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Response of the Io Plasma Torus to Comet Shoemaker-Levy 9

M. A. McGrath, D. T. Hall, P. L. Matheson, H. A. Weaver, J. T. Trauger, T. E. Smith, N. Thomas, R. Gladstone, N. M. Schneider, W. M. Harris, T. A. Livengood, R. Prangé, M. C. Festou

Spectroscopic and imaging observations of the Io plasma torus were made in June and July 1994 in conjunction with the encounter of periodic comet Shoemaker-Levy 9 with Jupiter. Characteristic emissions from sulfur and oxygen ions showed a decline of about 30 percent in the extreme ultraviolet and an increase of about 40 percent in the far ultraviolet relative to preimpact observations. Changes in the extreme ultraviolet may be indicative of small changes in the torus electron temperature as a result of quenching of electrons by dust associated with the comet passage. However, no new emission features indicative of fragment dust within the torus were detected. The characteristic torus morphology seen in ground-based imaging was typical of that observed in the past.

An extensive program of observations was undertaken in July 1994 to determine what effect, if any, comet Shoemaker-Levy 9 (SL9) might have on the Io plasma torus. The torus is composed primarily of sulfur and oxygen species that are ejected as neutral atoms or molecules from the surface and atmosphere of Io, ionized by the plasma, captured by the jovian magnetic field, and swept into a toroidal region surrounding Jupiter near the orbit of Io (*1*). The ejection mechanism is widely thought to be sputtering by energetic charged particles in the torus. The potential for significant change to the torus was believed to exist because dust deposited by the comet into the jovian magnetosphere might be transported to and perturb the torus (*2*).

M. A. McGrath, H. A. Weaver, and T. E. Smith are at the Space Telescope Science Institute, Baltimore, MD 21218, USA. D. T. Hall is in the Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21218, USA. P. L. Matheson is in the Department of Aerospace Engineering, University of Southern California, Los Angeles, CA 90089–1191, USA. J. T. Trauger is at the Jet Propulsion Laboratory, Pasadena, CA 91109, USA. N. Thomas is at the Max-Planck-Institut für Aeronomie, Postfach 20, D-W-3411 Katlenburg-Lindau, Germany. R. Gladstone is at Southwest Research Institute, San Antonio, TX 78238, USA. N. M. Schneider is at the Laboratory for Astronomy and Space Physics, University of Colorado, CB 392, Boulder, CO 80309–0392, USA. W. M. Harris is at the Space Physics Research Laboratory, University of Michigan, Ann Arbor, MI 48109, USA. T. A. Livengood is at the Goddard Space Flight Center, Code 693.1, Greenbelt, MD 20771, USA. R. Prangé is at the Institut d'Astrophysique Spatiale, Orsay, France. M. C. Festou is at the National Center for Scientific Research, Observatoire Midi-Pyrenees, F-31400 Toulouse, France.

Source and Effect of Dust

The comet had extensive dust tails and dust "wings" at both the leading and trailing edges of the train of nuclei (*3*), and more dust came from the continuing fragmentation of the nuclei (*4*). The total mass of dust associated with SL9 was relatively large (*5*). Most of this dust did not impact Jupiter's atmosphere and could thus remain in the jovian magnetosphere for long periods of time, possibly even forming another tenuous jovian ring (*2*). The Ulysses spacecraft detected two dust streams in 1992 compatible with SL9 origin (*6*). We therefore monitored the Io plasma torus carefully near the time of impact (when the comet passed through the inner magnetosphere for a second time) to search for temporal variability and new emissions that might be associated with the SL9 passage.

Effects caused by an enhanced amount of dust in the magnetosphere and torus might include the absorption of torus plasma by the dust; the addition to refractories and ice mantle elements such as H, C, O, N, Si, Mg, or Fe to the torus as a result of ion sputtering of the dust; enhanced sputtering of surface material to the atmosphere and torus from

