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Early Energetic Particle Results from Jupiter

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The NASA Galileo spacecraft arrived at Jupiter on 7 December 1995, carrying onboard the Energetic Particles Detector (EPD) designed and built by the Applied Physics Laboratory and the Max Planck Institute for Aeronomy. The first Energetic Particles Detector data from Jupiter, collected on arrival during Galileo's passage through Io's plasma torus and at the flyby of Io, were received at Earth in June 1996. Data received steadily since that time continually show many surprises, new results, and discoveries. In this article we describe some of our early results from Jupiter, including the discovery of intense, bidirectional, magnetic-field-aligned electron beams at Io—a dramatic result of Io's interaction with Jupiter's magnetosphere.

(Keywords: Energetic particles, Io, Jupiter, Magnetosphere.)

INTRODUCTION

Following a remarkable 6-year journey through the solar system that began with launch from Earth on 18 October 1989, the NASA Galileo spacecraft arrived at Jupiter on 7 December 1995. This journey, described in a recent issue of the *Technical Digest*[1] along with a perspective of the 20-year Galileo program, culminated with the injection of the Galileo spacecraft into orbit around Jupiter. Arrival at Jupiter was highlighted by the onboard receipt of data from the Galileo probe as it penetrated the Jovian atmosphere and by the collection of data taken by instruments onboard the Galileo spacecraft during its passage past Jupiter's moon Io. These data were stored on tape for later transmission to Earth. After successful insertion into orbit around Jupiter, data transmission was begun and has continued steadily to the present. The data, now under intense study, show many new and surprising results from the strange and wonderful world of Jupiter. Initial probe and orbiter results were published in the 10 May 1996 and 18 October 1996 issues of *Science*, respectively.

In this article we present an early look at some of the initial measurements obtained from the Energetic Particles Detector (EPD) during Galileo's passage by Io. A relatively large moon with a radius of 1816 km, Io orbits Jupiter at a distance of ≈350,000 km above Jupiter's cloud tops. Through volcanic activity driven by gravitational tidal forces exerted on it by being so close to Jupiter, Io plays a central role in supplying particles for Jupiter's enormous radiation belts. This interaction with Jupiter's magnetosphere is complicated by the fact that Jupiter's charged-particle populations flow past Io at a relative speed of ≈57 km/h (Jupiter's magnetic field effectively transfers Jupiter's rotational velocity to a bulk motion of the charged particles). EPD data will help to understand both Io's role as a particle source and its interaction with the Jovian magnetosphere.

These early data have been analyzed by members of the original EPD Science Team (see the team photograph at the end of this article), with major contributions from Barry Mauk of the Space Physics Group at APL. Proposed in 1976, the EPD was designed and built by APL and the Max Planck Institute for Aeronomy. It measures the energy and angular distributions of ions above ≈20 keV, electrons above ≈15 keV, and the elemental composition from protons through iron above ≈10 keV/nucleon.[1,2]

