

Broadband Electrostatic Noise and Field-Aligned Currents in Jupiter's Middle Magnetosphere

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Voyager 1 plasma wave observations have revealed the presence of an impulsive electrostatic emission localized to the Jovian middle magnetosphere $10 < R < 30 R_J$ that appears on the edges of the plasma sheet. This plasma mode has the same spectral and morphological characteristics of an emission that has been extensively studied in the earth's magnetosphere and has been associated with the presence of field-aligned currents. We present the results of a detailed study of the properties of this Jovian emission by using comparisons with terrestrial observations as a basis for mode identification. The occurrence regions of the waves are compared with the measured magnetic field configuration to establish a correspondence with the plasma sheet. We then argue for a quasi-permanent global system of field-aligned currents linking the ionosphere of Jupiter to the middle magnetosphere, which powers energetic plasma heating processes occurring there. On the basis of knowledge of the consequences of field-aligned currents in the terrestrial magnetosphere, we suggest a scenario for acceleration/precipitation of inverted V electrons concomitant aurorae, and energetic (~ 10 keV) proton deposition into the middle magnetosphere resulting from field-aligned potential drops associated with this current system.

1. INTRODUCTION

The plasma wave subsystem (PWS) on board Voyager spacecraft has returned a wealth of information regarding a variety of plasma waves throughout Jupiter's magnetosphere. A program of long-term studies of the earth's magnetosphere—a veritable plasma wave laboratory—has served as a guide for the interpretation of the Jovian plasma wave data based on phenomenological similarities with terrestrial emissions. These investigations have contributed to our understanding of how Jovian plasma waves are related to plasma-physical processes on a microscopic level and have clearly indicated the key active role these waves have in affecting magnetospheric particle dynamics. As a diagnostic, plasma waves provide conspicuous and unambiguous signatures of magnetospheric boundaries, structures, plasma regimes, and important dynamical processes as well as accurate measurements of plasma parameters. The reader is referred to the initial reports of Scarf *et al.* [1979] and Gurnett *et al.* [1979c] and the papers in this special issue for a discussion of the Jupiter encounter results to date.

The purpose of this paper is to report the detection and identification of a particular class of Jovian plasma waves that hitherto have not been discussed. Since the PWS instrument did not have a magnetic sensor, the interpretation is hampered somewhat by our inability to identify characteristic magnetic signatures that usually accompany and single out this plasma wave phenomenon. Nonetheless, we shall draw heavily on the spectral and morphological similarities of this plasma emission to its terrestrial counterpart, and when viewed in perspective of the magnetic field configuration determined by the on board magnetometer a reasonably good case can be made for our identification although the arguments are in large part based on circumstantial evidence. Our

conclusions, however, are really not surprising. The growing awareness of the role and function of field-aligned currents (FAC) in magnetosphere-ionosphere coupling has permitted a conceptual framework within which the plasma wave results and their significance may be readily understood.

Terrestrial Observations

The particular plasma mode under consideration is an intense, very impulsive electrostatic wave that high altitude satellites have associated with the presence of field-aligned currents. Early on, theoretical considerations of the possibility of current-driven plasma instabilities and the concept of anomalous resistivity spurred a number of investigators to search for the presence of such waves in the polar cusp region [Fredericks *et al.*, 1973; Scarf *et al.*, 1975] and on nightside auroral field lines [Scarf *et al.*, 1973, 1974]. A few cases were found and these authors interpreted their results in the context of temporal events associated with geomagnetic substorms and storms. Later on, extensive survey studies of the tail plasma sheet [Gurnett *et al.*, 1976] at high altitudes/latitudes [Gurnett and Frank, 1977] and in the polar cusp [Gurnett and Frank, 1978] revealed the persistence of a characteristic wave mode in regions where field-aligned currents were suspected to flow. This emission, which Gurnett has termed broadband electrostatic noise (hereafter referred to as BEN), has the nature of being very impulsive with large peak-to-average field ratios, very intense, ($E_{\max} \sim 10$ mV/m) and extends over a broad range of frequencies from 10 Hz to several kHz with a power law dependence, the peak intensity occurring at about 10 to 50 Hz (Gurnett and Frank [1977], hereafter referred to as GF). When intensity-time profiles of the spectrum analyzer are displayed (as in Figure 2 of GF) this mode can be distinguished from other magnetospheric noise by the usually sharp protuberance out of the lower intensity surrounding noise (e.g., auroral hiss, etc.) and it is localized to very narrow portions of the orbit when the satellite is not rapidly changing in magnetic local time. That is to say the noise is confined to discrete field lines (auroral) at high latitudes or the edges of the plasma sheet in the magnetotail [Gurnett *et al.*, 1976]. BEN is almost always accompanied by a cospatial yet distinct emission with a conspicuous magnetic signature. GF refer to this other mode as whistler magnetic noise bursts. If any ambi-

