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Europa's near-surface radiation environment

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[1] As flux tubes are carried over Europa, hundreds of keV to tens of MeV electrons are absorbed by the moon due to their short bounce times. This results in an asymmetry in energetic charged particles in the near surface environment and in the bombardment of Europa's surface. For example, electrons between about 0.1 and 50 MeV do not have direct access to more than 50% of the sphere at 100 km Europa altitude. Moreover, a hypothetical orbiting spacecraft at this altitude would see a reduction of about 33% of the sky, based on Europa's obstructing its field-of-view. We find that the predicted radiation reduction due to the moon's presence is consistent with data from Galileo's Energetic Particles Detector (EPD). In this paper, we present data that illustrate this consistency and use standard models of the radiation environment to evaluate the energetic electron fluence at 100 km. **Citation:** Paranicas, C., B. H. Mauk, K. Khurana, I. Jun, H. Garrett, N. Krupp, and E. Roussos (2007), Europa's near-surface radiation environment, *Geophys. Res. Lett.*, *34*, L15103, doi:10.1029/2007GL030834.

1. Introduction

[2] Data from the Galileo spacecraft have quantified the intense radiation belt that exists inward of the orbit of Jupiter's satellite Ganymede ($R \sim 15\ R_J$). A recent summary of findings using Galileo Energetic Particles Detector (EPD) data [*Jun et al.*, 2005], for example, has reported that the flux of $\geq$11 MeV electrons increases by roughly 2 orders of magnitude inward from Ganymede's orbit to Europa's ($R \sim 9.4\ R_J$). Jun's work also illustrates that this steep gradient is encountered on all Galileo passes through this region. But the Galilean satellites co-located with this radiation belt, do not receive the full radiation dose characteristic of their surroundings at all points on their surfaces. This is because the presence of the body as an absorber and/or its electromagnetic fields tend to reduce or deflect the radiation. For example, Ganymede's internal magnetic field reduces the access of charged particles to the surface [see, e.g., *Williams et al.*, 1998]. At low Ganymede latitudes, that satellite's surface is threaded with closed field lines (i.e. magnetic field lines with both footpoints passing through the surface), which can support very little trapped flux. In this paper, we will consider the reduction of radiation near and into Europa's surface.

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[3] Previous illustrations of flux reduction near Jupiter's satellites have been demonstrated both with data and models. In addition to the work of Williams and his colleagues on the Galileo Ganymede data, *Thorne et al.* [1999] showed how charged particle trajectories are perturbed by fields near Io. Using relatively weak satellite fields in their model, they predicted that energy- and pitch-angle dependent electron drift paths would be distorted near that satellite. In some cases electrons would not have direct access to Io's trailing hemisphere. These predictions using calculated trajectories were compared with Galileo measurements. In a previous study of Europa, *Paranicas et al.* [2000] presented data from a few close passes of Europa showing several examples of decreases in count rates of both ions and electrons. Some of these count rate decreases were associated with Europa as an obstacle. For example, ions would have had to pass through the moon to reach the detector when the EPD telescope was close to and viewing in the direction of Europa. Other decreases were assumed to be due to the spacecraft encountering flux tubes that had previously been in contact with Europa. Such flux tubes can be emptied of some electrons as they come into contact with Europa's surface.

[4] With both NASA and ESA studying potential missions to Europa, the subject of Europa's radiation environment has again become topical. From the perspective of surface measurement, it makes sense to consider which regions would be most heavily weathered by charged particles. Extensive laboratory evidence exists, for instance, on how water ice is modified and new molecules are created by energetic ions and electrons [e.g., *Loeffler et al.*, 2005]. For spacecraft in orbit of the moon or landers, it is advantageous to describe regions most shielded from MeV electrons, since these particles have a high potential to disrupt other measurements. The plan of this paper is to review charged particle motion near Europa and to predict the electron fluxes near that moon. We use these predictions and the GIRE model [*Divine and Garrett*, 1983; *Garrett et al.*, 2002] to estimate the electron fluence into a hypothetical spacecraft at 100 km altitude above the moon. We then turn to the Galileo data to examine evidence of the predicted flux reductions.