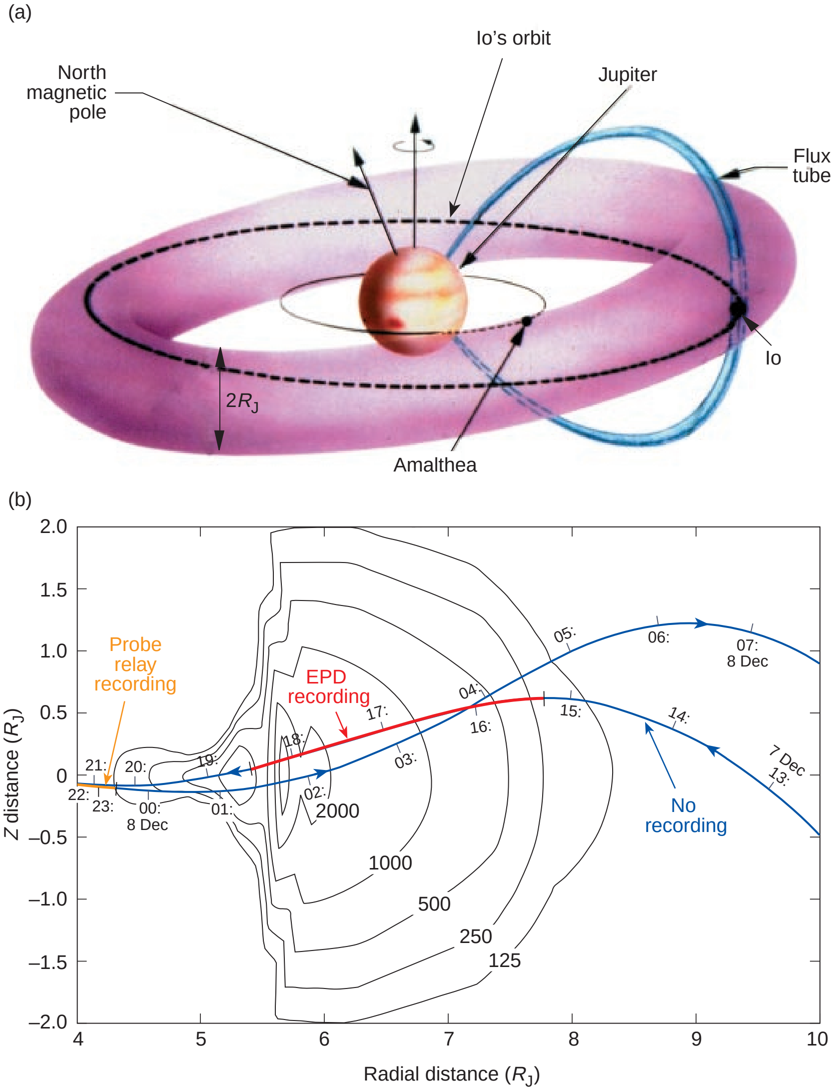

Figure 1. (a) Schematic showing the geometry of Io's torus with respect to the Io flux tube and Io's orbit around Jupiter. The origin of the torus lies in the volcanoes populating Io. R_J = Jupiter radius (≈71,400 km). (b) A cross section of the torus at Io showing Galileo's trajectory and region of EPD data collection prior to orbit insertion. Contours are of electron density (number of electrons/cm^3). Time tick marks are 1 h apart.

EARLY RESULTS

The first EPD data from Jupiter were from the Io torus, a doughnut-shaped ring of ionized and neutral gas encircling Jupiter established by the volcanic activity of Io (Fig. 1a). Figure 1b shows Galileo's path through the heart of the ionized gases that make up the torus. Figure 2 shows a sampling of EPD raw data for the entire torus passage. During the spacecraft spin (≈20 s), different phases of the particles' angular distributions are sampled. Because of the compressed time scale required for Fig. 2, the plots display a thickness directly related to the amount of asymmetry in the angular distributions; the thicker the width, the more asymmetric the angular distribution. The movement of the EPD behind a calibration shield results in the periodic intensity decreases seen in Fig. 2. These first direct composition measurements in the Io torus show generally that protons display the least amount of variation across the torus, whereas the heavier elements such as sulfur display an enhanced angular asymmetry at Io. In addition, high-energy electron intensities decrease over a broad region near Io, and low-energy electrons show large flux variations just at Io.

Figure 3 presents data from both the EPD high- and low-energy composition detectors, showing clearly the composition of the ion population. Note that the sulfur, sodium, and oxygen ions measured are produced by Io's volcanic activity and thus represent a unique feature of Jupiter's environment, namely, the existence of a major non-ionospheric particle source within a planetary magnetosphere. Figure 4 shows the flux profile through the torus for several ion species and an example of relative abundances measured at Io. These composition data are being used by members of the EPD Science Team to determine the major transport, loss, and

