, with data from Cassini’s Magnetospheric Imaging Instrument (MIMI) during that spacecraft’s distant Jupiter flyby. Mauk and his colleagues correlated the ENA signal with the torus and not Europa itself (e.g., there are two emission peaks at the radial distance in question). To summarize our findings then, Europa is heavily weathered by MeV ions and ENA emissions by low-energy electrons with much higher intensities than at Ganymede or Callisto. The dominant mechanism for loss of medium energy ions near Europa’s orbit is by charge-exchange collisions with neutrals in a gas torus.
south magnetic latitude. The weathering of the moon depends somewhat on its magnetic latitude, since off the equator a fraction of charged particles do not have access to the moon’s surface. However, this may be most important for the moon’s surface. In Fig. 4, we show energy spectra from the dominant ions separately: protons, oxygen, and sulfur. Fits to some of these ion data have been performed using the following function (Mauk et al., 1994).

\[
\text{counts per cm}^2 \text{s sr MeV} = 4.23 \times 10^5 E^{-1.5} \text{(MeV)}^{1.5} + 5.11 \text{ (1)}
\]

Galileo closest approach distances for these passes are approximately 692 km (E4), 586 km (E6), 201 km (E12), 1439 km (E19), and 351 km (E26) (data from JPL press release, 2003). Kivelson et al. (1999) provide details of these Europa passes and Paranicas et al. (2000) present energetic charged particle data taken during them. For the Galileo E4 encounter, the fit parameters corresponding to equation (2) for various ions are given in Table 1.

In this subsection, we turn our attention to how the energy spectrum of charged particles is transported inward radially, accompanied by some variability. For this figure, the omnidirectional flux of DGR3 was divided by 4 to obtain intensity per steradian for comparison.

Turning next to energetic ions near Europa, we compare data taken from several different Galileo encounters with Europa. In Fig. 4, we show energy spectra from the dominant ions separately: protons, oxygen, and sulfur. Fits to some of these ion data have been performed using the following function (Mauk et al., 1994).

\[
\text{counts per cm}^2 \text{s sr MeV} = C \times E^{-1} \left( E + kT + \gamma_e \right)^{-1} \gamma_e^{-1} + 1 \text{ (2)}
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One of the Galileo detectors was severely overdriven in the inner magnetosphere. For several of the data sets plotted here, a correction was applied to recover, where possible, the actual rate. The high uncertainty in the rate near the lower energy end of the range probably explains the large variation and it should not be interpreted as variation in the local environment. For this figure, the omnidirectional flux of DGR3 was divided by 4 to obtain intensity per steradian for comparison.

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pointing electric field (see Kluhrens and Kivelson, 1993, for a description of the origin of this field). Also, a complete description of charged particle motion in magnetospheres can be found in Blair (1994). For a rigidly rotating jovian magnetosphere, the plasma flow speed near Europa's orbit is approximately 118 km/s. Typically detected values are lower; for example, Peterson et al. (1999) report a speed that is about 80% of rigid corotation.

For the energies of interest to us here, it is also important to consider the gradient-curvature drift, which is caused by the deviations from a uniform magnetic field. In the corotating frame of the plasma, all ions drift in the same direction as the plasma flow and electrons drift in the opposite direction. This means that in the inertial frame, all ions are traveling slightly faster than the plasma corotation speed and all electrons slower. Above about 25 MeV, the gradient-curvature drift of electrons is comparable to the \( E \times B \) drift in magnitude but opposite in direction and the electrons consequently have a net azimuthal motion that is retrograde, opposite to the prograde motion of Earth and the plasma flow. All the charged particles, except \( > 25 \) MeV electrons, would therefore bombard Earth from the trailing hemisphere to the leading hemisphere. Here, by trailing hemisphere we mean the hemisphere that trails Earth in its motion around Jupiter. By convention, the center of the trailing hemisphere is 270°W longitude, where 90°W is the center of the leading hemisphere and 0°W points toward Jupiter.

