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ENERGETIC ION ACCELERATION AND TRANSPORT IN THE UPSTREAM REGION OF JUPITER: VOYAGER 1 AND 2

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ABSTRACT

Long-lived upstream energetic ion events at Jupiter appear to be very similar in nearly all respects to upstream ion events at earth. A notable difference between the two planetary systems is the enhanced heavy ion compositional signature reported for the Jovian events. This compositional feature has suggested that ions escaping from the Jovian magnetosphere play an important role in forming upstream ion populations at Jupiter. In contrast, models of energetic upstream ions at earth emphasize in situ acceleration of reflected solar wind ions within the upstream region itself. Using Voyager 1 and 2 energetic ($\gtrsim$ 30 keV) ion measurements near the magnetopause, in the magnetosheath, and immediately upstream of the bow shock, we examine the compositional patterns together with typical energy spectra in each of these regions. We find characteristic spectral changes late in ion events observed upstream of the bow shock at the same time that heavy ion fluxes are enhanced and energetic electrons are present. A model involving upstream Fermi acceleration early in events and emphasizing energetic particle escape in the prenoon part of the Jovian magnetosphere late in events is presented to explain many of the features in the upstream region of Jupiter.

INTRODUCTION

In contrast to the exploratory Pioneer 10 and 11 missions, Voyager 1 and 2 [1] were well-instrumented to examine the Jovian magnetospheric energetic ion populations in the range of $\sim$ 30 keV/n to several hundred keV/n [2]. The result was a wealth of new information about the fluxes, energy spectra, anisotropies, and elemental composition patterns of the ion populations at Jupiter both within the Jovian magnetosphere [2] and in the immediate environs of the planet [3].

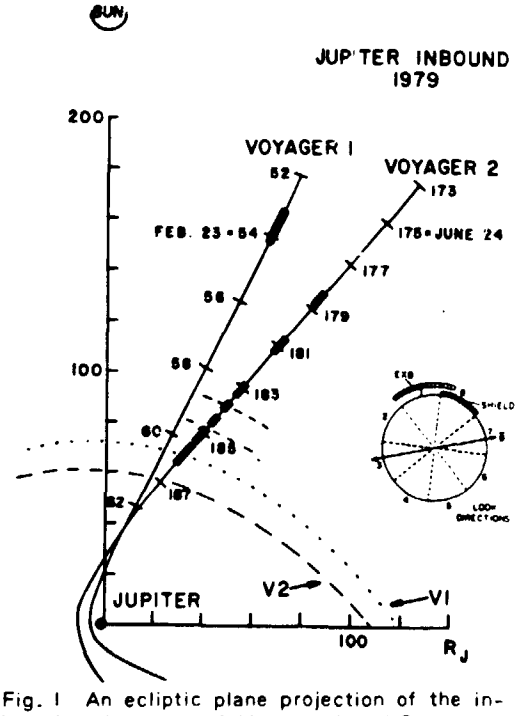

Fig. 1 An ecliptic plane projection of the inbound trajectories of Voyager 1 and 2 at Jupiter.

Figure 1 is a projection on the ecliptic plane of the inbound trajectories of Voyager 1 and 2. The cartesian coordinate system is scaled in units of Jovian radii (1 R_J = 7 x 10^4 km). Tick marks on the trajectory profiles are labeled by the day of year (day 1 = Jan. 1) in 1979. The dotted and long-dash hyperbolic curves labeled V1 and V2 are meant to illustrate the Jovian bow shock at its innermost encounters with Voyager 1 and Voyager 2, respectively.

The small inset in Figure 1 shows the angular distribution measuring scheme of the Low-Energy Charged-Particle (LECP) detector system used in the present study [2, 3]. The LECP scans in fixed time steps (ranging from 6 sec to 6 minutes depending on mode) from sector 1 to sector 8 and then scans backward from sector 8 to sector 1. Sector 8 is blocked by a shield and represents a background measuring position of the LECP. Convective particle transport in the solar wind would generally be expected to be seen in sector 1 as illustrated by the cross-hatched segment labeled EXB. Particles coming from Jupiter to the Voyager detectors would be expected to be seen in sectors 3 and 4.