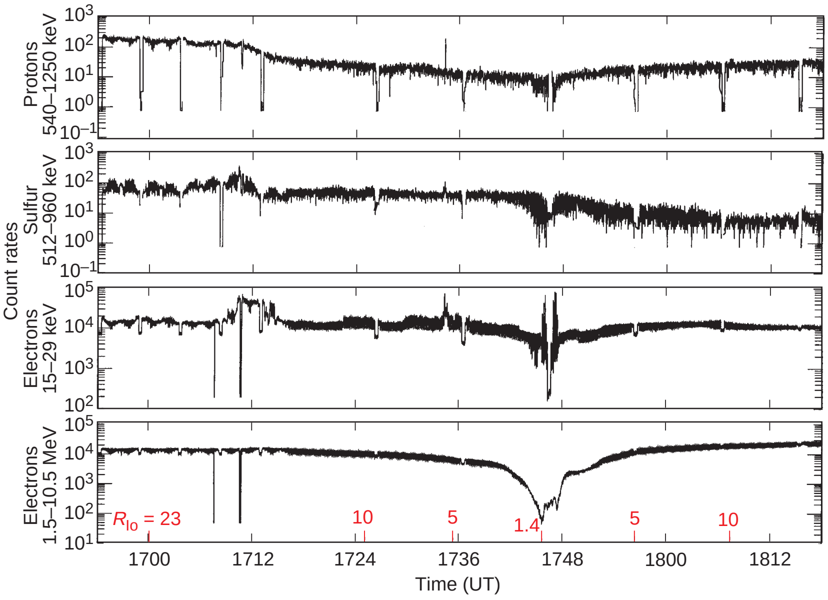

Figure 2. A sampling of EPD raw data during Galileo's passage through the Io torus. The count rates of selected channels measuring protons, sulfur ions, and electrons are shown as a function of time on 7 December 1995 and as a function of distance from Io in units of Io radii (R_{Io}= 1816 km). The apparent thickness of the plots is due to the spacecraft spin. The periodic intensity decreases are caused by the movement of the EPD behind a background shield for one spacecraft spin (≈20 s) every 10 min. The Io closest approach occurred at a radial distance of 1.5 R_{Io} (an altitude of 890 km). Prominent in the data are the strong spin modulation of the intensities as evidenced by the apparent thickness of the plots; the increasing spin modulation in the heavy ions right at Io; and the large variations in low-energy electron intensities at Io.

energization processes operating in this region of Jupiter's magnetosphere.

During its pass through the torus, Galileo flew past Io at an altitude of 890 km. Figure 5 shows the response of the lowest energy EPD electron channel during the flyby. Because of the greatly expanded time scale, the variation of the count rates due to the satellite spin can easily be seen. A series of large intensity spikes surrounding a step-like decrease in intensities are the most prominent features of the electron response seen in Figure 5. All electron channels up to an energy of ≈200 keV exhibit this behavior. The decrease is due to the EPD stepping behind a background shield to assess the ambient radiation background and verify the accuracy of the flux measurements obtained through the torus and at Io (the instument was programmed to step behind the shield for 20 s—one satellite spin—every 10 min). The spikes are intense bidirectional magnetic-field-aligned beams traveling back and forth on Jupiter's magnetic field lines that pass by Io. They occur twice per satellite spin, and since only a single spin of data was missed during the background check, we conclude that the beams were present throughout the region of closest approach, as indicated on the trajectory plot in Fig. 5.

Figure 6 shows other perspectives of these data, verifying their field-aligned nature and their intensity relative to the surrounding region. Figure 6a presents the intensities of 15–29 keV electrons at Io plotted on

