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Mirror mode structures and ELF plasma waves in the Giacobini-Zinner magnetosheath

B. T. Tsurutani[1], G. S. Lakhina[2], E. J. Smith[1], B. Buti[1], S. L. Moses[3], F. V. Coroniti[3], A. L. Brinca[4], J. A. Slavin[5], and R. D. Zwickl[6]

[1]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91103, USA
[2]Indian Institute of Geomagnetism, Colaba, Mumbai/Bombay, India
[3]TRW Systems, Redondo Beach, CA, USA
[4]Centro de Fisica de Plasmas, Instituto Superior Tecnico, Lisboa, Portugal
[5]Goddard Space Flight Center, Greenbelt, MD, USA
[6]Space Environment Laboratory, NOAA, Boulder, CO, USA

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Abstract. We show evidence for mirror mode structures at comet Giacobini-Zinner. These are plasma structures with alternating high β and low β regions driven unstable when $\beta_\perp/\beta_\| > 1+1/\beta_\perp$. These structures are detected in a region just adjacent to the magnetic tail and have scale sizes of ~ 12 H_2O group ion cyclotron radii. Calculations are presented to show that mirror mode instability can occur due to the perpendicular pressure associated with H_2O^+ cometary pickup ions in the region of mirror mode observation. Adjacent regions (in the magnetic tail and further in the sheath) are found to be stable to the mirror mode. Plasma waves are detected in relation with the mirror mode structures. Low frequency 56 to 100 Hz waves are present in the high beta portions, and high frequency, 311 Hz to 10 kHz, waves are present in low beta regions. These may be electromagnetic lion roar waves and electrostatic festoon-shaped waves, respectively, in analogy to plasma waves detected in the Earth's magnetosheath.

1 Introduction

Mirror mode structures have been well documented in the magnetosheaths of the Earth, Jupiter and Saturn (Tsurutani et al., 1982, 1993; Violante et al., 1995; Erdős and Balogh, 1996; Bavassano-Cattaneo et al., 1998, see the last reference for nearly a complete list of works on this subject), and in interplanetary space at solar wind stream-stream interfaces (Tsurutani et al., 1992).

Mirror mode structures are generated by the mirror instability due to plasma pressure anisotropies $\beta_\perp/\beta_\| > 1+1/\beta_\perp$ (Hasegawa, 1969, 1975; Patel et al., 1983; Migliuolo, 1986; Price et al., 1986; Price, 1989; Hasegawa and Chen, 1989, see also Southwood and Kivelson, 1993; Kivelson and Southwood, 1996). In the above, the plasma β is $8\pi nkT/B^2$, where T is temperature, B the ambient magnetic field, and n the ion number density. Anisotropic ion distributions for mirror instability can be generated by plasma heating across quasiperpendicular shocks (Kennel and Sagdeev, 1967) and from the Zwan and Wolf (1976) magnetic field line draping effect (Tsurutani et al., 1982). Mirror mode structures are therefore expected just downstream of quasiperpendicular shocks (Lee et al., 1988) and near planetary magnetopauses (where draping effects are most important). Published examples of planetary magnetosheath mirror mode structures (Tsurutani et al., 1982, 1993; Erdős and Balogh, 1996; Bavassano-Cattaneo et al., 1998) have shown that such structures are present throughout the magnetosheath with the smallest amplitudes near the bow shocks and the largest near the magnetopauses (Tsurutani et al., 1982, 1993; Bavassano-Cattaneo et al., 1998).

Mirror modes have also been detected in the sheath of comets (Yeroshenko et al., 1987; Russell et al., 1987; Mazelle et al., 1991). For comets, the bow shocks are generally weak and little or no ion heating occurs through this process. Field line draping occurs at comets (Alfvén, 1957; Slavin et al., 1986a) and can lead to perpendicular (ion) anisotropies necessary for mirror mode instability (Tsurutani, 1991; Brinca, 1991). At comets, ionization of cometary neutrals plus solar wind pickup, may lead to very strong temperature anisotropies (Tsurutani and Smith, 1986a,b). The dominant ions in the pickup process are the H_2O group ions. The purpose of this paper is to present the first observation of mirror mode structures at comet Giacobini-Zinner (hereafter referred to as G-Z).