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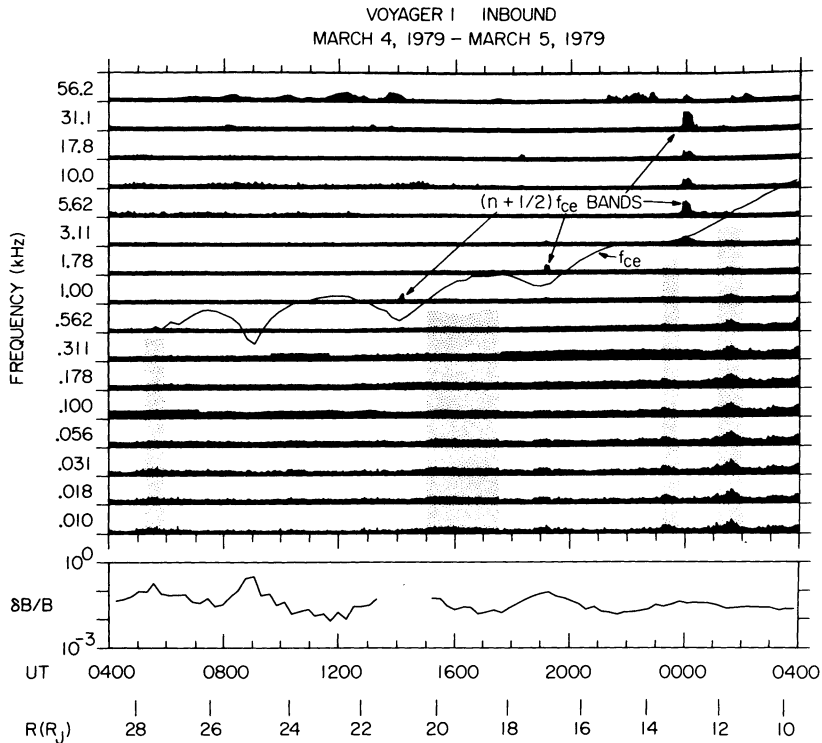


Fig. 1. Intensity-time display for 16 channels of the spectrum analyzer data averaged over 96-s intervals for Voyager 1 inbound traversal of the middle magnetosphere. The superposed solid line is the measured electron gyrofrequency. In the bottom panel we show the fractional rms magnetic fluctuation observed during 16-min averaging intervals.

guity occurs in the identification of BEN, the presence of magnetic noise bursts usually removes any doubts.

A number of theories exist that ascribe the generation of BEN to current-driven instabilities of the plasma distribution [Ashour-Abdalla and Thorne, 1978; Huba et al., 1978; Gary and Eastman, 1979]. We cannot relate our observations to genera-

tion theories at this time. Our purpose here is to advance further the observational association of BEN with FAC and exploit that association in this study of Jovian waves.

Recently, Frank et al. [1981] have measured the distribution function of 221 eV- to 45.6-keV electrons at the northern edge of the earth's tail plasma sheet at about $20 R_E$. They gave evi-