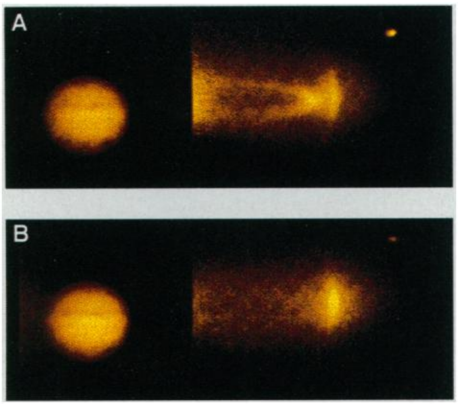

Fig. 1. Two images of Jupiter and its plasma torus taken from a series of ground-based observations between 24 and 30 July 1994 at Las Campanas Observatory. The structure of S^+ at 6731 Å (**A**) and of S^{2+} at 9531 Å (**B**) west of Jupiter were obtained at ~23:54 UT on 27 July and 0:12 UT on 28 July, respectively, with Jupiter's CML near 76° (System III). The jovian disk was attenuated in both images by a stripe of neutral density material, in order to render both Jupiter and the torus visible within single exposures. The star at upper right in each image has been elongated by the proper motion of Jupiter during the exposures. These images are representative of the torus appearance during the week following comet impacts, which is typical of the torus structure seen in ground-based observations since 1981. The relatively dense limb-brightened shell of the warm torus follows the curve of Jupiter's magnetic field lines near the radius of Io's orbit, extending radially outward with a rapid decrease in density. A cold inner torus is seen only in S^+.

