Energy Spectra Near Ganymede From Juno Data

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Abstract The moon Ganymede has a strong internally generated magnetic field that separates the surface into two regions, with the polar surface magnetically connected to the Jovian environment. Consequently, the weathering of Ganymede's surface by plasma and energetic charged particles trapped in the Jovian magnetosphere is not uniform. At the same time, optical data suggest differences in the surface ice between the polar and equatorial regions. Here, we use Juno spacecraft data to characterize the charged particle environment along Ganymede's orbit (from about 50 eV to 1 MeV for electrons and 10 eV to 6 MeV for protons). These results put us into a better position to test the hypothesis that space weathering by electrons causes the brighter poles of Ganymede, given that electron fluxes are likely to be more clearly separated between the polar and equatorial regions.

Plain Language Summary Electron weathering of ice may be the reason Ganymede's poles are brighter. These particles are well separated by the two magnetic topologies of Ganymede, whereas ions are not as well separated. We suggest ions may be converted to energetic neutral atoms near Ganymede and reach the surface despite the magnetic barrier. We quantify the environmental inputs in this paper.

1. Introduction

The moon Ganymede is in a phase-locked orbit deep within Jupiter’s magnetosphere, at a radial distance of about 15 R⊕, where 1 R⊕ is 71,492 km. It generates its own magnetic field that is competitive in strength with the Jovian field above the moon’s surface (Kivelson et al., 1997). Its local magnetic properties likely mean that as the corotating magnetospheric plasma and charged particles drift past Ganymede not all of them have direct access to the surface. Electrons and ions that do precipitate can modify the surface. In fact, albedo differences have been linked to the magnetic field configuration near the moon, with the bright polar region coinciding with open Ganymede field lines (Khurana et al., 2007). Furthermore, the equatorial region itself displays variations, with evidence of more non-ice materials, i.e., less water ice in the uppermost layer, near the trailing apex point at 270° W and the equator (Ligier et al., 2019).

To understand how the terrain on Ganymede might be modified from the external plasma environment, it is useful to characterize, as completely as possible, the energy spectra of the particles at the orbital distance of Ganymede. The Galileo spacecraft made several close flybys of Ganymede but, as we describe below, analysis carried out after the mission ended found counting rates in some instrument channels were erroneously higher due to contributions from penetrating background. This measurement limitation is partly due to the moon being near the edge of Jupiter’s main radiation belts. In any case, several researchers attempted to characterize the environment from that data set. Paranicas et al. (1999) fit Ganymede electron spectra including the plasma energy range and Mauk et al. (2004) fit ion energy spectra above the tens of keV energy range. Other works, such as Jun et al. (2005; 2019) provide context for the Ganymede fluxes.

The Juno spacecraft has made excellent plasma and particle measurements in the inner magnetosphere of Jupiter. With its high inclination orbit, it has been encountering Ganymede’s orbital distance closer to the magnetic equator of the planet as the line of apsides has evolved. Data in recent years has been very good for a study of Ganymede’s environment.
In this paper, we present electron and proton energy spectra based on data from the Jovian Auroral Distributions Experiment (JADE) and the Jupiter Energetic-particle Detector Instrument (JEDI). Complete details of these instruments can be found in, McComas et al. (2017) and Allegrini et al. (2020) for JADE and Mauk et al. (2017) for JEDI. We describe the issues involved in making spectra of this type and provide fits to the data that can be used for further analysis. We also describe new ideas about how particles in the local environment can reach the moon’s surface and connect this to optical observations.

2. Considerations for Data Selection

The work of Connerney et al. (1981; 2020) has illustrated that Jovian magnetic field lines are stretched radially out of their dipole configuration at Ganymede’s orbital distance, due to the circumplanetary ring current. This makes it more difficult to associate magnetic field lines and their corresponding trapped flux with Ganymede’s orbit.

In Figure 1, we show JEDI electron and proton intensities around a time when the spacecraft crossed Ganymede’s orbital distance. Ganymede and Juno are on opposite sides of Jupiter at the time, and the narrow feature between 1708 and 1709 UT is due to a change in instrument modes. But since Juno was near the magnetic equator at this time, associating Juno with Ganymede’s orbital distance is more straightforward than it would be if the spacecraft were well off the equator. Also, the JEDI data do not suggest high levels of activity at this time, for example, recent injections.