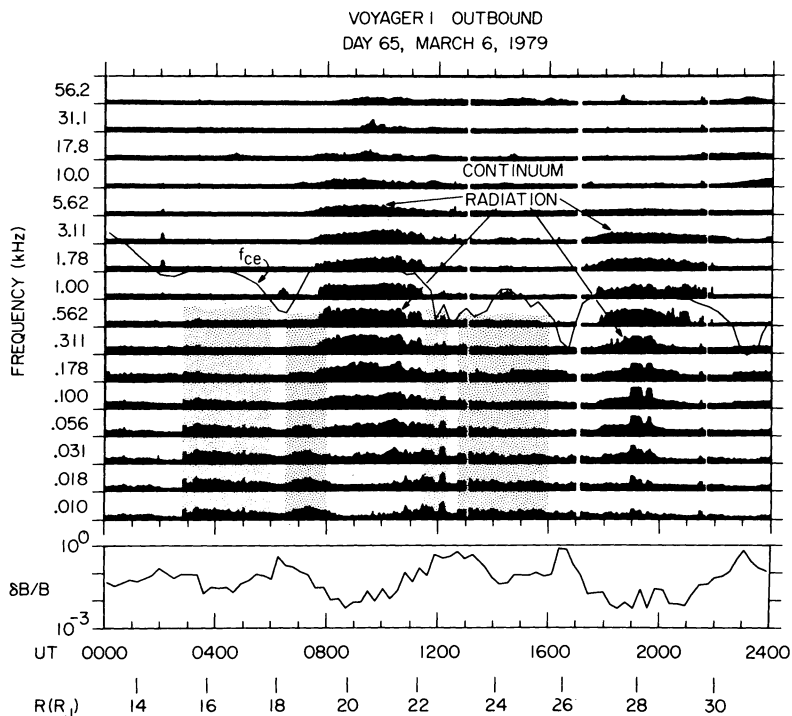


Fig. 2. Same format as Figure 1 for the outbound pass through the middle magnetosphere. Note the large magnetic rms $\delta B/B \approx 1$ in the plasma sheet beyond $R \approx 18 R_J$. The magnetic field in general shows excellent correlative detail with the plasma wave data.

dence for direct measurement of FAC revealed as a skewing in the distribution of low-energy electrons in the range of hundreds of eV. We remark here that their event coincided with an unambiguous broadband electrostatic noise and magnetic noise burst signature in the Isee plasma wave data. This is the first confirmation of the BEN/FAC association with plasma instrumentation although it pertained to substorm dynamics. The BEN survey papers seem to indicate that observations of this type of noise are not just restricted to substorms but are a persistent, quasi-permanent, global phenomenon occurring under most circumstances where FAC may be expected to flow. The initial results of the Isee investigation [Gurnett *et al.*, 1979b] have confirmed the presence of BEN in the low-latitude boundary layer over the broad dayside magnetopause, another locale where FAC may be expected without being tied down to substorm dynamics [Barbosa, 1979b]. Other revealing evidence is the occurrence distribution of BEN on a geomagnetic sphere at $5.6 R_E$ [Figure 12 of GF]. This plot bears a similarity to the occurrence locations of the region 1 and 2 FAC as described by Iijima and Potemra [1976, 1978]. The low-altitude polar passes of the Hawkeye 1 satellite also give clear indications that BEN occurs where region 1 and 2 FAC occur on a statistical basis, although no extensive study of this has been undertaken. We feel that it is very important to establish a firm BEN/FAC association with the region 1 and 2 currents not only on an event-by-event basis but also on a statistical basis. Such an association would no doubt be useful for our understanding of how the waves are generated. But from an observer's viewpoint this association would be invaluable, as it would provide a powerful and sensitive diagnostic for FAC since the plasma wave signatures are so conspicuous at every satellite altitude.

The reader is referred also to the review articles of Potemra [1978, 1979] for a summary of the Triad satellite magnetometer survey results of Birkeland currents.

Jupiter Considerations

Earth-based observations of decametric radio bursts from Jupiter gave evidence for an Io control of the radiation and suggested an electromechanical coupling between the moon and Jupiter existed. The Voyager magnetometer was able, in fact, to measure magnetic field perturbations transverse to the background field consistent with the expected Io-Jupiter current circuit [Ness *et al.*, 1979a]. Field-aligned currents can also be expected from a large-scale magnetosphere-ionosphere interaction driven by the rotational motion of Jupiter (see Barbosa [1979a] for a general discussion of electrical coupling between two electromotive systems). Kennel and Coroniti [1975, 1977] investigated the mechanical aspects of coupling the Jovian atmosphere to either a radial outflow or a convection model of the magnetosphere. They concluded that the low inertia of the hydrogen atmosphere posed difficulties for Jupiter in enforcing corotation throughout its vast magnetosphere. Recently, McNutt *et al.* [1979] have given evidence for low-energy plasma travelling at subcorotational speeds based on in situ measurements. Any departure from corotation must be associated with field-aligned currents coupling the ionosphere to the magnetosphere to transmit the torques involved in the interaction [Barbosa, 1979a]. It is true for Io and it is true for thermal plasma in the magnetosphere. We propose to offer observational evidence for this basic element of the interaction, field-aligned currents.