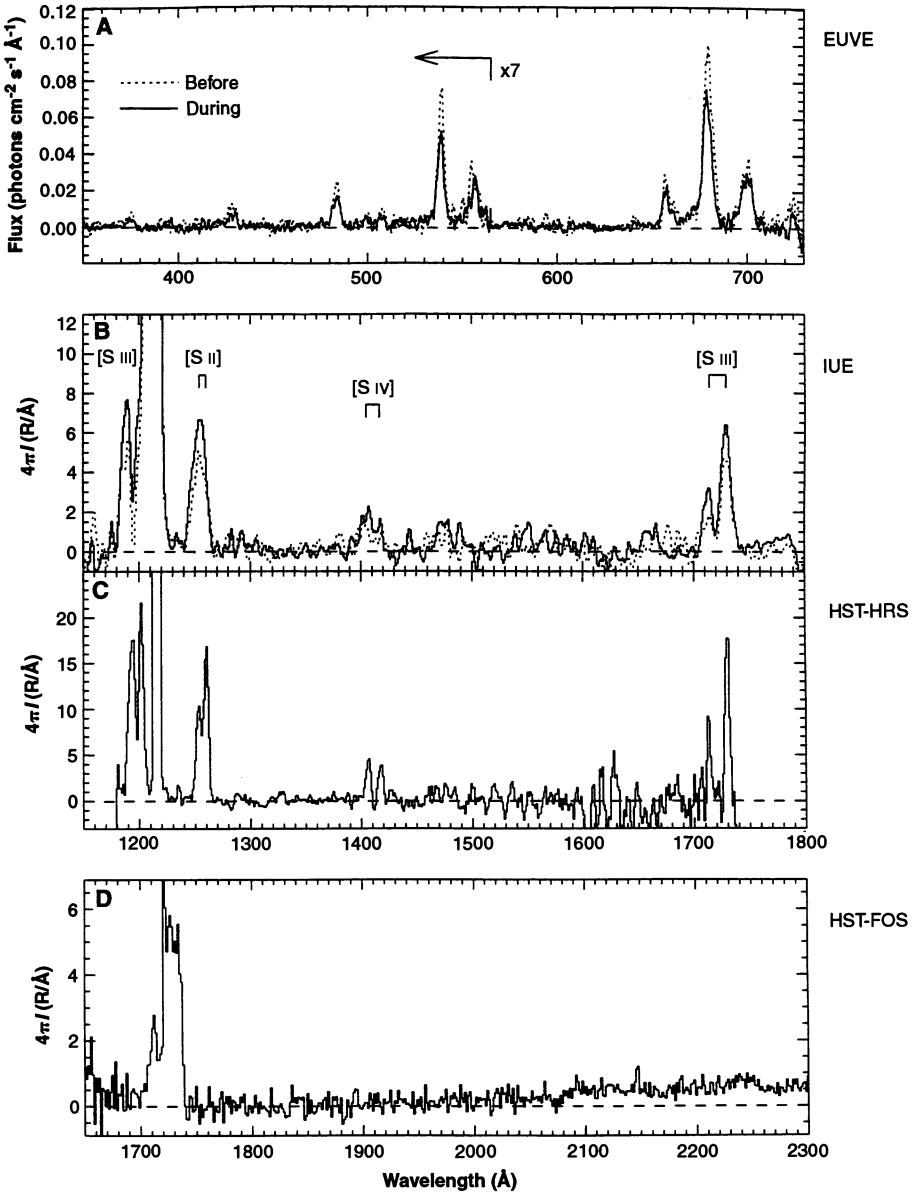

Fig. 2. Ultraviolet spectra of the Io plasma torus that are representative of the data collected in conjunction with the SL9 campaign by (**A**) the EUVE long-wavelength detector, (**B**) the IUE short-wavelength camera, and the two spectrographs on HST: (**C**) GHRS and (**D**) FOS. The low-level continuum present in the FOS spectrum is caused by instrumentally scattered Jupiter light. No new spectral features from constituents other than sulfur or oxygen were detected by any of the observations (dotted line, before; solid line, after impacts). In particular, the C II line at 1335 Å and the Si III line at 1892 Å were not detected. *I*, intensity.

dust impact with Io; and enhanced C, O, N, H, or S from comet coma volatiles (primarily OH, CN, H, C_2, C_3, NH_2, and CS) find their way into the torus. Molecules released from grains into the torus would be quickly dissociated, and neutral material would ionize rapidly on the time scale of hours and, in the warm torus, quickly become doubly ionized on a time scale similar to that of S^{2+}. With characteristic torus residence times of 50 to 100 days, the new ions might last long enough to be observed.

Dust is also prone to rapid electrostatic charging. In the absence of significant photoionizing radiation or energetic electrons, grains would remain at a negative potential of a few volts, corresponding roughly to the electron temperature of the plasma. However, should there be a significant population of energetic electrons present, ejection of secondary electrons could leave the grains with a net positive charge. Grun *et al.* (*7*) suggest that the bursting of grains under electrostatic stress may be a major contributor to the release of neutral gas in the magnetosphere. Morfill *et al.* (*8*) also predict dust-driven interchange instability in the plasma torus: If the dust already present in the torus from Io itself were substantially altered, plasma transport would be considerably enhanced, even over the 1-week time scale of the torus observations. Another predicted outcome of the comet's presence within the magnetosphere was a large change in the mass loading and electron temperature of the torus (*9*), implying the possibility of large changes in the emission line brightnesses.

Observing the Torus

Our observing programs had two major objectives: Measure the known emissions and morphology of the torus to determine if they suffered any significant change as a result of the comet's presence within the system, and search for new emission features, particularly from ions of silicon and carbon, both of which have higher abundances and stronger transitions in the far- and mid-ultraviolet (UV) regions relative to other expected species. The C II line at 1335 Å is sometimes observed from comets, and the Si III line at 1892 Å is a particularly strong far-UV transition.

We present observations made from three Earth-orbiting observatories—the Hubble Space Telescope (HST), the Extreme Ultraviolet Explorer (EUVE), and