The MHD (macroscopic) mirror mode instability can also couple to several microscopic instabilities. Electromagnetic (ELF) whistler mode waves and electrostatic (VLF) ion acoustic emissions have both been previously detected in association with mirror waves (Anderson et al., 1982). Electromagnetic lion roars (Smith and Tsurutani, 1976) can be driven unstable by the high-β low-field plasma portions of the mirror structures (Thorne and Tsurutani, 1981; Tsurutani et al., 1982; Lee et al., 1987; Zhang et al., 1998; Baumjohann et al., 1999), as an absolute instability (Moreira, 1983). See Zhang et al. (1998) for a current update on lion roar observations. An instability is "absolute" when a finite source leads

Correspondence to: Bruce T. Tsurutani

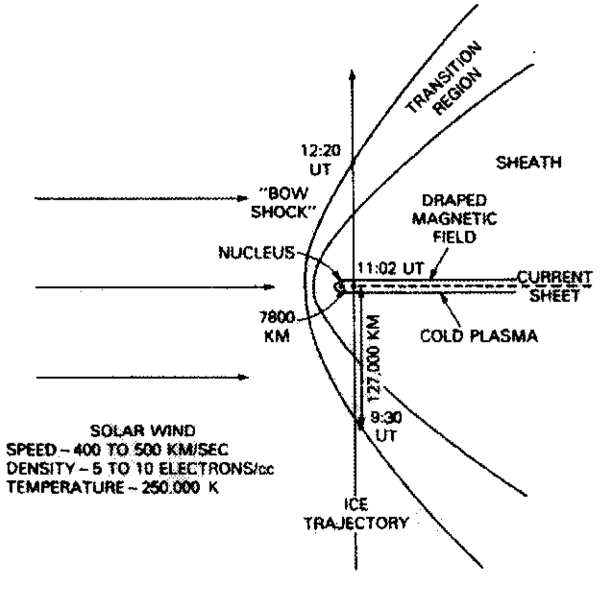

Fig. 1. The International Cometary Explorer (ICE) pass through the comet Giacobini-Zinner (G-Z) tail.

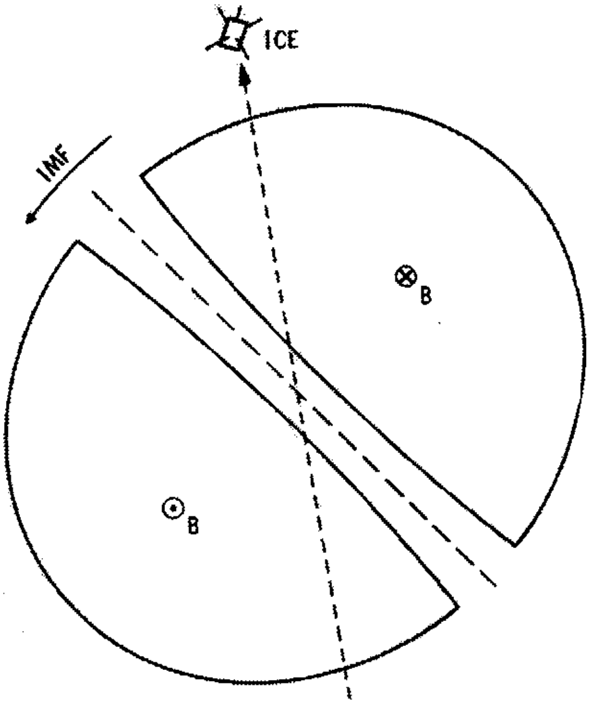

Fig. 2. ICE passage through the G-Z tail lobes and plasma sheet.

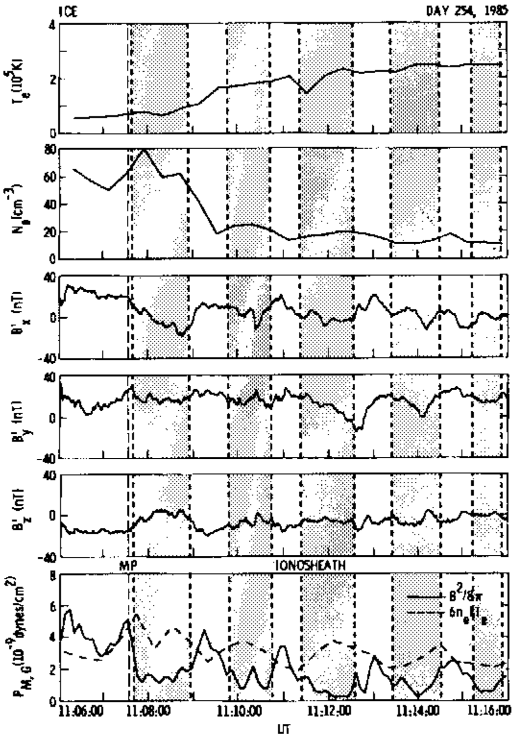

Fig. 3. Mirror mode structures in the outbound pass of comet Giacobini-Zinner (bottom panel). The plasma and magnetic pressures are ~ 180° out-of-phase.