The only other evidence for this system of currents at Jupiter prior to the Voyager encounters has been given by Kivel-

son and Winge [1976] on the basis of the Pioneer 11 magnetometer data. Since they found only one isolated event, their results were ambiguous, and they chose to interpret their results in terms of either a Ganymede-Jupiter interaction or a Jovian substorm. While our suggested FAC system is for the most part consistent with where Kivelson and Winge found FAC, our interpretation is different. We think that the Ganymede association was simply circumstantial, being that the moon happens to be located in the middle magnetosphere. We exclude the Jovian substorm concept primarily for practical reasons. The limited observational coverage of the Jupiter system does not permit an operational/experimental definition of what a Jovian substorm might be (in the very general sense of a large scale temporal and dynamic 'event'). We do not have a good theoretical understanding of what terrestrial substorms are [McPherron, 1979] and that excludes the possibility of exporting any established theoretical concepts to the radically different environment of Jupiter. However, as we have previously discussed, there is theoretical justification for the expectation of a field-aligned current system resulting from the rotation of Jupiter and the recent Voyager results have given substantial evidence for extensive plasma heating and high-energy particle acceleration in the magnetosphere. It is in this framework, therefore, that we propose and give evidence for a quasi-permanent, global system of field-aligned currents to the middle magnetosphere that exists to power the energetic processes that occur there. When an unambiguous substorm mechanism is found, it is to be superimposed on this FAC structure.

2. THE OBSERVATIONS

Overview

Figures 1 and 2 give intensity-time profiles of wave measurements taken by the Voyager 1 PWS spectrum analyzer. Sixteen channels are shown from 10 Hz to 56.2 kHz, and the height of the envelope of the dark area is proportional to the logarithm of the intensity averaged over 96-s intervals with a dynamic range of 100 db below ~ 100 mV/m. Twenty-four hours of data are shown in each figure to encompass all of the identified BEN events and to indicate other classes of wave activity to put the BEN in perspective. The time intervals cover what we may refer to as the transition region from the inner to outer magnetosphere. The superimposed solid line is the electron gyrofrequency and the lower panel of each figure gives the fractional rms magnetic fluctuation observed during 16-min averaging periods both of which are determined by the on board magnetometer [Ness *et al.*, 1979a].

Referring to Figure 1 we note the three events occurring at approximately 1410, 1910, and 2400 UT above the local electron gyrofrequency. These are electrostatic electron cyclotron harmonic (ECH) waves of the $(n + 1/2)f_{ce}$ class and they have been discussed in detail by Kurth *et al.* [1980]. The third event at 2400 UT is interesting in that it clearly demonstrates the multiharmonic character of these emissions extending over a large number (10) of half-integral harmonics. The very intense report at 31.1 kHz has been interpreted by us as emission near the upper hybrid resonance frequency $f_{UH} = (f_{pe}^2 + f_{ce}^2)^{1/2}$ [Kurth *et al.*, 1980] as it has all the characteristics of this mode expected of it from theory [Barbosa, 1976, 1980a; Barbosa and Kurth, 1980] and from terrestrial observations [Christiansen *et al.*, 1978; Kurth *et al.*, 1979; Gurnett *et al.*, 1979a]. Under these circumstances $f_{UH} \approx f_{pe} \approx 9\sqrt{n_e}$ kHz and the electron density so determined, $n_e = 12 \text{ cm}^{-3}$, is also seen to be

consistent with the falloff of density determined by the planetary radio astronomy (PRA) team in the Io plasma torus [Warwick *et al.*, 1979] and the density profile of the nightside plasma sheet [Barbosa and Kurth [1980], Figure 9). This event was also shown in Figure 5 of Scarf *et al.* [1979] along with a preliminary density profile determined by the plasma science (PLS) team superposed [Bridge *et al.*, 1979a]. Since the upper hybrid emission for this event was not identified in that article and there is an apparent discrepancy with the PLS profile, we take the opportunity here to emphasize our opinion as to the identification of the upper hybrid resonance frequency near 31.1 kHz. A similar controversy regarding f_{UH} identification with the PRA team occurred for an event near periastron of Voyager 2 [Gurnett *et al.*, 1979c].