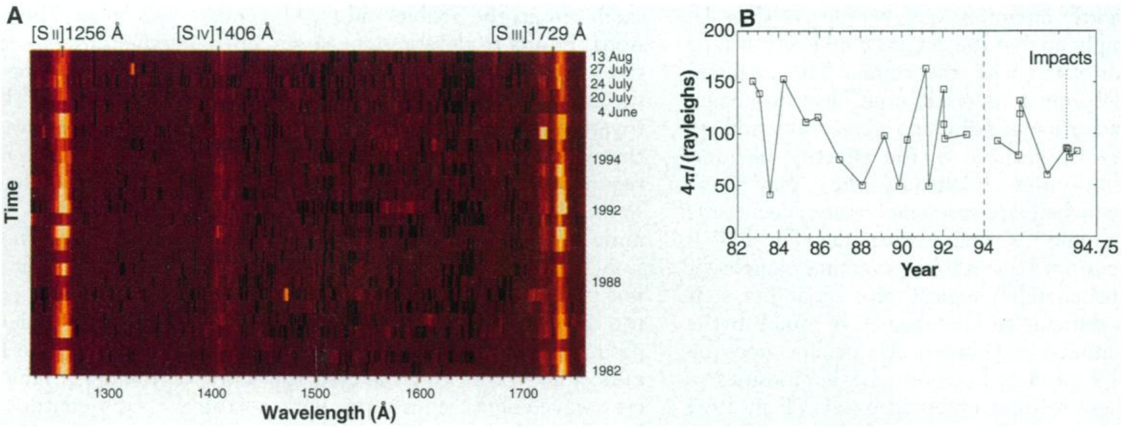

Fig. 3. Temporal variability of the Io plasma torus over the past 12 years as measured by IUE far-UV spectra. (**A**) The complete IUE short-wavelength spectral coverage in observations made between September 1982 and 13 August 1994 in image format on the same brightness scale. Large variations of the individual spectral features from S^+, S^{2+}, and S^{3+} with time, and relative to one another, are apparent. (**B**) The quantitative variation of an individual spectral feature, S II (1256 Å), with time, with the 1994measurements shown on an expanded scale. The time period of the impacts is indicated by the dashed vertical lines. The S II emission increased by ~40% between the 4 June 1994 (preimpact) and 24 July 1994 (during impacts) observations.

Table 1. Observation summary.

Observatory	Start time* (day:hour:min)	Total integration time (min)	Description
EUVE	194:19:15	1253.5†	Before impacts
EUVE	198:14:06	1574.7†	During impacts
IUE	155:05:43	430	Before impacts
IUE	201:04:55	360	During impacts
IUE	205:08:44	240	After impacts
IUE	208:05:15	500	After impacts
IUE	226:01:40	350	After impacts
HST-HRS	205:06:35	58†	After impacts
HST-HRS	205:06:58	58†	After impacts
HST-FOS	208:07:04	183†	After impacts

*Impacts began on 16 July 1994, day 197 of the year. †Not continuous following start time.

the International Ultraviolet Explorer (IUE)—and from a ground-based (GB) observatory at Las Campanas with the 2.4-m telescope (Table 1). The EUVE, IUE, and GB observations associated with the SL9 campaign are identical to observations of the torus performed previously (*10*). Existing data provide a basis against which the comet campaign observations can be compared in the context of known torus variability. Although the HST Goddard High Resolution Spectrograph (GHRS) was used to make the first detection of the [O II] line (brackets denote a forbidden transition) at 2471 Å from the Io torus (*11*), the GHRS and Faint Object Spectrograph (FOS) observations associated with the SL9 campaign are the first HST observations of the well-known far-UV sulfur emissions from the torus (*12*). No observations of the torus were made during the comet's outbound passage through the jovian magnetosphere shortly after perijove in July 1992.

The S^+ and S^{2+} images obtained on 27 and 28 July 1994 (Fig. 1), which are representative of the state of the torus during the comet fragment impacts, show that the familiar torus structures are within the range of variability seen over the past decade. There is no evidence of new morphological features: The warm torus is bright and well-defined in S^+ and S^{2+} emissions at radial distances at and beyond the orbit of Io, and the cold torus appears in S^+ emissions along the centrifugal confinement equator just inside Io's orbit.

The predominant radiative output from the torus is in the extreme UV. Comparison of EUVE spectra of the Io torus acquired before and during the week of impacts (Fig. 2) shows no new spectral features associated with the impacts but suggests that the average brightness of the extreme-UV emissions declined moderately during the week of impacts and the next few days. Furthermore, although the relative brightnesses of the features are generally the same in the before and during spectra, they are significantly different than the relative brightnesses observed by EUVE in 1993, more than a year before the impacts (*13*).

The spectra covering the far- and mid-UV regions taken with IUE and HST (GHRS and FOS) (Fig. 2) show characteristic emissions from the [S III] line at 1198 Å, the [S II] line at 1256 Å, the [S IV] line at 1406 Å, and the [S III] lines at 1713 and 1729 Å. They reveal no pronounced changes in the ion content of the torus or the radiative output associated with the SL9 passage. No new statistically significant features are present, and the carbon and silicon ion transitions that we specifically targeted—C II, C III, and Si III at 1335, 1909, and 1882 Å, respectively—were not detected. Comparison of IUE spectra from 4 June and 20 July 1994 (before and during impacts) shows a moderate increase in the radiative output of the torus, being noticeably brighter during and after the impacts than before, which is opposite to the decrease seen with EUVE.

