be measured. The impact direction was determined by the spin position (or rotation angle) of the spacecraft at the time of impact. This sensor mounting direction constrained the directions from which dust grains could be sensed. This limitation varied with spacecraft rotation angle and with spacecraft location along its trajectory. During Galileo's approach to Jupiter dust particles impacting the DDS from the inner jovian system (that is, from inside the position of Galileo) could be detected when the detector was facing Jupiter; at a spin position half a rotation later DDS was facing away from Jupiter and these particles could not enter the detector. Shortly after Galileo's CA to Jupiter, Jupiter and the inner jovian system was in the Earth-facing hemisphere as seen from Galileo, and no dust grains emanating from that region could reach the dust detector.

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Electron Beams and Ion Composition Measured at Io and in Its Torus

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Intense, magnetic field–aligned, bidirectional, energetic (>15 kiloelectron volts) electron beams were discovered by the Galileo energetic particles detector during the flyby of Io. These beams can carry sufficient energy flux into Jupiter's atmosphere to produce a visible aurora at the footprint of the magnetic flux tube connecting Io to Jupiter. Composition measurements through the torus showed that the spatial distributions of protons, oxygen, and sulfur are different, with sulfur being the dominant energetic (>~10 kiloelectron volts per nucleon) ion at closest approach.

On 7 December 1995, the Galileo spacecraft flew through Io's plasma torus on a trajectory that included a close flyby of the moon at an altitude of 890 km [0.5 R_{Io} (Io radii)]. Measurements made by Galileo's energetic particles detector (EPD) (*1*) were recorded on the tape recorder and transmitted to Earth in June 1996. Here we present the spatial dependence of charged particle intensities through the torus passage and observations of the particle pitch angle distributions at Io.

The correspondence of Galileo and Voyager 1 (*2*) total ion intensities (Fig. 1A) is quite good given the time and spatial differences between the observations. Voyager 1 passed by Io at a distance of nearly 22,000 km (~11 R_{Io}) about 17 years ago. An important new aspect of the EPD composition data is that although all species decrease in intensity as Io is approached from higher jovian altitudes, the proton (P) and oxygen (O) intensities increase at altitudes below the orbit of Io whereas sulfur (S) intensities continue to decrease. At either a given fixed energy or energy per nucleon, S ions have the largest intensities at Io closest approach. At higher energies, O and S intensities display a mild decrease inward of Io, whereas P intensities again increase, as inferred from the total ion intensity plot. This behavior may reflect gyroperiod effects through the spatially varying density of the torus, gyroradius dependencies in the transport properties of the observed ions, and possible differences in charge exchange and Coulomb losses as the ions are transported through the Io torus, or a combination of these effects.

Localized high-energy particle intensity decreases (Fig. 1A) occur within several Io radii of Io closest approach but are most noticeable in the higher energy (greater than a few hundred kiloelectron volts) electron channels. The effect of the much closer Galileo flyby (compared with Voyager) is evidenced by a more than two-order-of-magnitude decrease in the electron fluxes. At lower energies, the electron intensities display a markedly different behavior (Fig. 1B), with a number of sharp spikes seen. The spikes are presumed to continue through the instrumental mode change period that yielded the large decrease in count rates nestled within the observed spike structure (*3*). The region where the spikes were observed was centered near Io closest approach (Fig. 1C).

Expanding the region of closest approach reveals that S ions surprisingly show a broad field-aligned maximum that contains a small decrease of intensities in the most field-aligned directions throughout the entire Io flyby (Fig. 2). As Galileo approaches Io, intensities of ions with pitch angles close to 90° steadily decrease and cause the increasing anisotropy (Fig. 2). Given the observed orientation of the magnetic field (*4*), this is qualitatively consistent with the expected pitch angle dependence of energetic S ions that can come closest to Io and be lost to its surface or atmosphere; that is, S ions at a 90° pitch angle are most likely to be lost as compared with ions with field-aligned pitch angles.