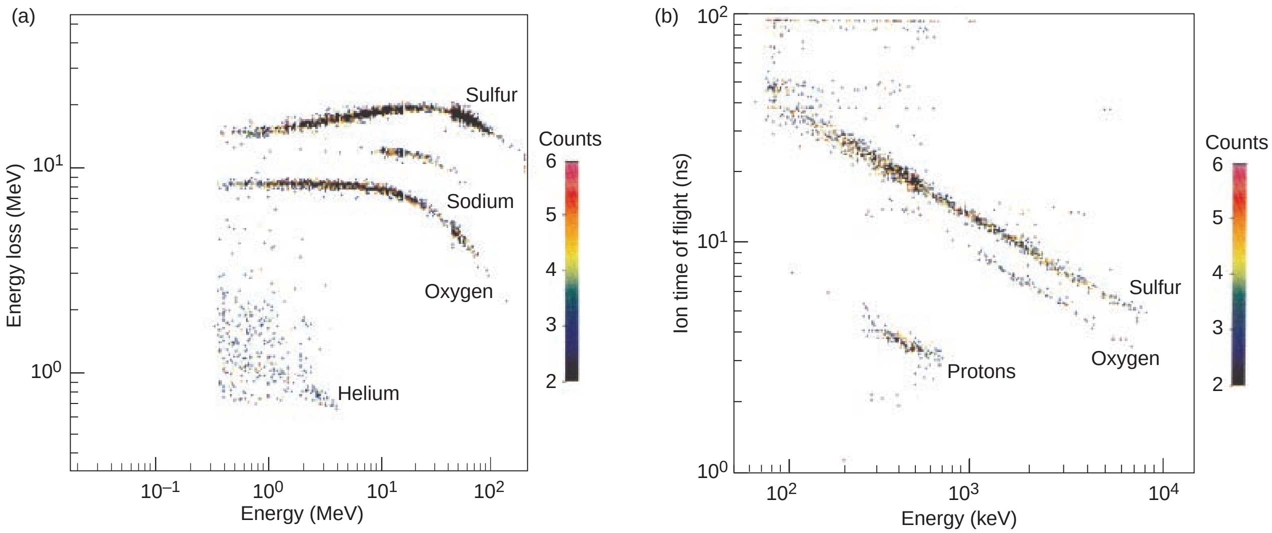

Figure 3. Data from the (a) high-energy and (b) low-energy EPD composition detectors. The high-energy detector, similar to the APL detector flown aboard the Voyager spacecraft, measures both the energy loss and the total energy of the ions as they travel through a stack of detectors, providing the clear identification of energetic, heavy ions seen in part a. The low-energy detector is new to the planetary program and provides the first measurements of its kind at Jupiter. It measures the time-of-flight and total energy of ions as they traverse the telescope, providing the ion signatures seen in part b.