The torus radiative output varies intrinsically in time with changing conditions of mass loading, density perturbations, and (possibly externally imposed) changes in electron temperatures, much of which may presumably be ascribed to the time-varying supply rate of source material from Io. For cometary gases or dust to produce a perceptible change in the radiative energy balance, the mass loading would temporarily have to be much larger than that produced by native sources or the radiation would somehow have to be quenched. To understand the significance of the changes seen in the torus radiative output in the IUE and EUVE observations, we present a more detailed time history of the existing observations.

The IUE time history (Fig. 3) reveals variability of the [S II] line at 1256 Å by as much as a factor of 4 on time scales shorter than a few months on several occasions. This variability is not well understood (*14*). The [S III] doublet at 1713 and 1729 Å has shown similar variability over the same time period. The ~40% brightening seen in the IUE [S II] emission at 1256 Å between 4 June and 20 July 1994 is well within the range observed in the past and therefore cannot be unambiguously related to the SL9 passage.

The two brightest EUVE features, S III at 680 Å and O II at 539 Å, show a decline of ~30% between the baseline observations in early July and observations during and shortly after the week of impacts (Fig. 4), implying that the decline could very well be correlated with the comet. The extreme-UV emissions result from electron-impact excitation of sulfur and oxygen ions and are highly sensitive to the effective electron temperature. Cometary dust may have quenched electron temperatures, decreasing extreme-UV radiative output. The EUVE does not have a long prior time sample for understanding typical torus variability, so it is difficult to unambiguously establish the connection between the decline and the SL9 passage; however, the luminosities of these features observed by EUVE in 1993 (*12*) are similar to those observed in days 80 to 160 of 1994, further strengthening the possibility that the decline is associated with SL9.

It is not implausible that the EUVE observations might show an SL9 effect while the visible imaging and far-UV spectroscopic measurements do not because the extreme-UV emissions are much more sensitive to changes in electron temperature (*15*). The ion emissions from the torus at visible wavelengths originate predominantly from inside Io's orbit at 5.9 jovian radii ($5.9R_J$), whereas the extreme-UV ion emissions come predominantly from outside Io's orbit, peaking near $\sim 7R_J$. A small change in electron temperature, say from the absorption of electrons by cometary dust, could cause a relatively large change in the extreme-UV emissions but a relatively small one in the visible and far-UV emissions. Efforts to determine a single, effective electron temperature from the EUVE spectra have been unsuccessful to date. A superthermal electron population, in addition to a core electron temperature, is required to explain the extreme-UV emissions, but it is difficult to uniquely determine the characteristics of such a population from the data. The observations are not consistent with a simple decrease in the core electron temperature ($\sim$5 eV) to produce the reduction in extreme-UV luminosities. If this were the case, the shortest wavelength emissions within the EUVE bandpass would have decreased by a larger fraction than the longer wavelength emissions; to within experimental uncertainty, the luminosities of all Io torus emission multiplets in the 400 to 730 Å bandpass decreased by the same fraction.

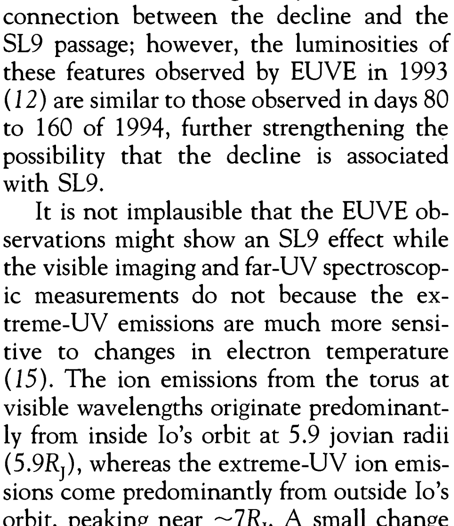

Fig. 4. Luminosities of the Io plasma torus as detected by EUVE. The total luminosity of the Io torus is shown for (**A**) S III at 680 Å and (**B**) O II at 539 Å. Vertical dashed lines on each plot show times of the first and last impacts of comet SL9. Each data point represents an average over one Jupiter rotation, and the error bars show $\pm 1\sigma$ statistical uncertainties. The luminosity of both emission features decreased by about 30 to 50% between 13 and 25 July. Other torus emission features in the 370 to 730 Å spectral range show a similar decrease.