2. Particle Motion Near Europa

[5] If the magnetosphere of Jupiter is rigidly corotating, plasma flow speeds at Europa's orbit are about 118 km/s. Europa travels about 14 km/s in its orbit, so that charged particles are overtaking the satellite at all times. Energetic charged particles do not corotate at the same speed as the cold plasma because of additional gradient and curvature drifts in the azimuthal direction [e.g., *Thomsen and Van Allen*, 1980]. Ions drift in the same direction as the plasma, so their net azimuthal motion is faster than the cold plasma

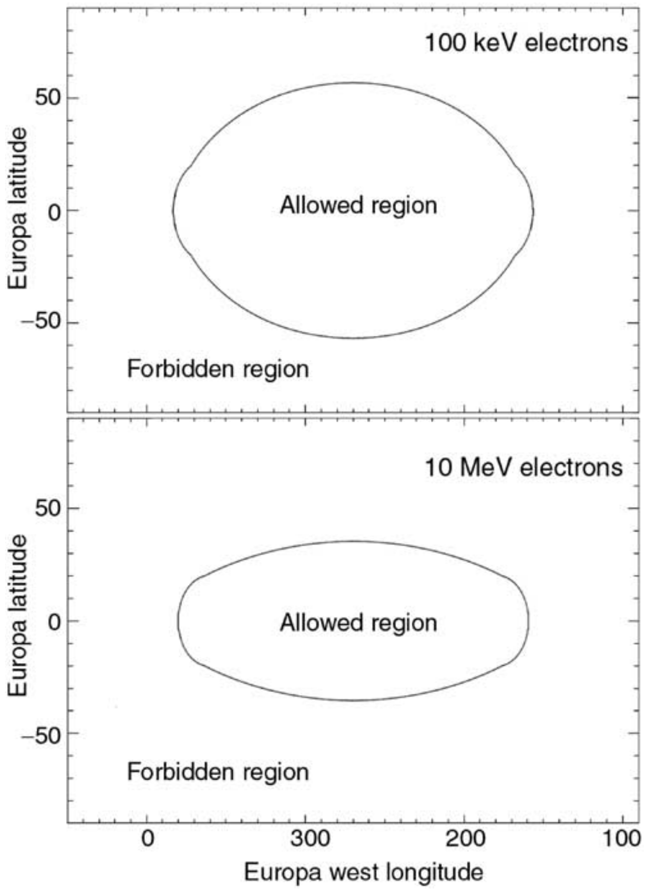

Figure 1. Calculation results separating allowed (inside enclosure) and forbidden positions for electrons at a Europa altitude of 100 km. The traces are centered on the trailing hemisphere of Europa (270°W). Electrons have a magnetic mirror latitude of 10°.

motion. Electrons drift opposite to corotation and therefore move slower than the cold plasma. Above about 25 MeV, the electron gradient-curvature drift becomes about equal and opposite to the rigid corotation speed of plasma at Europa. This means that the guiding center field lines of all charged particles except >25 MeV electrons sweep past Europa from its trailing hemisphere to its leading hemisphere and for >25 MeV electrons, the electrons sweep over Europa from its leading to its trailing hemisphere.

[6] In addition to a net azimuthal motion, an electron also gyrates around the magnetic field line and its guiding center moves in latitude between magnetic mirror points. For a 5 MeV electron, with a magnetic mirror latitude of 10°, the electron gyroradius near Europa is about 33 km or 0.02 R_E compared with 587 km for a proton with the same parameters (where we take 1 R_E = 1561 km). We therefore neglect the gyroradius of electrons and use the so-called guiding center approximation. The total bounce time for such an electron is about 7 s (compared with 67 s for a proton). During the 3.5 s or so it takes an electron to travel from the magnetic equator to its mirror point and back to the equator, the electron's guiding center magnetic field line moves about 283 km in azimuth (4938 km for a proton). These distances become shorter if the magnetosphere is not corotating rigidly [*Paterson et al.*, 1999] and for energetic electrons these azimuthal distances are much smaller than the diameter of Europa.

[7] These numbers suggest that as field lines are carried past Europa, electrons of all bounce phases will precipitate into the near-equatorial surface close to the first point of contact between the magnetic field line and the satellite. Put another way, a 5 MeV electron cannot "leapfrog" over Europa [*Paonessa and Cheng*, 1985], no matter what its bounce phase. Lower energy electrons and energetic ions of similar energies would bombard Europa over more of its surface. Energetic protons, for instance, would bombard the entire surface of Europa, partly because as magnetic field lines are carried past Europa, protons of some bounce phases can survive. In a previous study, we connected this prediction of the differential ~MeV electron loss rate at Europa's surface with radiolytically modified surface constituents observed spectroscopically [*Paranicas et al.*, 2001].