Some equations that quantify these effects further are provided next. The net azimuthal speed of the charged particle's guiding center with respect to Earth can be expressed as

\[
\omega = \Omega_0 + \omega_G(L_\lambda m) - \omega_0
\]

(3)

Here \( \Omega_0 \) corresponds to Jupiter's rotation rate in radians, \( \omega_G \) is the angular speed of Earth in radian per second, \( L_\lambda m \) is the particle's mirror latitude, and \( \omega_0 \) is the gradient-curvature drift rate. Following Thomsen and Van Allen (1994) this drift rate can be written

\[
\omega_0 = \pm 6.856 \times 10^{-4} E^{1/2} \frac{L_E}{G}
\]

(4)

We have modified the leading constant for Jupiter by taking the equatorial field strength as 4.28 G, \( L \) is the L shell, \( m_0 \) is the ion or electron rest mass in MeV, and \( \omega_0 \) is negative for electrons. We have preserved the Thomsen and Van Allen (1980) notation in using a function, "\( F \)," to express the dependence on the particle's mirror latitude \( \lambda_m \).

\[
F = \left( 0.04675 + 0.45333 \sin^2 \lambda_m \right) - 0.04675 \exp\left( -6.34566 \sin^2 \lambda_m \right)
\]

(5)

The net azimuthal speed of the particle's guiding center, \( \omega \), is very important for understanding the bombardment of Europa. This speed can be compared with the speed of the particle along the magnetic field line to understand the satellite bombardment. For these purposes, it is useful to define a field line contact time, \( t_c \), as

\[
t_c = \frac{2 \times (R_E - d)^2}{v} \quad d < R_E
\]

\[
t_c = 0 \quad d > R_E
\]

(6)

Here \( d \) is the impact parameter of the guiding center field line to Europa's center of mass and \( v \) is the net azimuthal speed of the guiding center field line with respect to Europa in kilometers per second. For charged particles of both species with energies less than about 200 keV, the maximum contact time in a rigidly corotating magnetosphere is about 30 s. This can be compared with the particle's half-bounce time, the time it takes a charged particle to travel from the magnetic equator to its magnetic mirror point and back to the equator. For a 100-keV charged particle with an equatorial pitch angle of 45°, the half-bounce time is about 7 s for an electron and 271 s for a proton (see Table 2). Therefore, for 100-keV protons, the contact time is much shorter than the half-bounce time. This means not all bounce phases have yet come into contact with Europa. Therefore, 100-keV and lower-energy protons are at least in principle capable of bombarding all points on Europa's surface with approximately the same flux.

TABLE 2. Charged particle parameters near Europa; all equatorial pitch angles are 45° and mirror latitudes are 23.1°.

<table>
<thead>
<tr>
<th>Species</th>
<th>( E ) (MeV)</th>
<th>( t_c ) (s)</th>
<th>( t_b ) (s)</th>
<th>( d ) (d/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrons</td>
<td>0.1</td>
<td>7.22</td>
<td>1.5</td>
<td>30.1</td>
</tr>
<tr>
<td>Electrons</td>
<td>1.0</td>
<td>4.2</td>
<td>6.5</td>
<td>31.51</td>
</tr>
<tr>
<td>Protons</td>
<td>0.1</td>
<td>271</td>
<td>62</td>
<td>30.69</td>
</tr>
<tr>
<td>Protons</td>
<td>1.0</td>
<td>105</td>
<td>250</td>
<td>29.69</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>0.1</td>
<td>343</td>
<td>789</td>
<td>29.78</td>
</tr>
<tr>
<td>( \alpha )</td>
<td>1.0</td>
<td>1535</td>
<td>353</td>
<td>29.69</td>
</tr>
<tr>
<td>( \beta )</td>
<td>1.0</td>
<td>486</td>
<td>1115</td>
<td>27.82</td>
</tr>
</tbody>
</table>

Formulas are based on the work of Thomsen and Van Allen (1980). For the calculation of the contact time, we assume that the magnetosphere is rigidly corotating at Europa's orbit.
Fig. 6. Trapped electrons below the critical energy can bombard Europa's surface. The horizontal axis is the distance in the projected plane between the first point of contact of the electron's guiding center field line with Europa and the point of interest. The value 1.0 on the x-axis includes the pole. For this plot, electrons with an equatorial pitch angle of -45° (solid line) and -10° (dashed line) were used.