While Ganymede is not deep within the Jovian radiation belts, there are still, for example, >15 MeV electrons in the environment of Ganymede that can penetrate the JEDI housing and reach the detectors. The principle of detection is based on deposited energy so such particles can be counted even though they are outside each nominal energy passband. Since our goal is to create energy spectra from data, we wanted to select a time where the signal-to-noise ratio is high.

![Figure 1](image-url) Time-energy spectrograms computed from JEDI-090 data obtained between 1700 and 1720 UT on day 2019–148 and averaged into 30-s bins. The color represents particles per cm²-sr-keV for electrons (top) and protons (bottom). The gap is an instrumental artifact of a mode change and not a feature of the environment.
To illustrate this is the case here, we show singles rates in Figure 2 from five of the JEDI-A180 ion solid-state detectors (SSD1 through SSD5); the sixth detector, SSD0, is partially obscured by the collimator and is not shown. Singles rates are counting rates onto the detectors that are not channelized. Two of these detectors (SSD1 and SSD3; called “witness” detectors) have additional shielding in front of them such that the energy responses of these detectors to foreground particles are very different from the responses to the foreground of the other three detectors. However, we expect the responses of all five detectors to shielding-penetrating particles to be similar. Therefore, if the witness and non-witness rates are comparable, it is an indication that shielding-penetrating particles are present in high numbers and the extraction of a clean foreground within the energy passband sought is much more difficult (see, Paranicas et al., 2018).

The top three curves of Figure 2 correspond to the non-witness detectors and the deviations among them are likely due to the nature of the pitch angle distribution of the tens to one or two hundred keV electrons that likely dominate the singles count rate. The two lower curves are witness detectors. It has been proposed that when the witness detectors are measuring around the 8% level of the foreground, the counts are likely due to scattering of the foreground onto these detectors (see, for example, Mauk et al., 2018, supporting information text S7). The relative levels of these curves give us confidence that the electron signal-to-noise ratio at this time is suitable for this analysis.

3. Data and Fits

In Figure 3, we show JADE and JEDI electron spectra from day 2019–148 averaged between 1700 and 1720 UT. The JADE data are re-binned into 32 energies from 50 eV to 100 keV for this time period. The data are averaged over time and the full 180° of local pitch angle (calculated using the onboard magnetic field; Connerney et al., 2017). The JEDI data are fully corrected (and averaged over local pitch angle, ignoring 20% variations in flux that occur). For this time period that means the corrected energy spectrum is harder (i.e., the intensity falls off slower with increasing energy) near the high energy end of the range than is indicated by the raw counts of the energy channels. Electrons above several hundreds of keV begin to fully penetrate the JEDI detectors and to account for this, an efficiency has been computed and applied. A complete description of this subject can be found in the supplemental material of Mauk et al. (2018).

We have also compared the JEDI data plotted here with data from 2019-201 1303 UT (not shown) and found similar values to those reported here. We next compared with a few data points obtained by Galileo; see discussion below. In Figure 2 of Paranicas et al. (1999) we found an intensity of \(~10^7\) at 1 keV and \(~10^6\) at 10 keV (or a factor of \(~2–3\) lower than JADE) and \(~3 \times 10^5\) at 100 keV (or a factor of \(~10\) lower than JEDI). It is useful to keep in mind that the local environment is changing on the timescale of hours (e.g., Mauk et al., 2004; Yoshiako et al., 2018). Bagenal et al. (2015) noted variations in the plasma near Europa’s orbit, for example, the electron density could vary up to a factor of 10 or so. Kollmann et al. (2018) bracketed the
level of time variability that might occur in the energetic particles using Galileo data and found comparable but smaller variations. Jun et al. (2005) looked at MeV electron data from Galileo and found at least factor-of-10 variations near Ganymede. Therefore, this spectrum and the proton one below should be interpreted as a single snapshot of the environment.