3. Estimated Flux Reductions

[8] In this section, we discuss the near space environment of Europa and the effects of the moon on trapped ~MeV electrons as a function of altitude, longitude and latitude. Based on the discussion in the previous section, it is possible to determine whether electrons can gain access to the near surface of Europa. To perform such calculations, we assume that flux tubes carried over an inert Europa lose flux as it precipitates onto the moon's surface. We assume the Jovian field can be represented as a dipole and that the corotation speed of the plasma is rigid. Europa is taken at 0° Jovian latitude for simplicity. In Figure 1, we show two examples of the boundary between allowed and forbidden positions at 100 km Europa altitude. The positions outside the enclosed areas represent locations where electrons do not have direct access. The smaller number of allowed positions of the more energetic electrons has to do with their shorter bounce times. This area shrinks in size with increasing electron energy up to about 25 MeV, at which point the region of allowed positions shifts hemispheres and becomes centered on the leading hemisphere. As the energy increases above 25 MeV, more of the sphere becomes allowed (this is because the relative azimuthal speed of the electron guiding center and Europa is increasing from its minimum around 25 MeV).

[9] To further illustrate the dependence of allowed positions with energy, mirror latitude, and Europa altitude, we have presented estimates in Table 1 for several of these parameters. These numbers represent the fraction of the sphere with allowed positions. Generally speaking, electrons between about 100 keV and 50 MeV cannot populate half the sphere at low altitude because their bounce periods are fast compared to their transit time past the satellite in azimuth. Using Table 1, we calculated the electron fluence using an updated Jovian radiation environment model [*Divine and Garrett*, 1983], the GIRE model [*Garrett et al.*, 2002]. In Figure 2, we show the electron fluence onto a hypothetical spacecraft. The upper curve assumes a spacecraft in free space at Europa's orbital distance for 30 days, i.e. as if the moon were not there, while the lower curve assumes a circular polar orbit of Europa at 100 km. We do

Table 1. Fraction of Sphere Allowed for Electrons as a Function of Altitude, Energy and Mirror Latitude

Altitude, km	Energy, MeV	Mirror Lat., deg	Fraction Allowed
100	0.01	10	0.71
100	0.1	45	0.50
100	0.1	10	0.42
100	0.5	10	0.35
100	1	10	0.34
100	5	45	0.36
100	5	10	0.31
100	10	10	0.29
100	50	10	0.34
200	0.01	10	0.72
200	1	10	0.39
200	5	10	0.37
500	1	10	0.51

not consider electrons above 100 MeV. Europa is assumed to always be at 0° Jovian latitude for this calculation, so this is a slight overestimation of the dose. Such a reduction in dose due to the presence of Europa would be critical to a spacecraft in orbit of Europa because MeV electrons are potentially hazardous to spacecraft electronics and are very hard to shield out. A circular orbit over the pole of Europa is predicted to receive a lower dose than an equatorial orbit.

[10] It is worth noting further that while we assume some positions are allowed in our calculation, electron fluxes would not impact a hypothetical spacecraft from all look directions. For example, a hypothetical spacecraft above the moon's surface along its trailing hemisphere at high latitude would only receive electron flux from one field line direction and not the other. This second reduction is similar to that expected by purely geometric arguments, i.e. ignoring the trapped particle motion. The approximate amount of obscuration due to the presence of Europa would be about 33% at 100 km, 27% at 200 km and 17% at 500 km. This is based on the reduction of the sky (or of 4π solid angle field of view) because of Europa's presence.

[11] A third and final reduction to the flux into Europa's near environment is due to its induced field [*Kivelson et al.*, 1999]. The induced field cancels changes in the surrounding Jovian field. The background Jovian field at Europa varies in a regular way because of the tilt of the dipole and the rotation of the planet. Near its largest excursions in Jovian north and south latitude, Europa's induced field strength would be at a maximum. The induced field reduces the varying horizontal component of the background field. When such an induced field is added to the background field, it qualitatively results in the field lines being draped around the body (i.e. not passing through it as they do near Jupiter's magnetic equator). This would have the effect of reducing the rate at which new flux tubes are carried over the satellite. Quantifying this effect on MeV electrons requires a simulation where particles are followed, such as performed by *Thorne et al.* [1999] for Io.