to growth in time at every point in space, in contrast to the convective instability where there is a growing, propagating disturbance (which decays in time at a fixed point in space). See Swanson (1989) for further information. The instability is caused by a local decrease in the critical energy, E_c, allowing cyclotron resonance with a great portion of the thermal electron population (Thorne and Tsurutani, 1981). Electrostatic waves are generated in the low-β high-field plasma regions of mirror mode structures (Anderson et al., 1982). Gallagher (1985) has argued that these are ion-acoustic waves. A second purpose of this paper is to explore ELF waves associated with comet G-Z mirror mode high-β and low-β regions.

2 Results

Figure 1 is a schematic of the International Cometary Explorer (ICE) trajectory at G-Z taken from Von Rosenvinge et al. (1986). ICE passed through the comet tail at a distance of ~ 7800 km from the nucleus. The trajectory was from south-to-north and the encounter occurred when the comet was ~ 1.0 AU from the sun. Neutral water molecules sublime from the comet nucleus and escape at speeds of ~ 1 km s^{-1}. These neutrals are ionized on time scales of ~ 10^6 s. The ions are picked up by the solar wind through plasma instabilities (Brinca, 1991).

Figure 2 is a schematic of the ICE passage through the two tail lobes taken from Slavin et al. (1986a). ICE passed through the center of the G-Z plasma sheet at ~ 1102:30 UT and exited the north tail lobe at ~ 1107:40 UT.

Figure 3 is a composite plasma and magnetic field data plot for the time interval when ICE just exited the north tail lobe. The electron temperature and density values are given in the top two panels, respectively. The magnetic field components in aberrated cometary solar ecliptic coordinates (i.e., x' is anti-parallel to the upstream solar wind velocity vector; Slavin et al. (1986b)) are displayed in the next three panels. The bottom panel contains the magnetic pressure and the plasma pressure (represented by 6 times the electron pressure; Slavin et al. (1986b)) assuming a T_i/T_e ratio of 5 which brings the plasma sheet and lobe pressures into approximate balance). The Los Alamos ion instrumentation unfortunately stopped functioning earlier in the mission, and the energetic ion flux temporal resolution was too low to be useful for this type of high time resolution study.

In Figure 3, it can be noted that although there are fluctuations in the B_y and B_z components, the field is relatively constant in direction but with major magnitude (pressure) variations after G-Z exited the magnetotail at 1107:40 UT. The plasma pressure is observed to have peak values where the field has minimum values (see bottom panel). It can be noted that there are about 5 major magnetic field and plasma oscillations over the $\sim$ 10 minutes displayed. In each oscillation, the field and plasma pressures are out-of-phase. Taking the interval from the magnetopause ($\sim$ 1107:40) to 1114:50 UT, the average period is 107 s. Over this interval, the magnetic field decreases from ~ 30 nT to $\sim 15 - 20$ nT as ICE moves further from the sun-comet nucleus line. Assuming these structures are convecting past the spacecraft ($V \approx 30$ km/s in the cometary ionosheath adjacent to the tail; Bame et al. (1986)), the scale size of the structures is $\sim 3.2 \times 10^3$ km. The average ambient magnetic field strength is $\sim$ 20 nT, the ion velocity is $\sim$ 30 km/s, and thus the ion gyroradius is $\sim$ 270 km. The mirror mode scale size is $\sim 12 r_{H_2O^+}$.

The plasma and magnetic pressures are given in the bottom panel of Fig. 3. The beta value (plasma pressure divided by magnetic pressure) is approximately 1.0 in the high field regions (1107:40 UT, 1113 UT and 1115:50 UT) and 2 to 10 in the low field regions (a maximum β of $\sim$ 10 occurs at 1112:10 UT).