Fig. 7. Electron energy flux into surface as a function Europa latitude at 270°W. Plusses represent the integral using the energy spectrum in equation (1) and assuming an isotropic pitch angle distribution; the open circles use a simple power law, \( J = 1.0 \times 10^{-5} \), for comparison; and the filled circles use the energy spectrum above assuming the pitch angle distribution goes as \( \sin \theta \).

Fig. 8. Power per unit area into Europa surface for 10 keV to ~25 MeV electrons. Contours are labeled in units of \( \text{W m}^{-2} \times \text{MeV cm}^{-2} \). In this longitude system, the center of the trailing hemisphere of Europa is at 270°W.

On Galileo is not very distorted from the nominal corotation direction (Patermann et al., 1999).

For completeness, we also present the value of \( P \) (equation (7)) as a function of Europa longitude and latitude. In Fig. 8, we show a contour plot of electron energy per unit area per second based on the energy spectrum given in equation (1). Here we assume the plasma flow is 80% of rigid and that Europa is an inert body whose orbit is in Jupiter's magnetic equatorial plane.

4. EXPECTED SURFACE EFFECTS

As previously reviewed by Johnson et al. (2004), the magnetospheric particle population contributes to the surface composition of Europa in three major ways: (1) the low-energy magnetospheric plasma impacts plasma ions, most notably ionogenic sulfur, and contributes to sputtering; (2) more-energetic ions, the dominant sputtering agents, eject neutrals that contribute to an ambient atmosphere, cause transport of material across Europa's surface, and contribute to the neutral torus; and (3) energetic electrons and light ions, the primary source of ionization energy, drive the surface chemistry. Ignoring possible ionospheric diversion of the flow and effects of the then-unknown induced fields from the ocean, Pospieszalska and Johnson (1989) computed a bombardment pattern of 1 keV sulfur ions on Europa's surface (their Fig. 5). In their calculation, the trailing hemisphere apex (i.e., 270°W, 0°N) received the highest flux and modeled fluxes fell away toward and onto the leading hemisphere. The implanted sulfur from radiation-induced chemistry and any endogenic sulfur will be in a radiation-induced equilibrium with a sulfate, \( \text{SO}_4 \), polymeric sulfur. Similarly endogenic or delivered carbon will be in radiation equilibrium with a carbonate, \( \text{CO}_3 \), and polymers of carbon. In addition, as discussed, the irradiation of the ice matrix will lead to \( \text{H}_2 \), \( \text{O}_2 \), and \( \text{H}_2\text{O} \) all detected in either the atmosphere or the surface (see the chapter by Carlson et al. for a discussion of surface species and chemistry). An important goal of future work is to separately determine the role of these effects in producing the darkened terrain on the trailing hemisphere, the production of an atmosphere, and the population of the ambient plasma. In discussing the surface reflectance spectrum, we note that the various spectral signatures (UV, visible, IR) sample different depths. Therefore, implantation primarily affects the very near surface and electrons affect the material to greater depths. However, gardening buries the implanted sulfur, so that a separation by depth may not be straightforward. The similarity of the bombardment patterns of 1 keV sulfur ions and energetic electrons (Pospieszalska and Johnson, 1989; Parpia et al., 2001) will only lend itself to separation if the sampling depth of the spectral signatures are
carefully analyzed. Further understanding of the moon-plasma interaction (see the chapters by Kivelson et al. and Khurana et al.) will help us refine our understanding of the sulfur ion bombardment once the effects of the induced field are included. Such comparisons address a major theme of this chapter: the extent to which exogenic processes are understood in producing observable features on Europa.