As reported by Zwickl et al. [3], many energetic ion events of probable Jovian origin were seen as the Voyagers approached and receded from

Jupiter. The long-lived events observed near the bow shock in the upstream region are indicated by the thick black shading shown on the trajectory profiles of Figure 1. The Jovian ion bursts were seen to extend in energy from the LECP detection threshold of ∿ 30 keV (assuming the ions are protons) to ∿ 1 MeV. It is important to note, however, that significant enhancements of Z > 6 ions were detected in association with these events. Since the Jovian magnetosphere is rich in Z >6 particles [2], a magnetospheric source for a significant fraction of the energetic particles in the upstream events was thus suggested [3].

The purpose of this paper is to explore further the properties of the long-lived upstream ion events at Jupiter. In particular, we wish to examine the relationship of the energetic ions to the magnetic fields measured on the same spacecraft [4] and to study the energy spectra and compositional patterns in order to understand better the origin and transport of the upstream ions. We will then compare and contrast the Jovian results with the very similar phenomena reported in the upstream region at earth [5, 6]. By this means we would hope to illuminate the differences between the Jovian and terrestrial cases and test the generality of acceleration and transport models in the vicinity of collisionless shocks.

OBSERVATIONS

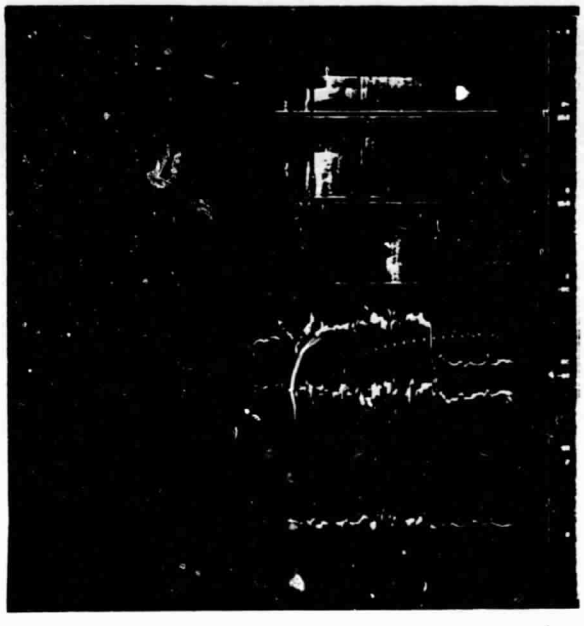

Fig. 2 The upper three panels are color-coded Voyager 2 spectral and angular distribution data for 29-30 June 1979. The lower three panels summarize concurrent Voyager 2 magnetic field observations.

Figure 2 illustrates a typical long-lived energetic ion event observed upstream of Jupiter by Voyager 2 on Days 180 and 181 (June 29-30) 1979. The upper three panels of the figure show LECP ion information in a color coded format and the lower three panels show magnetic field data. The top panel of Figure 2 shows an energy-time spectrogram for the LECP-measured ions. We have converted the scan-averaged ion count rates in each channel to fluxes using nominal proton energy passbands and geometric factors. The vertical energy scale is logarithmic and (as shown at the right of the panel) extends from ∿ 0.04 MeV to ∿ 4 MeV. The absolute intensities of the measured protons (ions) are represented by the color bar to the left of the figure with deep blue being 10^{-3} p $(cm^2\text{-s-sr-keV})^{-1}$ and red being 10^2 p $(cm^2\text{-s-sr-keV})^{-1}$. The next two succeeding panels summarize color-coded angular distribution information in two energy ranges. The second panel from the top shows data for the channel designated 'PLO 2' which is nominally 43-80 keV for protons. The third panel corresponds to data from the channel designated 'PLO 5' which is nominally 215-540 keV for protons.