Figure 4 gives the amplitude of the electric plasma waves in the frequency range from 17 Hz to 100 kHz, covering the same time interval as Fig. 3. Each channel has a frequency bandwidth of $0.5 f_{center}$, where f_{center} is the center frequency of the channel. The amplitude is given using a logarithmic scale. The ambient magnetic field magnitude is plotted in the bottom panel again for reference. In the top panel of the figure, the value of the local electron gyrofrequency has been added (shown as a dashed line). Vertical dashed lines and shading have been added in order to help the reader visualize the correlation between the VLF/ELF plasma waves and the plasma and field structures.

It is believed that there are two different ELF modes present at frequencies $f < 562$ Hz: a low frequency mode detected primarily at $f \approx 56.2$ to 178 Hz and a broadband sporadic mode that extends to higher frequencies. The lower frequency band is most easily observed in the 56.2 and 100 Hz channels, and the broadband bursts in the 311 Hz to 10 kHz frequency channels. The latter is more noticeable where there is less power associated with the lower frequency mode. Examples of the lower frequency (56.2 and 100 Hz) mode

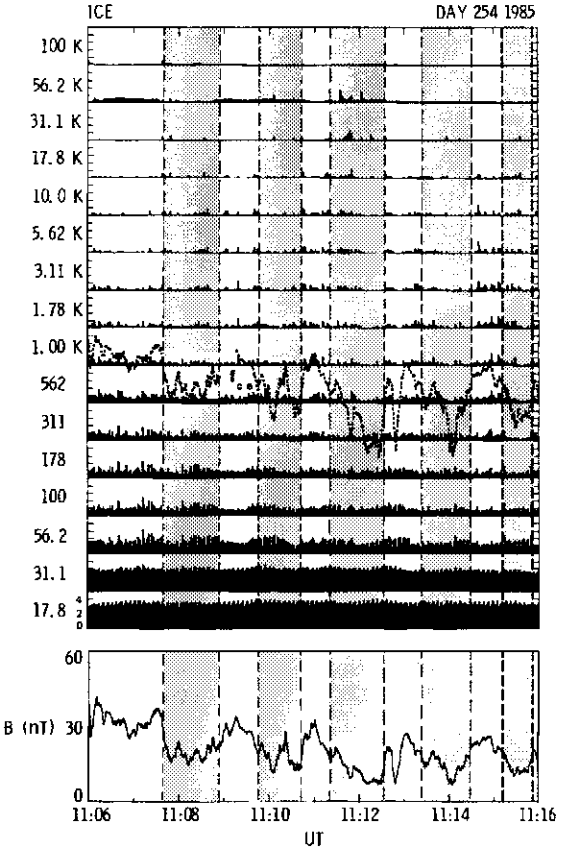

Fig. 4. The electric component of ELF/VLF waves related to the mirror modes (top panel) and the magnetic field magnitude (bottom panel).

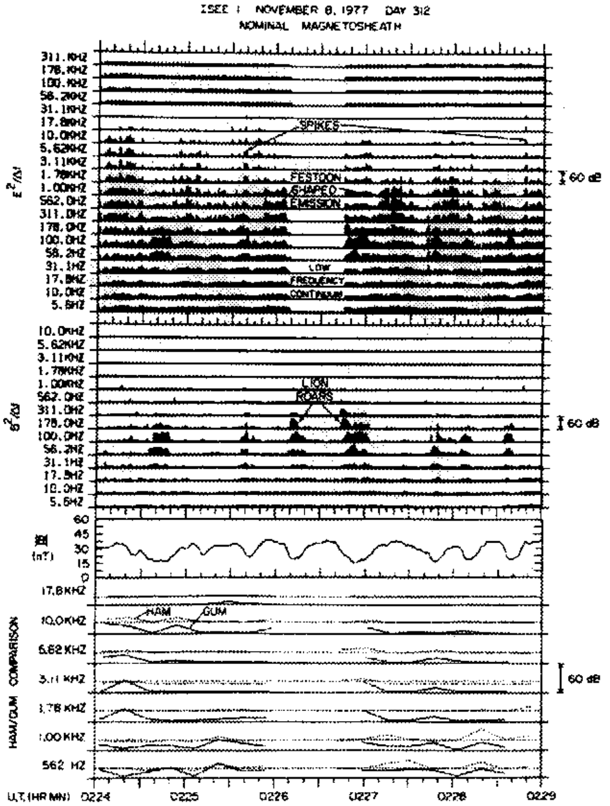

Fig. 5. Electromagnetic lion roars and electrostatic emissions associated With mirror modes in the Earth's magnetosheath. Taken from Anderson et al. (1982) (their Fig. 2).