As noted in the previous section, the penetration depth of charged particles into ice depends on a number of factors, including charged-particle type and energy. A published estimate of the maximum dose vs. depth for charged particles into water ice at Europa’s surface is shown in Fig. 9. These curves were created using a Novice radiation transport code and various energy spectra based on spacecraft data as described in Paranicas et al. (2002). An important feature of this plot is that the trailing hemisphere dose near Europa’s equator is dominated at almost all depths by the electrons. This fact, combined with the asymmetry of the electron dose onto Europa’s surface described above, led us to compare the dose pattern with the distribution of hydrated sulfates, potentially sulfuric acid hydrates (see Paranicas et al., 2001, and references therein). The favorable comparison suggested that the surface material in the dark regions, which are primarily on Europa’s trailing hemisphere, are radiolysis processed to significant depths by the energetic electrons. This also suggests other leading/trailing asymmetries, such that at 1-keV sulfur ions, might be a secondary effect.

Impacts of the various radiation dosage components in Fig. 9 must be considered separately for surface effects on the leading and trailing hemispheres. Energetic heavy ions deposit most of their energy very close to the surface. Noting that grain sizes are ~50 μm, sulfur ions are only implant into the surficial grains and the heavy ions are the primary spattering agents having the highest rate of energy loss per ion at submicrometer depths. Because of the dynamics of their motion, these heavy ions globally impact the surface in both hemispheres. Therefore, the curves in Fig. 9 for ions can be used as approximate dose-depth curves everywhere on the surface of Europa. The protons and especially energetic electrons lose energy in the ice more slowly and deposit this energy at much larger depths. Energetic electrons deliver the most total energy to the trailing hemisphere and electrons between about 100 keV and 25 MeV have much less impact on the leading hemisphere. Just above 25 MeV, electrons preferentially impact the leading hemisphere and become more uniform over the surface with increasing energy above that.

In Fig. 10, we show a dose-depth presentation with specific energy ranges represented separately. These are based on our implementation (Sturner et al., 2003; Cooper and Sturmer, 2006, 2007) of the GEANT transport code with inclusion of all significant nuclear and electromagnetic (e.g., bremsstrahlung) interactions for primary and later generation particles and γ-ray photons. These researchers further employed the semi-analytical moon interaction model of Fillius (1988) to derive energy ranges of electrons primarily impacting the trailing (1–20 MeV) and leading (20–40 MeV) hemispheres of Europa with highest probability. Broadly speaking, the dosage profiles for these two respective energy ranges suggest a drop by 2 orders of magnitude from the trailing to the leading hemisphere for MeV electrons. However, at each surface point and at each depth, care must be taken in assessing which particles dominate the dose. For instance, around the apex of the leading hemisphere, the 10-keV to 100-MeV proton dose dominates over the 20–40-MeV electron dose down to about 3 mm from Fig. 10. Selected times to accumulate a net dose (from all sources) of ~100 eV per water molecule, equivalent to a volume dosage of 60 Gigardins per gram of H₂O, are also indicated. These times are only ~10 yr at the micrometer level but 10^9 yr at tens of centimeters. On multi-billion-year timescales the dosage effects of cosmic rays penetrating from outside the Jupiter magnetosphere for energy deposition to several meter depths in the surface ice, and decay of naturally abundant radiotopes (e.g., K⁴⁰) throughout the ice crust to kilometers in depth (Chyba and Hand, 2001) become important.

4.1. Radiolysis

As described in the chapter by Carlson et al., the energy deposited by the charged particles and also by the UV photons cause dissociations and chemical reactions in Europa’s surface. A principal product is hydrogen peroxide based on the reaction 2 H₂O → H₂O₂ + H₂. Since H₂ is volatile and mobile in ice at the temperatures relevant to Europa’s surface, it diffuses out more readily than other products. The
The surface sputtering rate is determined by the energy spectra of ions and the yield, the number of neutrals ejected per incident ion. Furthermore, decomposition and loss of H₂ and O₂ from ice also takes surface material into gas phase, so the surface erosion rate has a temperature dependent component that dominates above ~100 K (chapter by Johnson et al.). Sputtering yields these trapped species could potentially include complex organics of high interest for astrobiology. The presence of radionuclides in the character of the organic. Discrete peaks in a molecular mass spectrum can be indicative of biological sources but these peaks can be displaced by radiation processing. A key implication for astrobiology is that, whereas neutral mass spectrometry techniques can provide clues to the presence of organic biosignatures that have not been highly degraded by irradiation (see also the chapter by Hand et al.). One approach is to focus on gas-phase ions, e.g., on the leading hemisphere and in topographically shielded locations.