As the spacecraft approaches Io, the electron distributions gradually evolve (Fig. 2) from a trapped-like distribution with maximum fluxes at a 90° pitch angle to a distribution with peaks appearing between 0° and 90° and between 90° and 180° (butterfly distributions). Near closest approach the electron distribution suddenly (within one spacecraft spin, ~20 s) changes to an intense, bidirectional field-aligned beam,

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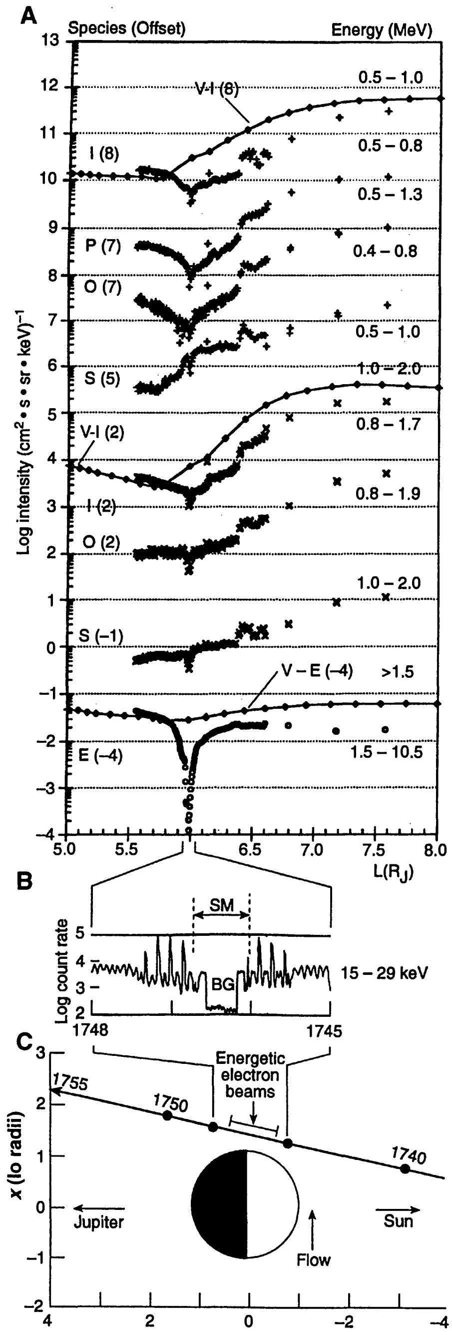
Fig. 1. An overview of the EPD response through the torus and the Io flyby. (**A**) These panels show intensities versus L (the equatorial crossing distance of Jupiter's magnetic field lines) measured by EPD on 7 December 1995 and by the Voyager 1 low-energy charged particle detector (designated V) on 5 March 1979. The labels on the left show the species measured, where I = total ion fluxes, P = protons, O = oxygen, S = sulfur, and E = electrons, and the numbers in parentheses show the logarithm of the multiplicative offset of the data. Voyager measurements are given as line plots and are marked in the figure. The numbers on the right show the energy band in megaelectron volts for each plot. (**B**) The response of the lowest energy EPD electron channel during the Io flyby. Spin modulation of the fluxes is seen as are several large spikes in the electron intensities. The steplike decrease, labeled BG, is due to the EPD stepping behind a background shield for a background calibration (3). The spikes are not fully apparent adjacent to the BG region because of the stepping motion of the instrument (region labeled SM). The spikes are intense bidirectional, magnetic field–aligned flows of electrons. A similar behavior is seen in electron energy channels up to ~150 keV. (**C**) The Galileo trajectory past Io and the region where the electron beams were observed.



evidenced by the red spots at 0° and 180° pitch angles (these are the spikes seen in Fig. 1B). These beams are tightly aligned with the magnetic field and coexist with a less intense trapped-like electron population (Fig. 3). The electron beams appear at closest approach (Fig. 1C) and have much higher intensities than the pre-encounter trapped electron intensities (Fig. 2).

These intense electron beams may be related to Io's modulation of Jupiter's decametric radiation (DAM) (*5*) and to observations of an aurora located at the footprint of Io in Jupiter's ionosphere (*6*–*8*). Previous work predicts the establishment of a major current system linking Io, its flux tube, and Jupiter's ionosphere (*9*). It is this current system that is thought to be responsible for the modulation of DAM by Io. Unresolved issues include the closure of the current system, the 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 as a result of its 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. Although field-aligned electron beams have been observed in Earth's magnetosphere and elsewhere in Jupiter's magnetosphere (*10*), the beams discovered by EPD are unique because of their association with Io and its interaction with the jovian magnetosphere.