The lowest three panels of Figure 2 show the Voyager 2 magnetic field data as transformed into the LECP coordinate system. The azimuth is the angle (in degrees) of the field projection on the LECP scan plane (0° is approximately sunward). The polar angle is measured from the LECP scan plane, i.e. 0° would lie in the LECP scan plane. The two light horizontal lines at ± 45° in the polar field panel illustrate the FWHM field of view of the LECP detectors.

Figure 2 illustrates many of the essential features of the long-lived events. When ions were first detected at ∿ 0900 UT on Day 180 they were seen only in the lowest energy channels. This feature is seen in all three top panels. Note also in panel 2 that the ions are strongly anisotropic and by comparing the second panel to the field direction in panel 4 we see that the initial ion flow is roughly field-aligned. As time proceeds, the ions appear at progressively higher energies and the angular distributions become nearly isotropic. Note that PLO 5 shows little significant ion activity until ∿ 1400 UT; at this time these detected ions are anisotropic but the anisotropy is of the gradient ($\nabla p \times \vec{B}$) type, rather than the field-aligned streaming anisotropy.

Note in all three magnetic field panels in Figure 2 that field fluctuations were quite insignificant until ∿ 1100 UT. Large amplitude fluctuations then began to be clearly detected and the wave amplitudes grew as the ion event progressed. Low-frequency wave activity ceased abruptly when the field azimuth shifted by $\gtrsim$ 180° at ∿ 0230 UT on Day 181. Coincident with this field direction change and coincident with the cessation of wave activity, it is seen that major low-energy ion activity also ceased. From ∿ 0400 to ∿ 1000 UT on Day 181 there were some further ion fluxes detected but these were of generally low intensity.

Throughout the course of the Jovian ion event itself (1100 UT on Day 180 to 0300 UT on Day 181)

the field azimuth on average rotates gradually from -30° to +60°. As is clear from Figure 1, a linear extrapolation of the field direction from Voyager 2 to the bow shock during this rotation would give a nominal connection that progressed from the subsolar region to the dawn sector.

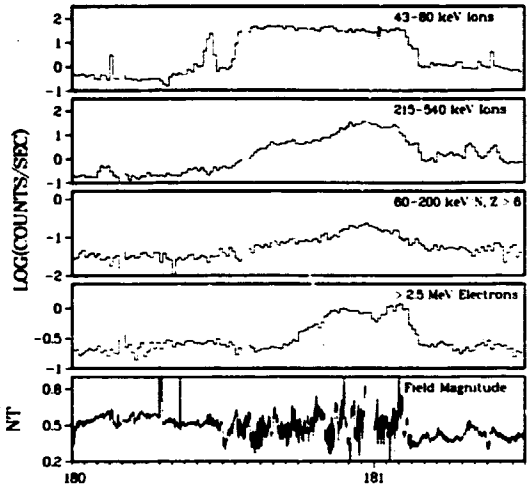

Fig. 3 Scan-averaged energetic particle data (upper four panels) and magnetic field strength (lower panel) for 29 June and 30 June 1979.

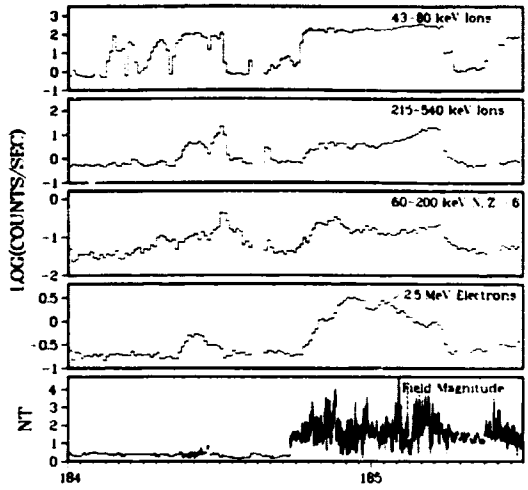

Fig. 4 Same as Figure 3 for 3-4 July 1979.