The far- and extreme-UV measurements are also very different. The EUVE measures the total radiative output from the torus, whereas the IUE and HST observations are small-slit measurements with very limited spatial coverage that may be much less sensitive to global changes in the torus. The EUVE observations suggest that SL9 dust transported to the torus was perhaps enough to affect the extreme-UV emissions of the torus but not enough to generate detectable quantities of previously unseen species. The species Si^{2+} radiates efficiently and could have been seen at column densities of only $\sim 10^{11}$ cm^{-2}. However, even the most optimistic assessments of possible observable effects required a micrometer-sized grain density of at least 0.02 m^{-3}, a number much larger than compatible with estimates of dust production (*2*).

The amount of material sputtered from the surface of the dust, ionized, and then picked up by the corotating magnetic field during the brief transit of the fragments through the inner magnetosphere was likely to have been small compared to the continuous injection of sulfur and oxygen species from Io itself. The effective sputtering area of Io is around 10^{13} m^2. The total cross-sectional area of dust in SL9 was 3×10^{11} m^2 (*5*), around 1/30 of the sputtering area. Sputtering from cometary dust would be more efficient than sputtering from Io because the sputtered particles would not have to attain escape velocity from the satellite. On the other hand, most of the dust did not cross the higher-density regions of the torus where sputtering would have been most effective. If we assume that the magnitudes of these two effects approximately cancel and that the production rate from Io is around 1 ton s^{-1} (*16*), then the sputtered loss from the dust particles would have been around 30 kg s^{-1}. The dust particles crossed the inner magnetosphere in about 3 hours, so this additional input to the torus provided only about 3×10^5 kg to the torus compared with the total mass content of $\sim 10^9$ kg. Thus, if the input of cometary ions was uniformly distributed about the torus, the mixing ratio of cometary species should have been about 0.03%. The column density of torus ions at the ansae, $5.9R_J$ from the planet, is about 6×10^{13} cm^{-2}. Even if the input cometary dust was composed of pure silicon and converted to Si^{2+}, the column density would not have exceeded 2×10^{10} cm^{-2}, about one-fifth of the upper limit set by the FOS spectra.

By contrast, the jovian synchrotron radiation belts, located at $\sim 2R_J$, were significantly affected by the fragment impacts (*17*), as plume material or shock waves traversed the magnetic field lines connected to the impact sites, and auroral arcs were observed in the northern hemisphere at the conjugate latitude after the impact of fragment K (*18*). The absence of marked changes in the Io torus implies that a significant amount of plume material or shock waves did not reach field lines passing through the torus. Because it is well separated both spatially and magnetically from the direct impact sites of the fragments, this is not surprising.

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Auroral Signature of Comet Shoemaker-Levy 9 in the Jovian Magnetosphere

R. Prangé, I. M. Engle, J. T. Clarke, M. Dunlop, G. E. Ballester, W. H. Ip, S. Maurice, J. Trauger

The electrodynamic interaction of the dust and gas comae of comet Shoemaker-Levy 9 with the jovian magnetosphere was unique and different from the atmospheric effects. Early theoretical predictions of auroral-type processes on the comet magnetic field line and advanced modeling of the time-varying morphology of these lines allowed dedicated observations with the Hubble Space Telescope Wide Field Planetary Camera 2 and resulted in the detection of a bright auroral spot. In that respect, this observation of the surface signature of an externally triggered auroral process can be considered as a "magnetospheric active experiment" on Jupiter.

Inside the jovian magnetosphere, the comae of comet Shoemaker-Levy 9 acted as ionized bodies that disturbed the electrodynamical equilibrium of the magnetosphere-ionosphere system. As a result, a variety of plasma processes, depending on the geometry of the field lines and the characteristics of the comae (including the dynamo effect resulting from the motion of charged dust through the ambient plasma), were expected to trigger energetic particle precipitation along field lines into the jovian ionosphere (*1*). The observable signature of such precipitations is auroral-type collisionally excited emissions in the far ultraviolet (FUV) at the magnetic footprints of the nuclei.