We see no evidence of an energy peak in the electron beam spectra at energies associated with the ~400-kV induced electric potential across Io (the EPD response at energies >150 to 200 keV remains near background levels). Past reports show intensity spikes near Io in the radial profiles of electrons from >0.16 to >1.0 MeV (*11*). These spikes, observed for particles with a 90° pitch angle, have been associated with possible acceleration processes at Io. The radial profiles measured by the EPD through the torus show no evidence of similar spatial structures. We conclude that during the Galileo pass only a fraction of the induced potential appears as a field-aligned potential capable of accelerating particles.

Integration of the electron spectrum in the beams yields an energy flux of about 0.05 erg cm^{-2} s^{-1} over the energy range 20 to 140 keV as defined by the center point energies of the channels. Beams flow in both directions along the field line and, from their evolution along the trajectory, we estimate that both are equal in intensity. From the present analysis we are unable to determine whether or not fluxes exist in the loss cone (those pitch angles for which the particles would impact Jupiter's atmosphere). The assumption that the Io flux tube either is filled with these electron beams over a diameter of 1.0 R_{Io}, or 1.5 R_{Io} (Galileo's closest approach distance), or in a shell from 1.0 to 1.5 R_{Io} yields an energy flow in each direction along the flux tube of ~10^9 W. Power law extrapolations of the measured spectrum to energies of 10, 5, and 1 keV yield powers of 1.5×10^9, 6×10^9, and 8×10^{10} W. Because the beams are unresolved, we do not know how much of this flow is contained within the loss cone and thus cannot accurately estimate how much of this energy impacts the jovian ionosphere. The calculated loss cone ranges from ~1.5° to ~2.5° over one Ionian revolution around Jupiter. If the electron beams are the result of a field-aligned acceleration of the ambient cold electron populations (~10 eV), they will be contained within the loss cone, in the absence of pitch angle scattering effects, regardless of the location of the acceleration mechanism. In this case the beams will reach the jovian ionosphere. For this assumption the observed electron beams represent an upper limit to the energy deposition flux at the foot of the Io flux tube of ~80 ergs cm^{-2} s^{-1} (or 120, 460, and 6000 ergs cm^{-2} s^{-1} for the extrapolations to 10, 5, and 1 keV discussed above). If the observed field strength at Io of ~1200 nT (*4*) is used, the foot of the Io flux tube has an area of about 1×10^{14} to 2×10^{14} cm^2 and a corresponding rough linear dimension of ~100 to 150 km.

The estimated magnitude of the energy deposition flux is more than sufficient to produce visible aurora in the jovian atmosphere. Clarke *et al.* (*7*) report on observations of aurora at the foot of the Io flux tube requiring ~30 ergs cm^{-2} s^{-1} to produce the ~200-kR (1 kilorayleigh = $10^9/4\pi$ photons cm^{-2} sr^{-1} s^{-1}) emissions measured in their brightest pixel. However, they also report an observed footprint size of 1000 to 2000 km in diameter, about 10 to 20 times as large as a simple projection of Io to Jupiter's ionosphere along the magnetic field line. This leads to a total power input estimate of ~10^{11} W. Thus, although these electron beams may provide sufficient specific energy loss in the jovian atmosphere to cause auroral emissions at the foot of the Io flux tube, they do not map to the large auroral footprints observed by Clarke *et al.* (7) and thus fall short in the total power delivered to the jovian atmosphere. One observed particle macrosignature that more closely matches the size of the Io flux tube auroral footprint reported by Clarke *et al.* (7) is the flux decrease observed in the intensities of higher energy (greater than a few hundred kiloelectron volts) electrons (Fig. 1A). This decrease occurs over a range of several Io radii and projects to a rough linear dimension of several hundred kilometers in Jupiter's atmosphere. Although we see no obvious signs of electron acceleration in this region, we are investigating whether sufficient energy may impact the atmosphere from the loss of these electrons to sustain the measured atmospheric emissions. Prangé *et al.* (8) have reported observations of aurora associated with the foot of Io's flux tube and have estimated sizes consistent with Io's projection along the magnetic field line. With their reported power input of $\sim 2 \times 10^{11}$ W [similar to that of Clark *et al.* (7)], the energy deposition in the jovian atmosphere becomes $\sim 10^4$ ergs cm^{-2} s^{-1}. The electron beams we report fall far short of such a large atmospheric energy input (only our extrapolation to 1 keV approaches this value).