can be noted at 1108:10 to 1108:50 UT, 1109:40 to 1110:20 UT, 1113:20 to 1114:30 UT and 1115:10 to 1115:50 UT. All of the above ELF wave enhancements occur in the magnetic field decreases. In contrast, the higher frequency (310 Hz to 10 kHz) emissions are detected at or near peaks in B magnitude. Examples are found at ~ 1111:00 UT, 1112:45 UT and 1114:50 UT.

The presence of these two possible wave modes and their dependence on the magnetic field magnitude (and plasma β) are similar to the case of the earth's magnetosheath. In the case of the Earth's mirror mode structures, Anderson et al. (1982) have noted that "festoon-shaped" electrostatic emissions are detected near high field (low-β) mirror mode regions and the electromagnetic lion roar emissions near high-β mirror mode regions. This is shown as Fig. 5. The analogy between cometary plasma waves and the Earth's magnetosheath plasma waves is nearly exact (even if the plasma emissions are quite weak in the G-Z example). Unfortunately, magnetic plasma wave data are not available to use to separate the electromagnetic from electrostatic modes. Otherwise we could make a more complete analogy between plasma waves at G-Z and at the Earth.

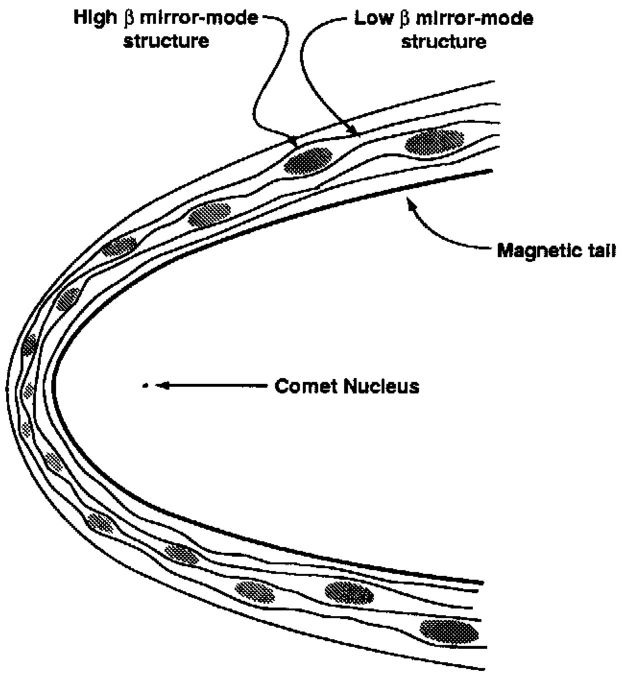

Fig. 6. A schematic of mirror modes at comet Giacobini-Zinner.

3 Discussion

At 1108 UT, day 254, 1985, ICE was ~ 11,000 km from the comet nucleus. The magnetic field orientation on average was close to orthogonal to the solar direction. The cometary neutral density is given by the usual expression (see Tsurutani and Smith (1986b)):

$$N_n = \frac{Qe^{-r/(V_G\tau)}}{4\pi V_G r^2} \qquad (1)$$

where V_G is the outflow velocity of neutrals ($\sim 1\ \mathrm{km\,s^{-1}}$), Q their production rate, r distance and τ mean time for ionization (at 1 AU, $\tau = 10^6$ s). Mendis et al. (1986) has obtained a value of 4×10^{28} mol. s^{-1} for the value of Q.

A straightforward calculation can be performed to determine if the mirror mode could go unstable due to cometary pickup ions. We assume ion accumulation begins at the dawn or dusk flank of the magnetic pickup region and extends to ICE distances (11,000 km back). Mendis et al. (1986) place the nose of magnetic pickup region between 2000 and 3500 km. We use 3000 km for the following calculation. A constant magnetosheath velocity of $30\ \mathrm{km\,s^{-1}}$ is assumed for the 11,000 km pickup accumulation region. The cometary ions (H_2O^+) are assumed to be picked up by the Lorentz force in the perpendicular frame. Each ion will thus have a perpendicular kinetic energy of $\sim 1.3 \times 10^{-10}$ erg. The rate of ionization is $\Delta N/\Delta T = Nn/\tau$ (Tsurutani and Smith, 1986b).