Figure 3 is a line plot of several selected energetic particle and magnetic field data for the same period shown in Figure 2. The upper two panels of Figure 3 are the scan-averaged PLO 2 and PLO 5 counting rates (15-min averages) while the third panel shows the counting rate of a channel sensitive primarily to heavy ions with $Z > 6$. The fourth panel shows the counting rate of an LECP channel which measures electrons with $E > 2.5$ MeV. Finally the bottom panel of Figure 3 shows the magnitude of $\vec{B}$ as in Figure 2, but shows this on an expanded vertical scale.

Note in the 43-80 keV ions of Figure 3 that after the brief burst of ions at $\sim$ 1100 UT, the fluxes seen in this energy range rise rapidly (< 45 min) to a nearly constant value and then remain there for over 15 hours. In contrast, the 215-540 keV ions build up gradually with time, more-or-less in concert with the field azimuth rotation seen in Figure 2. It is also clear in Figure 3 that after 1400 UT the $Z > 6$ fluxes began to increase above the detection threshold level, and only after $\sim$ 1700 UT do we see any significant increase of the > 2.5 MeV electrons above background.

Figure 4 shows another 36-hour period of Voyager 2 data on Days 184 and 185. The spacecraft crossed the bow shock and entered the magnetosheath at 1730 UT on Day 184. The first event in Figure 4 shows the same features as seen in the event illustrated in Figures 2 and 3. The initial short-duration bursts (0300-0600 UT) are seen only at low energies while after $\sim$ 0800 UT the high energy fluxes increase markedly. The third and fourth panels show, as in the previous example, that the $Z > 6$ and the electrons ($E > 2.5$ MeV) increase significantly only quite late in the event. The second long-lived ion event in Figure 4 occurs entirely within the magnetosheath. The bottom panel of Figure 4 shows that the low frequency wave amplitudes from 1830 UT to 0630 UT are very large ($\Delta B/B \sim 0.8$). Examination of the energetic ions for this period shows that the particle anisotropies are (in the spacecraft frame) generally consistent with flow from the subsolar region toward the dawn side.

Scholer and co-workers [6] have shown in the case of the upstream region at earth that there are two energetic ion populations. One population they attribute to upstream Fermi acceleration of solar wind ions which have been reflected by the terrestrial bow shock [7, 8]. These ions (protons) have soft energy spectra and are unaccompanied by energetic electrons. The second population Scholer et al. attribute to magnetospheric origin. This second group has a hard spectrum at high energies, bends over significantly at low energies, and is accompanied by energetic electrons. Since we see parts of many Jovian events to be accompanied by electrons and also by very substantial fluxes of $Z > 6$ particles (which almost certainly are of magnetospheric origin), we have examined typical ion energy spectra in each of the long-lived events.

Figure 5 shows several spectra from two illustrative periods. The first period on Day 178 was an event period in which we found no significant energetic electron enhancement and in which the $Z > 6$ fluxes increases were at a level barely above background. Throughout the event, the spectra were as shown in Figure 5 with a soft spectrum reaching the background level at $\lesssim$ 500 keV. This same type of soft spectrum was seen early in the Day 180 event (cf. Fig. 2 and 3) before energetic electrons or heavy ions were detected. This type of spectrum is illustrated by the Day 180 1300-1315 UT example. This contrasts markedly with the type of spectra seen when energetic electrons and heavy ions are present. As seen in the 2315-2330 UT example of Figure 5 this latter type spectrum is quite hard at high energies and rolls over at lower energies.