The three ECH events are relevant here as they occur almost exactly at the magnetic equator. This relationship will be demonstrated later in this article when we show actual magnetic field vectors for the Voyager 1 encounter. In the third event there are two columns of noise centered on 2320 UT and 0140 UT that extend down to 10 Hz. These noise bands are identified as the wave mode under consideration, broadband electrostatic noise. The light shading in the figure indicates the limits in frequency and time of the events. Note the clear avoidance of the wave signature with the center of the plasma sheet, the noise tending to occur at the edges of the sheet. Another interesting facet is apparent in Figure 5 of Scarf *et al.* [1979]: these bands occur coincident with the double peaks in the PLS density profile. We have no definitive explanation for this; however, the double peaked profile in density is somewhat unusual. If in fact that PLS density curve is model-dependent and influenced by either the composition or the temperature of the plasma sheet, this might give an explanation that BEN tends to occur on the cooler edges of the plasma sheet where whatever mechanism generates it is more efficient and the noise is absorbed in the hotter interior of the plasma sheet. Most of the published spectra of the PLS team have been shown away from the center of the plasma sheet at large (southern) magnetic latitudes where good resolution of the ion peaks is obtained [Bridge *et al.*, 1979a, b; Belcher *et al.*, 1980]. The magnetic fluctuations also show a slight but detectable depression coincident with the occurrence of BEN for this sheet crossing. Since the fluctuations reach a maximum, $\delta B/B \rightarrow 1$, in the center of the hot plasma sheet, this also argues for the possibility of cooler plasma near the edges. There is also a noticeable kink in the gyrofrequency contour at 0140 in association with the BEN suggestive of field-aligned currents. Other events in the figure identified as BEN occur at 0530 and 1600 UT. All of these cases can be seen to occur at one or both edges of the plasma sheet based on the spacecraft trajectory in a rotating tilted-dipole coordinate system. One exception is the column of noise at 1900 UT that occurs in the center of the plasma sheet and does not fit into the pattern of the other events.

Turning to Figure 2 for the outbound leg, we see basically the same effects with the addition of the broadband Jovian continuum radiation appearing in low-density pockets of the magnetospheric cavity when the spacecraft reaches high magnetic latitudes. A description of the properties of this noise can be found in Gurnett *et al.* [1979c, 1980] and Barbosa [1981]. There are five plasma sheet crossings as evidenced by the magnetic field depressions correlated with peaks in the magnetic rms [Ness *et al.*, 1979a]. The last three crossings in this figure also indicate the sharp contrast between the electron density in the tail lobe and the plasma sheet, permitting a den-

sity determination to be made from the continuum cutoff until the spacecraft exits the magnetosphere. We note again that for the plasma sheet crossings at $R \geq 18 R_J$, the magnetic fluctuations approach the high value $\delta B/B = 1$, which is entirely consistent with the situation of a hot, high $\beta = 8\pi nkT/B^2$ plasma sheet [Walker *et al.*, 1978; Barbosa *et al.*, 1979; Lanzerotti *et al.*, 1980] occurring beyond this distance.

In Figure 2 we can identify BEN as occurring in the four columns 0250–0600 UT, 0630–0800 UT, 1130–1215 UT, and 1240–1600 UT. The last event is not as clearly defined in the higher frequencies as the first three events and the intensity of the events is seen to decrease with increasing distance from the planet in Figures 1 and 2. We have searched the data for greater distances than these, especially in the tail plasma sheet and cannot find evidence for BEN other than the events shown in Figures 1 and 2. The second crossing is another clear example of how the BEN occurs on the edges of the plasma sheet with a drop in intensity at the center of the sheet.

The third crossing at approximately 1230 UT is very interesting from the point of view of the complexity of the magnetic field. This is evident in the 16-min averages shown in Figure 2 and also in Figure 4 of Ness *et al.* [1979a], where the high level of magnetic complexity is demonstrated over much shorter time scales. This crossing was the most chaotic from the standpoint of magnetic fluctuations, and it delineates the transition between the two classes of sheet crossings as described by Ness *et al.* [1979a]. Thus the region in the vicinity of $R = 20 R_J$ is considered to be the focal point for the transition from inner to outer magnetosphere, and this aspect is borne out not only in the magnetic field data as we have just discussed but also in consideration of the plasma sheet pressure profile [Barbosa *et al.*, 1979] and density/temperature profiles [Barbosa and Kurth, 1980]. We shall give further evidence in this paper in support of that contention on the basis of the assumed BEN/FAC association and suggest that this location also marks a region of energy deposition and energetic particle acceleration.