The mirror instability criterion is:

$$\frac{\beta_\perp}{\beta_\parallel} > 1 + \frac{1}{\beta_\perp} \qquad (2)$$

where $\beta_\perp$ and $\beta_\parallel$ are the plasma beta perpendicular and parallel components (relative to the ambient magnetic field), respectively. From Bame et al. (1986) and Fig. 3, the proton plus electron pressure is estimated to be $\sim 3.5 \times 10^{-9}$ dynes cm^{-2}. Assuming that this plasma is isotropic, $P_\perp = P_\parallel = 1.7 \times 10^{-9}$ dynes cm^{-2}. With the above assumptions, the H_2O^+ accumulated ion pickup pressure at ICE is 1.6×10^{-9} dynes cm^{-2}. Thus the total $P_\perp$ is $1.6 \times 10^{-9} + 1.7 \times 10^{-9}$ dynes cm^{-2} and $P_\perp/P_\parallel = \beta_\perp/\beta_n = 1.9$. The value of the right-hand side of Eq. 2 is ~ 1.3, and thus the mirror mode is unstable.

To check the stability of the magnetic tail proper, a similar calculation can be performed. We use the plasma and field values at 1106 UT (Fig. 3). The proton plus electron plasma pressure is $\sim 3 \times 10^{-9}$ dynes cm^{-2} and the magnetic pressure is 5×10^{-9} dynes cm^{-2} ($\beta \approx 0.6$). $P_\perp$ is thus $1.5 \times 10^{-9} + 1.6 \times 10^{-9}$ dynes cm^{-2} or 3.1×10^{-9} dynes cm^{-2}. $\beta_\perp/\beta_\parallel = 2.1$. The quantity $1 + 1/\beta_\perp$ is 2.6.

Why are the mirror mode structures detected only adjacent to the magnetotail? The neutral density falls off as the inverse distance squared (Eq. 1), and thus the production of ions decreases dramatically with increasing distance. The faster convection speed further from the tail will be compensation by greater ion pickup energy, and thus should not be a major factor.

These calculations should be verified using a full cometary code with a variety of initial magnetic field orientations. The results should prove interesting for understanding cometary microscale variability.

4 Final comments

The mirror mode structures were detected just adjacent to the magnetotail (or magnetic field pileup region) boundary. This is similar to the results of Mazelle et al. (1991) at comet Halley. The scale size of the mirror mode structures were shown to be ~ 12 times the (local) heavy ion (H_2O^+) gyroradius. In the Earth's magnetosheath where the dominant ions are protons, the mirror mode structures are approximately $20 - 30$ proton gyroradii (Tsurutani et al., 1982). Thus these cometary structures appear to be reasonably similar to those at Earth.

We have shown that cometary ions picked-up just outside the magnetic pileup region can be susceptible to mirror mode instability. The accumulation of free energy should be greatest closest to dayside nose to the dawn and dusk flanks and should decrease with increasing distance away from the comet nucleus. It should be noted that this mechanism for instability is different than either shock compression or field line draping, dominant effects that occur in planetary magnetosheaths. Contributions of mirror mode growth due to field line draping have not been assessed in this paper. A kinetic code model will be useful in determining the contribution towards instability due to this latter mechanism.

Mirror mode structures may play an important role in the formation of the magnetic tail. The structures (see Price et al. (1986), Fig. 8 for a schematic) would consist of high- and low-β patches aligned along magnetic field lines. Due to field line draping, the plasma clumps (high-β regions) will eventually flow into the antisunward direction along the magnetic field and these magnetic fields will eventually merge to become part of the magnetotail.

It is possible that these evolved mirror mode structures could become cometary rays, as discussed by Russell et al. (1987). However, if this is the case, then the elongated rays close to the comet head should have strong density variations. A schematic is shown as Fig. 6. High spatial resolution images should be able to determine if this is the case or not.

Finally, we should comment that the presence of the intense electrostatic emissions can very efficiently accelerate both ions and electrons. Buti and Lakhina (1987) have explored the consequences of stochastic acceleration of ions to energies above solar wind pickup values. The same process can be effective in accelerating electrons. The consequences for these processes and the eventual energy sink is yet to be explored.

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