The JADE and JEDI data were fit with an extended kappa distribution developed in Hawkins et al. (1998),

\[
 j = j_1 \left( \frac{E}{E_1} \right)^{\gamma_1 \left( 1 + \frac{E}{E_1} \right)^{\gamma_1-\kappa_1}} + j_2 \left( \frac{E}{E_2} \right)^{\gamma_2 \left( 1 + \frac{E}{E_2} \right)^{\gamma_2-\kappa_2}}
\]  

(1)

where \( j \) is electrons per cm\(^2\)-s-sr-keV and the energies are all in keV. The fit is shown as a dotted line in Figure 3 and the corresponding parameters are provided in Table 1. The two terms of Equation 1 are, coarsely, fits to the different instruments but our fit, using the sum, instead means they should not be applied separately for analysis. The advantage of this approach is that it provides a continuous analytic function valid for the entire energy range. Furthermore, we integrated this function from 10 eV to 100 MeV yielding \( 1.4 \times 10^9 \) electrons per cm\(^2\)-s into the surface (or about \( 6.8 \times 10^7 \) MeV/cm\(^2\)-s). The contribution from electrons in the extrapolated portion between 1 and 100 MeV is less than \( 4.5 \times 10^6 \) electrons per cm\(^2\)-s. Such an integration assumes there are points on the surface (e.g., in the polar regions) where electrons in the environment have unimpeded access over the whole energy range considered here. Liuzzo et al. (2020) found that the polar caps receive about \( 1 \times 10^8 \) electrons per cm\(^2\)-s by considering contributions between 4.5 keV and 100 MeV;

![Figure 3](image)

**Figure 3.** Electron energy spectrum relevant to the radial distance of Ganymede's orbit. The data are JADE (orange circles) and JEDI (blue triangles) along with a fit (dotted line) that can be used for further analysis. Measurements are averaged from day 2019–148 1700–1720 UT to form electron intensities and all pitch angles measured are included.

| Fit parameters | Electrons | Protons |
|---------------|-----------|---------|
| \( j_1 \)     | \( 8.48 \times 10^9 \) | \( 1.54 \times 10^9 \) |
| \( E_1 \)     | 0.057     | 2.38    |
| \( \gamma_1 \)| 0.81      | 0       |
| \( \kappa_1 \)| 1.89      | 4.07    |
| \( j_2 \)     | \( 1.62 \times 10^6 \) | \( 2.34 \times 10^4 \) |
| \( E_2 \)     | 300.69    | 215.53  |
| \( \gamma_2 \)| 0         | 0       |
| \( \kappa_2 \)| 4.18      | 2.09    |
the integration here for the same range is about a factor of 5 higher. Finally, the JEDI portion of this energy spectrum is similar to what we computed for Europa (Paranicas et al., 2001). These factors suggest the intensity is higher in our data sample than in some of the Galileo calculations, see below also.

In Figure 4, we show proton data from JADE and JEDI and a fit with the function presented in Equation 1. The data are averaged from 1700 to 1720 UT on day 2019–148. We have removed the brief time period with lower fluxes that are shown in Figure 1. The increase between 0.1 and 1 keV is due to corotation. Since we are interested in the protons flowing onto Ganymede, we fit these data in the spacecraft rest frame. Comparing with earlier proton fits, the value at $L = 15$ R$_J$ in Mauk et al. (2004) is just below about $10^4$ at 100 keV, which is in good agreement with the JEDI data. If all the particles in the spectrum were to reach a test location on the surface, the precipitating flux from 0.01 keV to 10 MeV would be about $1.8 \times 10^7$ protons per cm$^2$ s delivering $7.9 \times 10^6$ MeV/cm$^2$ s.

After the active Galileo mission, some channels of the Energetic Particles Detector (EPD) were shown to be affected by penetrating background, for example, the total ion channels during Galileo's Ganymede flyby called “G8” (Kollmann et al., 2020). Given that many Galileo EPD channels that made measurements in the radiation belts need to be corrected more extensively, we do not think it is sensible to make a detailed comparison here. But it is important to keep in mind that the EPD fluxes we cited above and the ones in the published literature for Ganymede's orbit (e.g., Poppe et al., 2018) are in most cases too high. For this reason, we recommend using the JEDI data for fluxes obtained in the Jovian radiation environment, as in Figures 3 and 4.