Wideband Dynamic Wave Spectra and Energy Spectra

In order to make further contact with terrestrial observations of BEN we show 48-s frames of wideband data in Figures 3 and 4 for the event near 0130 on March 5. The sharp semicontinuous lines of emission running horizontally are associated with the PWS electronics and other instruments on board and are to be ignored. The BEN appears as the irregular band of noise at the bottom of the frame, which appears to be composed of many vertical striations rising out of the lower frequencies. Two of the more intense striations occur 22 and 44 seconds into the frame which extend up to a horizontal band at higher frequencies in the vicinity of the electron gyrofrequency at 5.6 kHz. This higher frequency band is rather weak but still is perceptible in the 5.62-kHz channel of Figure 1 at this time.

Figure 4 shows two more frames taken during the same event. We have expanded the frequency scale in Figure 4b to highlight the fine structure of the vertical striations. The impulsive nature of this noise is evident in the figures on time scales of less than a second. Figure 5 is reproduced from Gurnett and Frank [1977] for comparison with the Jovian spectra. The spectrogram shows wave form analysis of BEN, the receiver switching periodically between the electric and magnetic antennas, during an Imp 6 high latitude/altitude pass through terrestrial auroral field lines on the nightside. The vertical striations and impulsive character are very similar to

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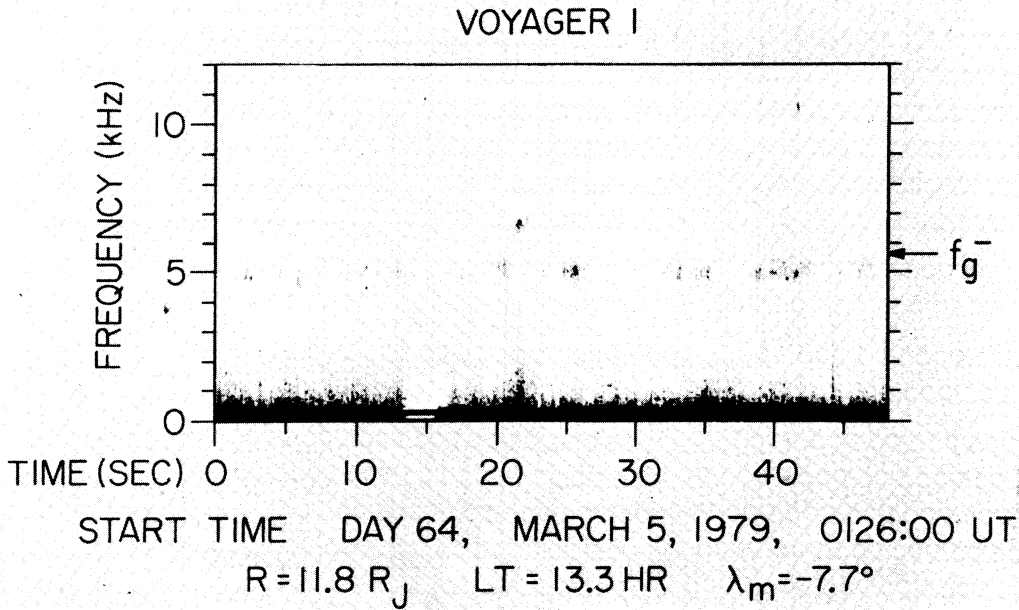


Fig. 3. High-rate wideband spectrogram of the waveform during 48 s of the inbound leg when we observed BEN as the irregular band of noise below 1 kHz with streaks rising out of it to considerably higher frequencies. A weaker emission band is also seen just above and below the electron gyrofrequency.

those in the Jovian events. Another comparison can be made with the dynamic spectra in Figure 12 of *Gurnett et al. [1979b]* for a terrestrial dayside magnetopause crossing.

Figure 6 shows 96 s of wideband data for the nightside BEN event near 0320 UT. The same temporal and spectral characteristics are apparent here, supporting the interpretation of BEN for both the inbound and outbound legs of the spacecraft trajectory.