Several issues made the study of such interactions different from other observations of the comet's collision. First, in contrast with atmospheric effects, some auroral signatures started long before the impacts, and the magnetic footprints of the fragments remained on the dayside, even when the nuclei reached the nightside (*2*). Second, the nature of magnetospheric effects was controlled by the relative geometry of the comae and the local jovian magnetic field (Fig. 1). Therefore, the effects were subject to the 10-hour rotation period of Jupiter, and we had to consider the comet path not in a fixed planetocentric frame of reference but in the corotating tilted magnetic frame of Jupiter (*3*). Third, by chance, the comet path sampled a variety of magnetospheric regimes, going from the day to the night sides, from dusk to dawn, and because of the latitude of the trajectory, near the polar cap boundary, from closed to open magnetic field lines. As an additional consequence, there were periods during which plasma interactions could give rise to conjugate auroral signatures in both hemispheres.

R. Prangé is with the Institut d'Astrophysique Spatiale, CNRS–Université Paris XI, 91405 Orsay, and the Institut d'Astrophysique de Paris, France. I. M. Engle is with the Physics Department, U.S. Naval Academy, Annapolis, MD 21402–5026, USA. J. T. Clarke and G. E. Ballester are with the Department of Atmospheric, Oceanic, and Space Sciences, University of Michigan, Ann Arbor, MI 48109–2143, USA. M. Dunlop is with the Space and Atmospheric Physics Group, Imperial College, London SW7 2BZ, UK. W. H. Ip is at the Max-Planck-Institut für Aeronomie, D-37191 Katlenburg-Lindau, Germany. S. Maurice is with the European Space Agency, ESTEC/SSD/SO, 2200 AG Noordwijk, Netherlands. J. Trauger is at the Jet Propulsion Laboratory, Pasadena, CA 91109, USA.

Auroral Features

Among the observations of the Hubble Space Telescope (HST) FUV Imaging Program (*4*), some were scheduled with the assistance of the magnetic field models described below. An unusual emission was observed on 20 July 1994. Four images were taken with the Wide Field Planetary Camera 2 (WFPC2) between 14:10 and 14:47 UT, within 1 hour of the collision of fragment P2 (*5*). The first two exposures (400 s) were taken with filters F160WB and F130LP, which isolate the H_2 Lyman bands. The last two (300 s) were taken with the Wood's filter F160WB only, providing the H Lyman α, H_2 Werner, and Lyman band emission (*4*). The images did not reveal any

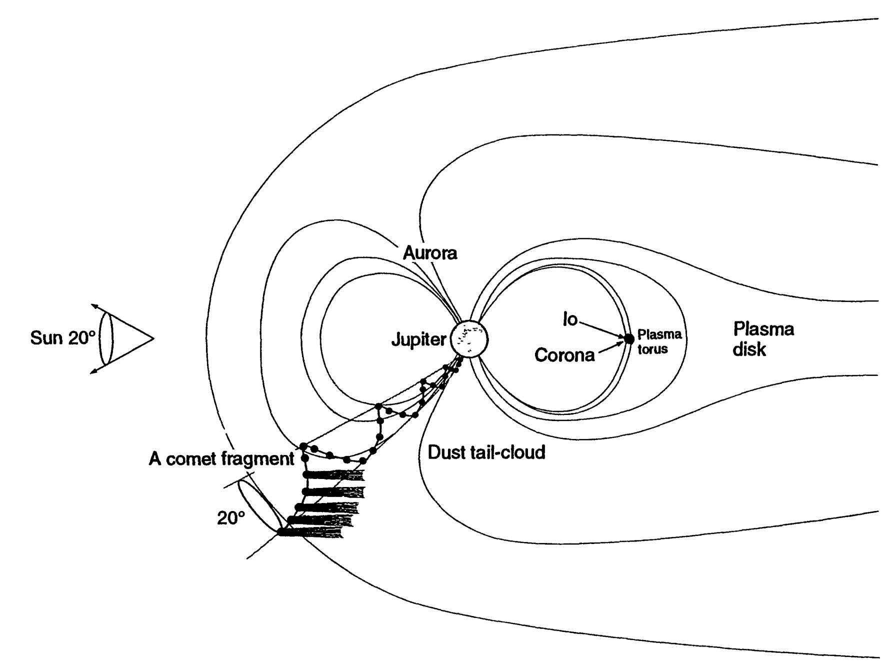

Fig. 1. Path of a fragment and its tail inside of the jovian magnetosphere (schematic) in the noon-midnight meridian. In the magnetic frame of reference, the trajectory is a pseudohelix, crossing alternatively open and closed field lines.