Figure 4. Proton data from JADE (blue circles) and JEDI (orange squares) with a fit that is the sum of two functions (solid line), see text. The data are in the spacecraft frame (e.g., see peak due to corotation between 0.1 and 1 keV) appropriate for weathering calculations.
4. Interpretation

Ligier et al. (2019) have observed that the presence of water ice on Ganymede's surface increases with increasing north and south satellite latitude. Early explanations for this finding included the idea that energetic ions sputter the surface and mobilize the molecules, which are then more likely to condense at the cold poles (see discussion in Johnson 1985). But Ligier et al. (2019) further found that when only the equatorial region is considered, a large area around the trailing apex is the most depleted of water ice in the top surface layer.

Ligier's work on the longitudinal variations are hard to interpret, given that Ganymede's magnetic field provides some shielding of the incoming particles from directly reaching the equatorial regions (e.g., Poppe et al., 2018). Particles can reach the equatorial region of the trailing hemisphere following drift after reconnection on the leading side, but this would not be expected to supply a lot of plasma or particles to the region above the trailing apex.

A possible way to resolve the longitudinal discrepancy is that singly charged ions can undergo charge exchange in the environment around Ganymede (Paranicas et al., 2020). As a result, the ion is converted to a neutral with almost the same initial energy. These neutrals can then progress to the surface unimpeded by Ganymede's magnetic field. The fraction of upstream ions that are converted to neutrals and then propagate to the surface in such a picture is not known. Hall et al. (1998) inferred column densities of between 1 and 10 times $10^{14}$ O$_2$ per cm$^2$ above Ganymede's trailing surface from measurements, so the presence of neutrals is not in question. Less is known about the distribution of neutrals around Ganymede generally, since their densities fall off with increasing altitude. But the advantage of such a picture is that it preserves the hypothesis put forward in Johnson's work that sputtering is a dominant process in forming the bright polar caps and furthermore explains Ligier's observations of the water ice fraction as it varies with satellite longitude.

If the ion fluxes onto Ganymede are not prohibited from reaching the equatorial region due to the shielding by the magnetic field, that is, because many energetic ions can still reach the surface as ENAs, then the more likely explanation of the differences in polar/equatorial Ganymede reflectance properties is electrons. The field topology separation suggests a charged agent. Modeling by Liuzzo et al. (2020) has shown electron bombardment patterns that are vastly different in the polar and equatorial regions over a wide range of energies. Electrons, depending on their energy, can affect water ice and non-ice in a number of ways and cause changes in its reflectance properties. It is not known at this time what portion of the electron energy spectrum is the most critical. Researchers have looked at modifications in the appearance of non-ice, for example, via color centers (likely related to keV electrons), see, for example, Hand and Carlson (2015). Davis et al. (2021) predict electron sputtering can be a dominant process depending on the relative fluxes of ions and electrons reaching the ice. But, Liuzzo et al. (2020) predict electrons below 40 MeV may reach low Ganymede latitudes only in very small numbers, so sputtering by electrons would not be consistent with the lack of water ice near the equator. Alternatively, electrons might deposit enough energy at high latitudes to fuse or sinter the grains (e.g., Howett et al., 2012), altering the way they absorb and reflect light. The present work offers a starting point for quantifying these effects.

5. Summary and Conclusions

Juno's orbit has evolved over the past several years to lower magnetic latitudes near Ganymede's orbit. We have taken advantage of this situation to create energy spectra relevant to the weathering of that moon. Electron and proton energy spectra are important quantitative inputs to how Jupiter's magnetosphere interacts with Ganymede's environment and also as inputs to weathering calculations. We believe that since ion bombardment of Ganymede can be smeared out by the effects of charge exchange, the more likely agent for causing the observed polar/equatorial albedo differences is electrons. Improved spectra, including the plasma and particles, put us in a better position to test this hypothesis.
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Data Availability Statement
The Planetary Data System provides access to the Juno JADE data, https://pds-ppi.igpp.ucla.edu/search/?sc=Juno&t=Jupiter&i=JAD, and the Juno JEDI data, https://pds-ppi.igpp.ucla.edu/search/?sc=Juno&t=Jupiter&i=JEDI.

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