**4.2. Sputtering**

In comparison to the volume ice effects of radiolysis dominated by electrons and protons, sputtering mainly applies to erosion of upper molecular layers by impact of high energy particles. The charged particles from cosmic rays and solar wind produce electrically charged ions originating from the ion torus that have undergone acceleration in the magnetosphere of Jupiter. Sputtering liberates molecules that transiently populate the atmosphere resulting in the ionization of sulfur, oxygen and carbon by energetic ions. Lighter molecules, such as H₂, may escape more easily, leaving behind an atmosphere that is richer in heavy molecules such as CO₂ (see also the chapter by Johnson et al.). Sputtering primarily affects water molecules from the icy surface, but also carries off any newly formed and earlier deposited by an impact event.

**4.3. Radiative Damage**

Both penetrating and non-penetrating radiation produces defects in ice. In addition, water vapor is sputtered and post-irradiated, which can lead to an amorphous layer, depending on the surface temperature. Both processes occur at very low rates, and it is important to be aware that reflectance spectra are sensitive to the abundance of the amorphous phase, leaving behind an atmosphere that is richer in heavy molecules such as CO₂ (see also the chapter by Johnson et al.). Sputtering primarily affects water molecules from the icy surface, but also carries off any newly formed and earlier deposited by an impact event. The porosity of Europa's regolith will reduce, by approximately a factor of 4, the effective sputtering yield of species such as H₂ and O₂, more easily escape (see also the chapter by Johnson et al.). Some O₂, CO₂ can be trapped in inclusions (Johnson and Jesser, 1997; Shi et al., 2007) or in mixed gas clathrates, whereas these are stable at the sur-
5. SUMMARY AND CONCLUSIONS

We have shown above that energetic particle fluxes typically increase inward from that orbit. We also show that there are heavily depleted because of charge exchange collisions with neutrons. Many of these energetic ions are lost from the system before they reach Europa or possibly radially inward from that orbit. We also show that there are species that preferentially impact Europa's surface, where the bombarding flux of some energetic electrons is relatively small. This is because the ratio of the speed of these particles parallel to the magnetic field line to the speed at which they are carried azimuthally around the magnetosphere is very large.

The radiation environment near Europa varies in time but only to a limited extent. At MeV energies, data reveal less variation in the magnetic field of the planet, as expected. This suggests that some of the variability due to injections and other types of magnetospheric activity are less likely, as is the case at Saturn, to dominate the fluxes near Europa for many species and energies. In fact, one study of the 21-MeV electron channel on Galileo over the entire orbital mission found that the standard deviation from the average value was only 5%. In medium energy ions, the total integrated variation in sparse sampling over about 4 yr found a factor of ~2 variation. Further studies of the radiation environment and Europa's place in it would be needed to provide a comprehensive measurement of the flux tube footprint.

We have shown above that energetic particle fluxes typically increase inward from that orbit. We also show that there are species that preferentially impact Europa's surface, where the bombarding flux of some energetic electrons is relatively small. This is because the ratio of the speed of these particles parallel to the magnetic field line to the speed at which they are carried azimuthally around the magnetosphere is very large.

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Europa's Interaction with the Jovian Magnetosphere

Margaret G. Kivelson and Krishan K. Khurana
University of California, Los Angeles

Martin Volwerk
Österreichische Akademie der Wissenschaften

Europe is embedded in Jupiter’s magnetosphere where a rapidly flowing plasma interacts electromagnetically with the moon’s surface and its atmosphere. In this chapter, the phenomenology of the interacting system is presented and interpreted using both qualitative and quantitative arguments. Challenges in understanding the plasma environment arise partly because of the diverse scale-lengths that must be considered as well as the non-linear nature of the interactions. The discussion that follows describes selected aspects of the interacting system. On the scale of gyroradii, we describe the effects of newly ionized particles on fields and flows and their relation to wave generation. On the scale of Europa radii, we discuss the structure of the local interaction. On the scale of the tens of Jupiter radii that separate Europa from Jupiter’s ionosphere, we describe the aurora generated near the magnetic footprint of Europa in Jupiter’s upper atmosphere. We end by stressing the relevance of plasma measurements to achievement of goals of a future Europa Orbiter mission.