It is possible that the beams observed at Io do not reach the jovian ionosphere. If, for example, they are at the edge of or outside the loss cone, they will experience the magnetic mirror force exerted by the converging magnetic field lines as they approach low altitudes, which could result in only partial energy deposition into the jovian atmosphere. If, on the other hand, the beams are the result of acceleration in double layers near Jupiter's ionosphere, the counterstreaming beams observed may simply be the result of reflection from double-layer structures in conjugate regions of the jovian ionosphere. It also is possible that the beams are confined to a much smaller region at Io and that to observe effects in Jupiter's atmosphere will require higher resolution imaging than that available to date. Nonetheless, the electron beams are direct evidence of a remarkable acceleration process operating at Io and along its flux tube.

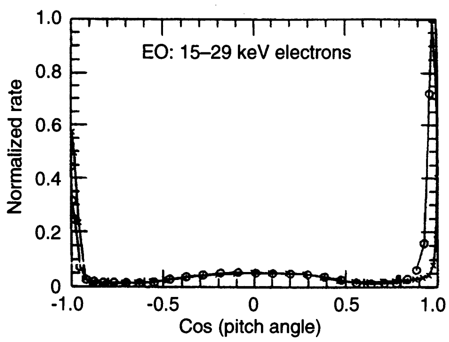


Fig. 3. A line plot of the 15- to 29-keV electron pitch angle distribution showing the field-aligned character of the electron beam.

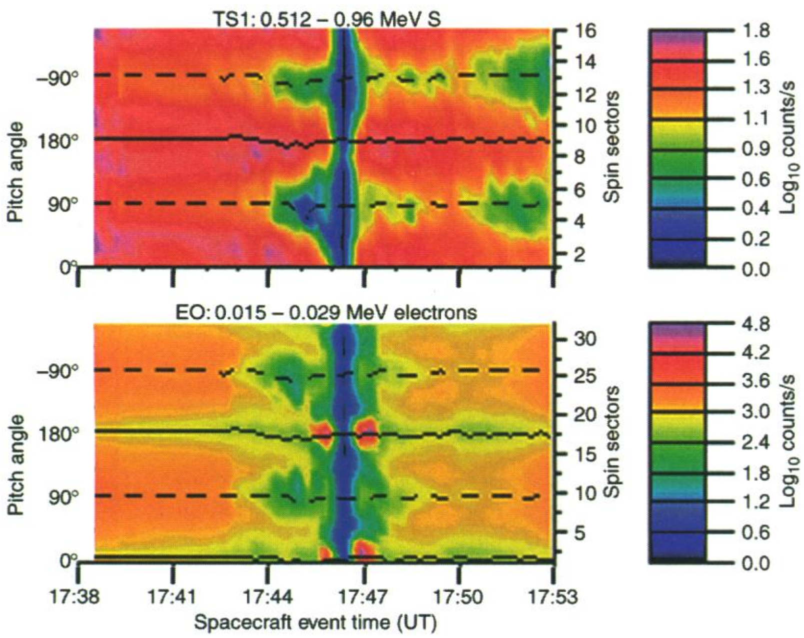


Fig. 2. The angular distribution of S ions (EPD channel TS1) and low-energy electrons (EPD channel E0) through the Io pass. The logarithms of the count rates are color-coded and plotted on a grid giving spin-phase versus time. The dashed and solid lines running through the plot represent the locus of 90° and field-aligned (0° and 180°) pitch angles as determined by the magnetometer. The vertical dark band beginning at approximately 17:46:12 UT is the ~20-s interval when EPD was behind the background shield (3).

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