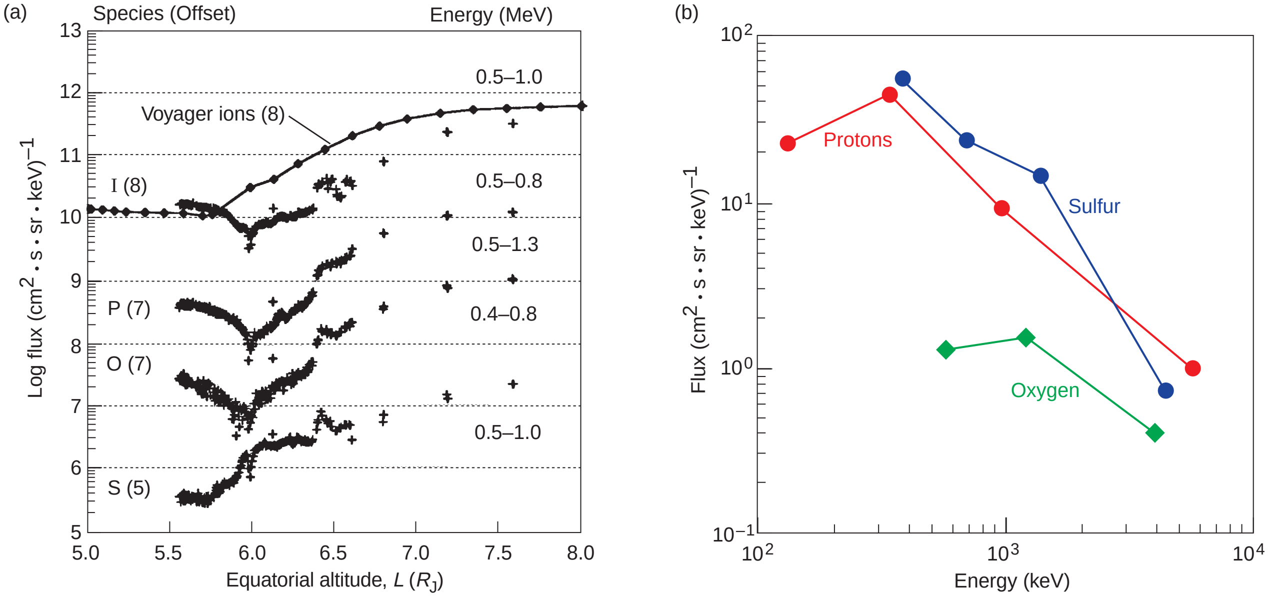

Figure 4. (a) Fluxes of protons (P), oxygen ions (O), and sulfur ions (S), measured by the EPD through the Io torus. Total ion fluxes (no species identification) measured by the EPD (I) and by Voyager[3] are also shown. The channel energy is given on the right, and the numbers in parentheses on the left give the logarithm of the multiplicative offset of the data. The Voyager and Galileo EPD data show good agreement given the 17-year time difference and spatial differences involved. The composition measurements are the first to be made at these energies in Jupiter's magnetosphere, and the differences observed between the species will be important in deconvolving the dominant transport, loss, and energization processes. (b) The energy spectrum of protons, oxygen ions, and sulfur ions at Io. Sulfur is the majority ion at this location, qualitatively consistent with Io's volcanoes being the dominant ion source in Jupiter's inner magnetosphere.

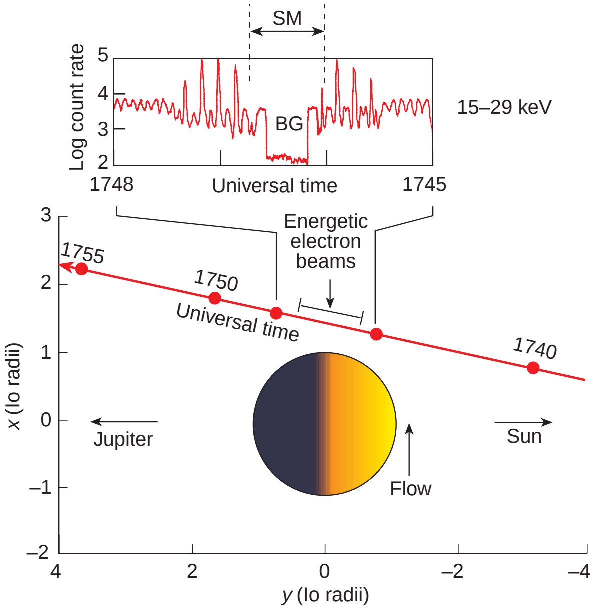

Figure 5. Detail of the Io flyby showing the count rate of 15–29 keV electrons. At this time resolution, the spin modulation of the count rate clearly can be seen. The series of tall spikes are intense, bidirectional beams of electrons traveling back and forth along the magnetic field line. BG represents the interval of one spin (≈20 s) when the EPD was positioned behind a background shield; SM is the period of stepper motor motion. The low backgrounds measured verified the accuracy of the EPD foreground observations. A close inspection of the data shows that just one set of spikes (one spin of data) was missed. Therefore, it is concluded that the beams were present throughout the entire flyby period as indicated in the bottom panel.

a grid of time versus satellite spin phase. The dark band represents the time that the EPD was behind the background shield. Contours of measured particle pitch angles (the angle that the particle velocity vector makes with the magnetic field) are shown for 0° (travel parallel to the field line), 180° (travel antiparallel to the field line), and 90° (travel perpendicular to the field line). The red spots are the spikes of Fig. 5 and can be seen to be field-aligned in both directions along the field. Figure 6b presents a three-dimensional perspective of the beams and shows how dramatically they stand out from the intensities in the surrounding regions.