[12] Lastly, when Europa is away from the Jovian magnetic equator, electrons can be trapped at lower latitudes without encountering the satellite. This slightly modifies the bombardment area. For example, if the moon is decreasing in Jovian north latitude, it would encounter the electrons whose mirror latitudes are very close to the moon's instantaneous latitude over its southern hemisphere. Since this is a very narrow part of the particle distribution, it would likely add only a small amount to the flux impacting the moon.

4. Galileo Data

[13] We have previously reported on several Galileo wake passes and showed how flux depletions appear in the data. It is worth revisiting that subject by looking at the data that are of interest to us here, namely MeV electron data. The Galileo EPD had only a single differential channel (i.e., with a fixed energy passband) to detect such particles, channel "b1," nominally measuring ~1.5–10.5 MeV electrons. These electrons are detected with full angular coverage, meaning the EPD telescope is stepped through about 180 degrees and at each step data are accumulated over a spacecraft spin (see *Willliams et al.* [1992] for details).

[14] In Figure 3, we show spin-averaged count rates of EPD channel b1 for three wake passes: E4, E11, and E15.

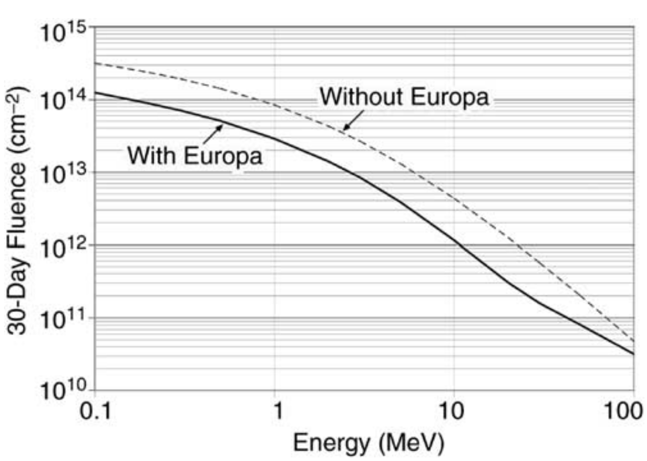

Figure 2. Calculation of 30-day electron fluence, or number of particles per cm^2 above a cutoff energy. The upper curve shows the fluence when Europa is absent and the lower curve shows the fluence when an approximate reduction is made, using the parameters of Table 1.

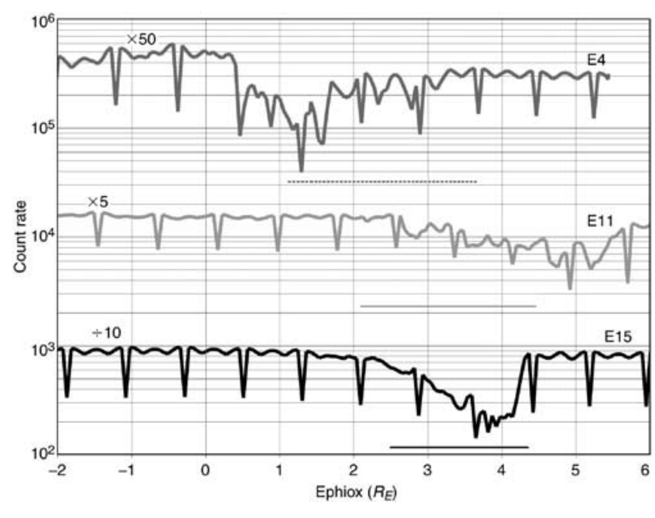

Figure 3. Spin-averaged count rates from the ~1.5–10.5 MeV electron channel on EPD plotted as a function of ephiox, the x-axis of the ephio system. The horizontal lines correspond to the nominal geometric wakes in ephio coordinates.