A quantitative comparison of spectra can be made by inspection of Figure 7 that shows 1-min averages of the spectrum analyzer data as the solid line and peak values during that interval as the dashed line. Five consecutive samples have been stacked to illustrate the temporal behavior of the BEN spectra for the event near 0400 UT of March 6 outbound. The impulsiveness of the emission is evidenced here by the large peak-to-average electric field ratio and the rapidity with which discrete spectral features appear and then disappear. There is a break in the slopes of the spectra at 1 kHz. The emission above this frequency is distinctly different from the spectra at lower frequencies, which we identify as BEN. This higher frequency noise is not as impulsive as the BEN, although there is some structure to it. It does lie above receiver threshold and may be composed of a combination of low level continuum radiation and/or kilometric emissions, although positive identification has not been made.

Below 1 kHz the BEN spectra can be approximated by a power law dependence. The sample at 0420:36 has a spectral index of $\epsilon(f) \sim f^{-2.5}$, and this is 'typical' of the samples around this time in the sense that if we ignore the peaked structures which occur, for instance in the first sample 0330:12, the average slope over 21 samples is also $f^{-2.5}$. These spectra can be compared with those in Figure 6 of *Gurnett and Frank [1977]* and Figure 13 of *Gurnett et al. [1979b]*. The latter authors characterize terrestrial BEN as having a slope of $f^{-2.2}$, and this is deemed to correspond well with the Jovian emissions.

Overall, the spectral characteristics of the terrestrial and Jo-

vian waves compare well, and on this basis, as well as on the other evidence presented in this paper, we identify this as Jovian broadband electrostatic noise.

Notable differences are that the Jovian emissions are less intense and we have not been able to detect any low frequency rollover. GF have reported that the peak frequency of BEN lies between the ion (proton) cyclotron frequency and the lower hybrid frequency. The proton cyclotron frequency for Figure 7 lies near 1 Hz beyond the frequency threshold of the instrument. The electric field energy density of the emissions in Figure 7 is approximately $u_w \sim 4 \times 10^{-18}$ ergs cm^{-3} , and this is much less than the plasma sheet energy density $\sim 2 \times 10^{-8}$ ergs cm^{-3} at $20 R_J$ [*Barbosa et al., 1979*]. Thus, these waves are not directly responsible for the high effective temperature of the plasma sheet by simple damping at these frequencies, since we have an estimate for the heating time of

$$\tau_H \sim \frac{u_p}{u_w} \frac{1}{\gamma} \geq \frac{u_p}{u_w} \frac{1}{f} \quad (1)$$

which for damping at $f = 10$ Hz is on the order of 10 years, much longer than the expected residence time of the plasma. However, there could be consequences of superthermal acceleration so long as the energetics and acceleration times are within acceptable bounds [cf. *Barbosa, 1980b*].

In Figure 8 we show spectra for an equatorial crossing near 0620 on March 6 for comparison. The intensities are significantly lower than those in Figure 7, confirming the fact that BEN 'avoids' the center of the plasma sheet being more a feature characteristic of the sheet edges. The peak at 1 kHz is the 3/2's emission, and a trace of higher harmonics is also evident in the figure. There is also notable structure just below the electron gyrofrequency.

Morphology

The events identified as BEN can be understood more clearly when viewed against the actual magnetic field configu-