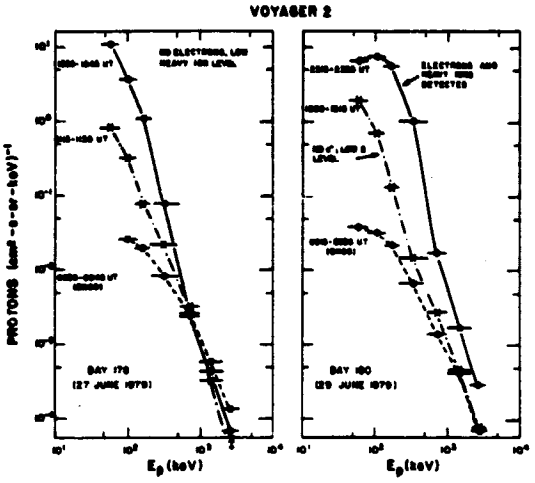

Fig. 5 Representative energetic ion spectra taken in the Jovian upstream region by Voyager 2 detectors on 27 June (left panel) and 29 June (right panel) 1979.

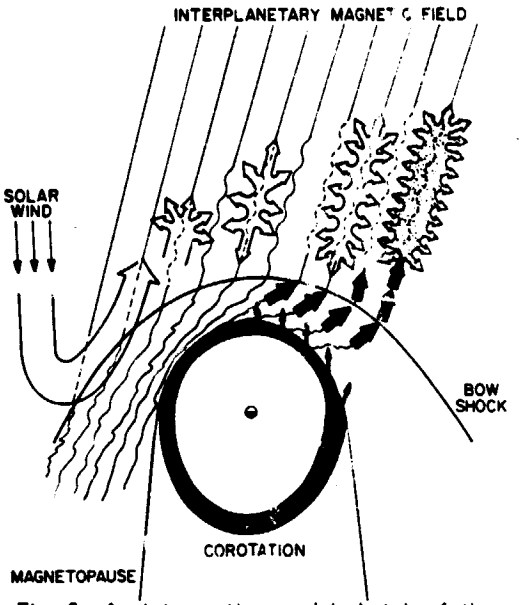

Fig. 6 An interpretive model sketch of the upstream region, the magnetosheath, and the outer magnetosphere of Jupiter. A preferred escape of Jovian particles at the dawn magnetopause is emphasized in the model as described in the text.

INTERPRETATION AND CONCLUSIONS

Figure 6 is a schematic model which is consistent with our observations in essentially all of our available upstream Jovian events. The interplanetary magnetic field is often nearly radial throughout most of the events studied, but the field frequently rotates gradually from a projected connection to the nose region toward connection at local dawn. We hypothesize that initally the IMF makes contact with the Jovian bow shock toward the dust side. In this region a small fraction of solar wind protons are reflected as has been suggested in the terrestrial case [7] and form a reflected beam streaming against the solar wind. This beam goes unstable via the electromagnetic ion beam instability [8] to form a diffuse population and low-frequency waves. We hypothesize further that as the IMF field convects across the bow shock toward the dawn side, some fraction of the protons present in the upstream region scatter back and forth in the foreshock region and accelerate to higher energy by the Fermi process [7, 9].

Field lines that have connected for very long times or field lines threading the spacecraft that rotate toward the prenoon side of the Jovian magnetosphere apparently become heavily populated with $Z > 6$ ions and energetic electrons that have escaped from the Jovian magnetosphere. We propose that there is a preferred escape region in the prenoon sector of the Jovian magnetopause from which energetic particles can escape with increased probability. These escaping particles then flow upstream along properly connected dawn side field lines and mix with the ion population formed by the upstream Fermi acceleration process.

A suggestion as to the cause of the preferred escape region is that particle corotation (which is quite clear immediately inside the magnetopause [2]) would give a strong directional component to the magnetospheric particle population. Corotational drift paths would tend to reach greater jovicentric distances on the nightside and then the corotating particles would be driven into the magnetopause boundary through out the local morning region. Under relatively time-stationary configuration conditions, this effect could produce significant velocity shears (Kelvin-Helmholtz instability) leading to enhanced leakage on the morning side as illustrated in Figure 6.

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