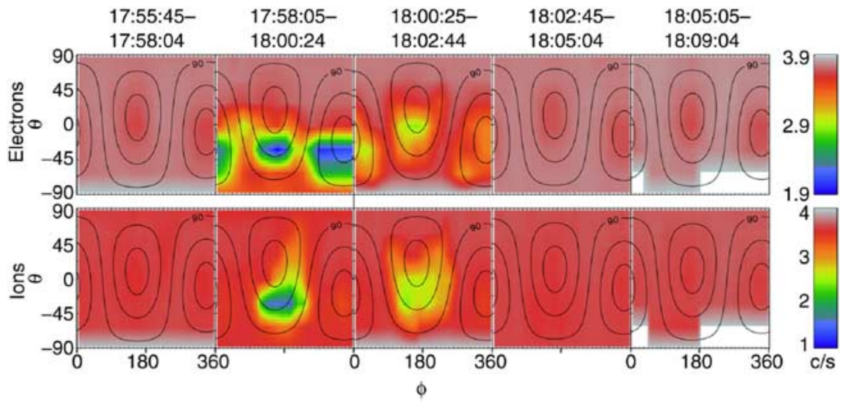

Figure 4. Ion and electron count rate decrease as the spacecraft passes near Europa during e26 (on 2000–003). Each box shows the sphere of the detector including about 2 min of data in counts per s. The horizontal axis of each box is detector φ from 0° to 360° and the vertical axis is the detector θ from −90° to 90°. The stepping through motor position means the sampling is sequential vertically, so not all data in each square are taken at the same time. Pitch angle contours are added at 30° intervals.

The count rate is plotted as a function of spacecraft position on the ephiox axis, the x-axis in the ephio coordinate system. The ephio coordinate system is a Europa-centered coordinate system that has its x-axis in the corotation direction at the time of closest Galileo approach, the z-axis is parallel to Jupiter's spin axis and the y-axis completes the system; units are in Europa radii [see, e.g., *Kivelson et al.*, 1999]. Lines are shown under each count rate corresponding to periods the spacecraft is within 1 R_E of the moon on the ephioy axis. This is equivalent to the spacecraft being in the nominal geometric wake of Europa. Periodic decreases in the count rate occur because the detector is stepped behind a foreground shield for calibration purposes. The main decrease in the count rate occurs when the spacecraft encounters flux tubes that had previously been in contact with Europa. Outside of these flux tubes, the data are fairly constant. The decrease in the count rate is up to about a factor of 5–10.

[15] To complement these wake decreases, there was a single Galileo Europa encounter when the spacecraft had a very close approach at high latitude. This was during the E26 encounter on day 2000–003 at about 18:00 UTC. In Figure 4, we show data from this encounter for one electron (b1, as above) and one ion channel a3 (nominally detecting 120–280 keV ions). Each box shows approximately 2 min of data where the log of the count rate is plotted as a function of detector polar angle, θ (ordinate) and azimuthal or spacecraft spin angle, φ (abscissa). Each box corresponds to a set of horizontal rows, each of which is at a fixed motor position with a full spin of the spacecraft. The data are therefore accumulated row by row, in vertical sequence up and down, as the motor position advances forward and backward. The spin period of the spacecraft is divided into sectors in the processing but here we have smoothed the data. Furthermore, pitch angle contours at 30° intervals have been added. The planetary loss cone creates a slight decrease in count rate along the magnetic field line. The θ = 90° telescope position lies along the spacecraft spin axis and φ = 0° points toward the south ecliptic.

[16] As the spacecraft passed Europa at about 18:00 UTC, the detector was oriented so that the direction to the sun ($\theta = -90$), was nearly in the direction of motion of the spacecraft. For the look direction associated with $\theta \sim -30$ and $\varphi = 180$, the detector was viewing toward Europa and a bite-out was seen in energetic ions. The small amount of electron and ion flux in this sector of the sphere corresponds to forbidden trajectories for both species. A similar absence of counts for selected look directions was observed in energetic ions during E4 and E12 [*Paranicas et al.*, 2000], when Galileo passed Europa at closest approach altitudes of 688 km and 196 km. The other decrease in the 17:58–18:00 UTC panel was when the detector was viewing around $\varphi = 0$ (note that no similar decrease was seen in the ions). This decrease corresponds to times the look direction of the telescope was in the direction of the Jovian field line and pointing away from the satellite. A smaller decrease in the electron count rate was seen in the same directions in the next time panel. This look direction corresponds to electrons that, when traced backward in time, would have passed through their southern magnetic mirror point and then Europa itself. These panels show the flux tubes in the process of emptying and a similar data set taken along the leading hemisphere, if one existed, would show essentially all positions depopulated.

5. Discussion

[17] This paper has illustrated, using calculations and data, that the hundreds of keV to tens of MeV electrons near Europa's surface fall off substantially in intensity from the trailing to the leading hemisphere. Data taken in Europa's plasma wake show remnants of these satellite absorptions. Decreases in the few MeV electron count rate were observed when the spacecraft encounters flux tubes that were recently in contact with the moon. The Europa E26 data, a unique combination of high latitude and low altitude, showed how flux tubes were depleted as they are carried over the satellite. In addition to data, we have estimated the amount of flux reduction over a hypothetical sphere at 100 km altitude, as a function of energy and mirror latitude. We incorporated these estimates into a statistical model of the Jovian radiation environment and estimated a fluence at 100 km. The reduction to about one-third of the fluence at similar Jovian

distances but away from the moon would be substantial for an orbiting spacecraft.