I. INTRODUCTION

The Galilean moons, although small, play a distinctive role in the history of solar system science. Galileo recognized that their motions in periodic orbits around Jupiter were compelling analogs of planetary bodies in a heliocentric system (see chapter by Alexander et al.). The complex orbital interactions of the inner moons were found to account not only for orbital stability (e.g., Goldreich, 1965), but also for enhanced tidal heating (Peale et al., 1979), which powers volcanic activity on Io and melting of the ice beneath the surface of Europa. That fluid oceans could be present beneath the icy crust of the three outer moons was discussed (Lewis, 1971) decades before spacecraft observations provided support for (if not full confirmation of; see chapter by Khurana et al.) this speculation for some of the moons, in particular, Europa.

Concurrent with studies of the interior, the particle and fields environments of the moons began to attract attention following the discovery of Io’s control of jovian decametric emissions (Bigg, 1964). Goldreich and Lynden-Bell (1969) recognized that an electromagnetic link between the moon and Jupiter’s ionosphere could explain the observations, a suggestion that implied the presence of plasma along the Io magnetic flux tube. Somewhat later, the existence of an extended nebula around Io’s orbit, the Io torus, was established (Kaput et al., 1976; Meckler and Evraire, 1977). In turn, the observations of plasma therein provided evidence for the existence of an induced magnetic field along the Io torus (Schunk, 1971). The discovery promoted the priority of Europa and its local plasma environment as targets for further planetary exploration. Although only 3 of the 12 flybys of the Galileo prime mission (1995 through 1997) passed close to Europa, the next phase of the mission, designated the Galileo Europa mission, devoted half of its 14 flyby opportunities to Europa. Table I summarizes various relevant features of Galileo’s flyby trajectories (or “passes”) plotted in Fig. 1. The final stage of Galileo’s odyssey included a specially designed pass in which magnetometer measurements found a predicted reversal of the orientation of the internal dipole moment, thus confirming the presence of an inductive field at Europa (Kivelson et al., 2000).

This chapter addresses the subject of Europa’s interaction with the particles and fields of the jovian magnetosphere. The topic presents a considerable challenge because the moon and its magnetized plasma environment interact nonlinearly. Relevant to the interaction are matters as diverse as the chemical composition of the surface from which particles are sputtered, the properties of the energetic particles responsible for the sputtering, the temporal and spatial characteristics of the magnetospheric plasma near the orbit of Europa, properties of the magnetic field that confines the plasma, and the electromagnetic characteristics of the moon and its ionosphere. Europa’s response to
Plate 26. Contour plots of the GIRE/DG83 model E > 10 MeV integral proton (left) and E > 1 MeV electron (right) fluxes for the jovian magnetosphere radiation region. The model provides the flux as a function of position, energy, and pitch angle. The fluxes presented here have been integrated over pitch angle. Note that outside the contour of L = 12, the proton model is set to 0, whereas the electron model fluxes outside L = 16 are only approximate since they are not considered trapped in the model (see DG83 for details). Figure courtesy of I. Jun.

Accompanies chapter by Parnicas et al. (pp. 529–544).

Plate 27. Observed and modeled magnetic field for the E4 flyby. Red = measurements of Kivelson et al. (1997); dashed black = modeled field with no internally induced field; blue, green, and black = modeled field including induction in a 100-km-thick ocean lying beneath a crust of 25 km for ocean conductivities of 100, 250, and 500 mS/m, respectively. From Schilling et al. (2007).

Accompanies chapter by Kivelson et al. (pp. 545–570).