These intense electron beams may be related to Io's modulation of Jupiter's decametric radio emissions[4,5] and to observations of auroras located at Io's footprint in Jupiter's atmosphere.[6–8] As knowledge of Io's environment has grown, so has the appreciation of the complexity of its interaction with Jupiter's magnetosphere. Rather than a simple conductor moving through a magnetic field, Io now is known to represent a conducting body with an ionosphere traveling through a torus of neutral and ionized gas imbedded in the Jovian magnetic field. Earlier work[9-15] predicts the establishment of a major current system linking Io, its magnetic flux tube, and Jupiter's ionosphere. This current system is thought to be responsible for the modulation of decametric radio emissions by Io. Unresolved issues include the closure of the current system, the

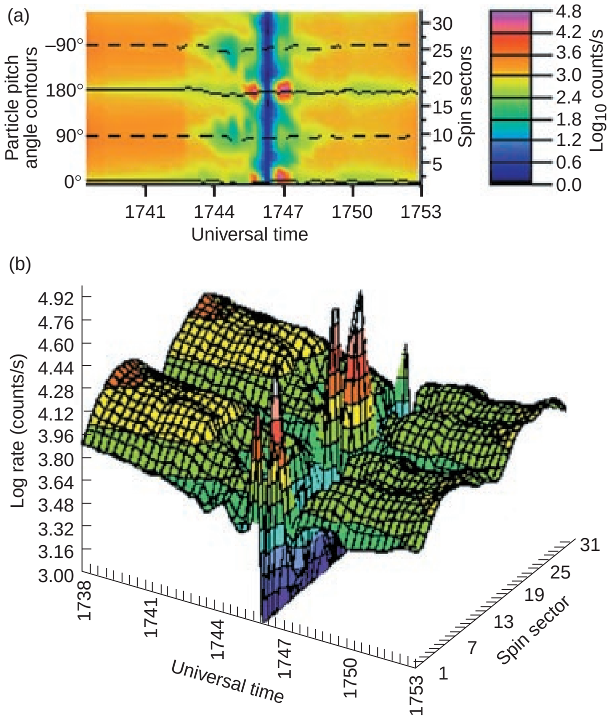

Figure 6. (a) A false-color representation of 15–29 keV electron fluxes during the Io flyby on day 341 of 1995. Fluxes are presented on a grid of time versus spin phase. Measured pitch angle contours of 0° (travel parallel to the magnetic field), 180° (travel antiparallel to the magnetic field), and 90° (travel perpendiculat to the magnetic field) are shown. The dark band near the center of the plot is the time when the EPD was behind its background shield. The red spots are the spikes seen in Fig. 5 and are seen to be aligned with the magnetic field and traveling in both directions. (b) A three-dimensional representation of the electron intensities measured as Galileo flew past Io. The dramatic appearance of the beams and their greatly increased strength with respect to the surrounding regions are clear.

energy of the current carriers (generally thought to be electrons), and the energization process for the carriers. Even with the large electric potentials (≈400 kV) expected at Io because of its relative motion through the Jovian magnetic field and plasma, it is not clear how they are transformed into an acceleration process resulting in the highly collimated, bidirectional, field-aligned electron beams observed by the EPD.

Integrating the electron intensities over the observed energy spectrum and assuming that the Io flux tube is filled with these beams yield an energy flow in each direction along the magnetic field line of $\approx 10^9$ W. The assumption that the beams are the result of a field-aligned potential and are contained within the particle loss cone (the pitch angle range for which the particles would impact Jupiter's ionosphere, ≈2° for particles at Io) gives an upper limit to the energy deposition in Jupiter's ionosphere of ≈ 80 ergs$\cdot$cm$^{-2} \cdot$ s^{-1}. This is more than sufficient to cause visible auroras at the foot of Io's flux tube. Such auroras have been observed.[6–8] However, the total power impacting Jupiter according to these observations is 2 orders of magnitude higher than that measured in the electron beams. The results reported by Clark et al.[8] require a specific energy deposition in Jupiter's atmosphere of ≈ 30 ergs$\cdot$cm$^{-2}\cdot$s^{-1}, well within that provided by the electron beams. However, they report an auroral area at the footprint of Io's flux tube that is ≈100 times that of a simple projection of Io along the field line, resulting in a total power requirement much larger than that provided by the electron beams confined to Io's flux tube. On the other hand, Prangé et al.[7] reported a footprint area that agrees with the projection of Io along the field line to Jupiter's atmosphere, consistent with the electron beams. However, they require an atmospheric energy deposition of $\approx 10^4$ erg$\cdot$cm$^{-2}\cdot$s^{-1}. Clearly, more work needs to be done to resolve the issue of auroras in Jupiter's atmosphere at the footprint of Io's flux tube.