[18] The challenge of missions to Jupiter has been the harsh radiation environment, especially that inward of the orbit of Ganymede. The Galileo spacecraft was designed to withstand a large radiation dose, dominated by energetic electrons, as it orbited the planet and repeatedly reached Jovian altitudes of only a few R_J. A recent report documents system failures on Galileo because of energetic charged particles [*Fieseler et al.*, 2002]. Hypothetical Jovian satellite orbiters and landers, conceptualized but not yet realized, may offer an opportunity to circumvent the most difficult radiation issues. As we learned from Galileo, Ganymede's near-space environment has much lower ion and electron fluxes than the surrounding medium. At Europa, we are learning the same is true, despite this satellite having no permanent magnetic field of its own. In both cases, the satellite's attenuation of the surrounding radiation means that a spacecraft in near-satellite orbit would receive a much smaller dose of radiation than a spacecraft at Europa's orbital distance from Jupiter but away from the satellite itself. Furthermore, instruments put onto the moon's surface along the leading hemisphere would receive a dose with lower fluxes of 100 keV to 25 MeV electrons than in the surrounding medium.

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References

Divine, N., and H. B. Garrett (1983), Charged particle distributions in Jupiter's magnetosphere, *J. Geophys. Res.*, *88*, 6889–6903.

Fieseler, P. D., S. M. Ardalan, and A. R. Frederickson (2002), The radiation effects on Galileo spacecraft systems at Jupiter, *IEEE Trans. Nucl. Sci.*, *49*, 2739–2758.

Garrett, H. B., I. Jun, J. M. Ratliff, R. W. Evans, G. A. Clough, and R. W. McEntire (2002), Galileo interim radiation model, *Rep. D-24811*, Jet Propul. Lab., Pasadena, Calif.

Jun, I., H. B. Garrett, R. Swimm, R. W. Evans, and G. Clough (2005), Statistics of the variations of the high-energy electron population between 7 and 28 Jovian radii as measured by the Galileo spacecraft, *Icarus*, *178*, 386–394.

Kivelson, M. G., K. K. Khurana, D. J. Stevenson, L. Bennett, S. Joy, C. T. Russell, R. J. Walker, C. Zimmer, and C. Polanskey (1999), Europa and Callisto: Induced or intrinsic fields in a periodically varying plasma environment, *J. Geophys. Res.*, *104*, 4609–4625.

Loeffler, M. J., U. Raut, R. A. Vidal, R. A. Baragiola, and R. W. Carlson (2005), Synthesis of hydrogen peroxide in water ice by ion irradiation, *Icarus*, *180*, 265–273.

Paonessa, M., and A. F. Cheng (1985), A theory of satellite sweeping, *J. Geophys. Res.*, *90*, 3428–3434.

Paranicas, C., R. W. McEntire, A. F. Cheng, A. Lagg, and D. J. Williams (2000), Energetic charged particles near Europa, *J. Geophys. Res.*, *105*, 16,005–16,015.

Paranicas, C., R. W. Carlson, and R. E. Johnson (2001), Electron bombardment of Europa, *Geophys. Res. Lett.*, *28*, 673–676.

Paterson, W. R., L. A. Frank, and K. L. Ackerson (1999), Galileo plasma observations at Europa: Ion energy spectra and moments, *J. Geophys. Res.*, *104*, 22,779–22,792.

Thomsen, M. F., and J. A. Van Allen (1980), Motion of trapped electrons and protons in Saturn's inner magnetosphere, *J. Geophys. Res.*, *85*, 5831–5834.

Thorne, R. M., D. J. Williams, L. D. Zhang, and S. Stone (1999), Energetic electron butterfly distributions near Io, *J. Geophys. Res.*, *104*, 14,755–14,766.

Willliams, D. J., R. W. McEntire, S. Jaskulek, and B. Wilken (1992), The Galileo energetic particles detector, *Space Sci. Rev.*, *60*, 385–412.

Williams, D. J., B. H. Mauk, and R. E. McEntire (1998), Properties of Ganymede's magnetosphere as revealed by energetic particle observations, *J. Geophys. Res.*, *103*, 17,523–17,534.

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