It is possible that the electron beams do not reach Jupiter's atmosphere. For example, if they are at the edge of or outside the loss cone, they will experience the magnetic mirror force exerted by converging magnetic field lines as they spiral toward Jupiter, which could result in only partial deposition into the Jovian atmosphere. It is also possible that the beams are confined to a much smaller region at Io, and the observation of effects in Jupiter's atmosphere will require higher resolution imaging than that available to date. Nonetheless, the electron beams observed at Io are direct evidence of a remarkable acceleration process operating at Io and along its flux tube, as depicted in Fig. 7.

Because of the APL connection, we have described in this report only data from the EPD. Unraveling the mysteries of the Jovian magnetosphere will require the assimilation of all the Galileo particles and fields data. For example, the electron beams measured by the EPD at Io[16] occur just when plasma densities reach unex-

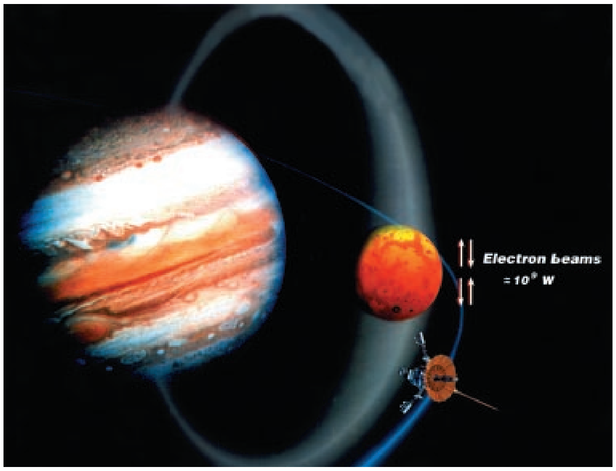

Figure 7. Schematic showing Galileo's flight past Io, the linkage to Jupiter's atmosphere via the Jovian magnetic flux tube passing through Io, and the bidirectional electron beams measured by the Galileo EPD.

The original EPD Science Team in 1984. From left to right: Edmond C. Roelof, Thomas P. Armstrong, Donald J. Williams, Richard W. McEntire, Berend Wilken, Louis J. Lanzerotti, Lawrence R. Lyons, Wolfgang Studemann (deceased), Theodore A. Fritz, and Stamatios M. Krimigis. Missing from the photo are Juan G. Roederer, William I. Axford, and Akira Hasegawa. Also not pictured is Barry Mauk of APL, a major contributor to the EPD data analysis.

pectedly high values[17,18] (>20,000 cm^{-3}—over 10 times the maximum density in the torus). Simultaneously, the magnetometer measured a magnetic field that was substantially reduced from the normal Jovian field at that altitude.[19] It seems that Galileo flew through Io's ionosphere or possibly through the high-altitude remnants of a volcanic plume.

The EPD remains in orbit around Jupiter, is operating normally, and continues to provide data replete with surprises and unexpected results. The success of this instrument and the scientific results being obtained and pursued make it a worthy successor to the first APL instruments to visit Jupiter, namely, the energetic particle detectors on the two Voyager spacecraft.[20,21]

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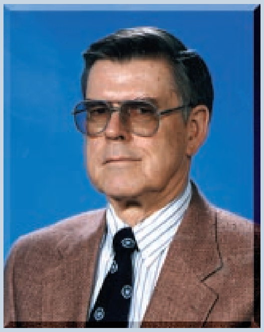

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