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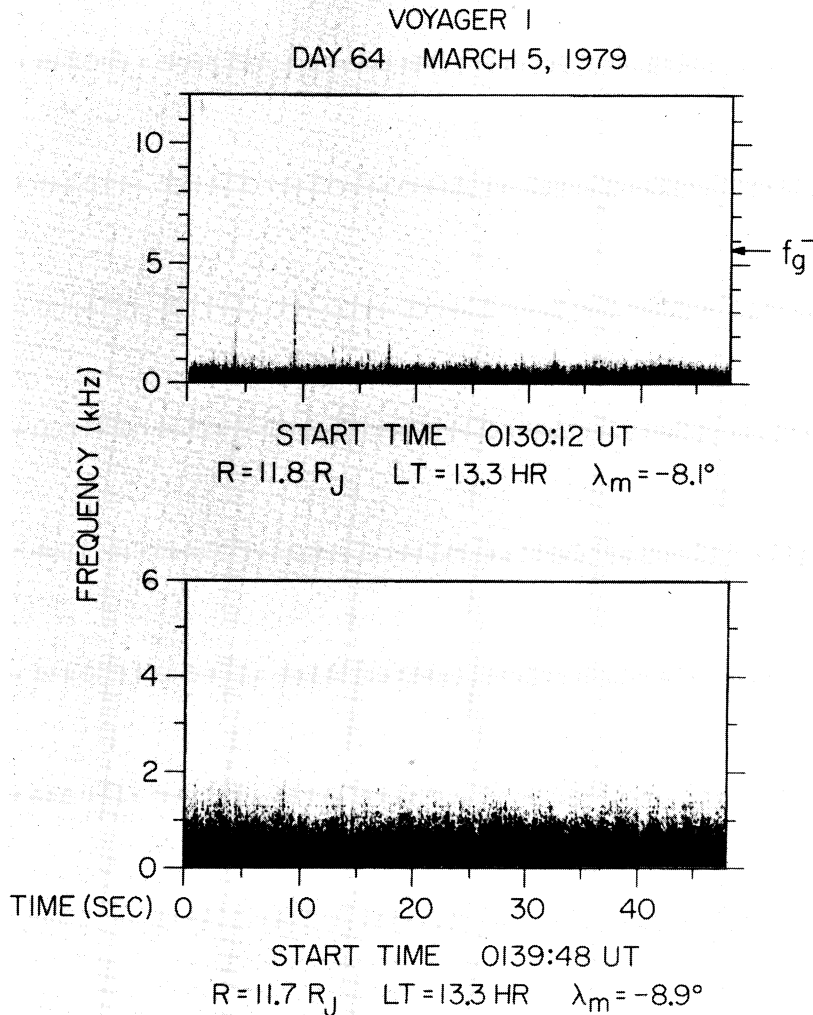


Fig. 4. The same as Figure 3 taken a few minutes later. The frequency scale in the bottom spectrogram has been enlarged to show the streaks and impulsiveness of this noise.

ration during the Voyager 1 encounter. Figure 9 is an encapsule summary of the plasma wave emissions that we have just discussed. Although it is somewhat busy a few minutes reflection will make the illustration transparent with the help of the following 'road map.'

We show the spacecraft trajectory in a wiggle diagram for a rotating tilted-dipole coordinate system centered at Jupiter. The dipole is tilted 9.6° to the rotational axis at a system III longitude of

$$\lambda_{III}(1965) = 205^\circ + 0.85^\circ (R - 14)H(R - 14) \quad (2)$$

where R is the planetocentric radial distance in units of R_J and $H(x)$ is the Heaviside step function. These figures are consistent with the dipole term of the O_4 model (tilt = 9.6° , $\lambda_{III}(1957) = 232^\circ$, Epoch 1974.9) [Acuña and Ness, 1976]. The second term in (2) allows for a systematic lag of magnetic information to reach the outer portions of the magnetosphere due to finite wave propagation times [Northrop *et al.*, 1974; Kivelson *et al.*, 1978]. This correction term did improve the location of the equatorial crossings at large distances in the figure. The magnetic field vectors were then projected into the instantaneous magnetic meridian plane of this rotating/slipping coordinate system and they are shown superimposed on the

trajectory. The third component of the field B_ϕ is shown along with the total field in the top two rows for $V - 1$ inbound and the bottom rows for $V - 1$ outbound. The base of the vectors is on the solid line trajectory and at $Z = \pm 10$ and ± 14 for the auxiliary rows of magnetic field vectors. The convention is that $B_\phi > 0$ (upwards) points into the page and the logarithmic scale for the lengths is given in the lower left corner of the figure, each tic representing two orders of magnitude above 1 nT. We have also drawn dipole field lines for comparison with the orientation of the actual magnetic field vectors.

The eight BEN events (4 inbound and outbound) are indicated on the trajectory as the half-rectangles that have been drawn away from the wiggle to avoid confusion. The beginning and the end of each event can be found by just projecting the ends of the half-rectangles onto the trajectory. We have also shown dark triangles used as 'thumb tacks' that point to the location on the trajectory where 9 identified ECH events occur. Finally, the dashed lines indicate an edge of the plasma sheet as determined by the onset and cutoff of the Jovian continuum radiation based on the 3.11-kHz channel ($n_e = 0.12 \text{ cm}^{-3}$ contour) in Figure 2. Those intervals are from 0750–1130 UT and 1740–2220 UT on March 6 for the two excursions into the northern tail lobe. In order to avoid confusion

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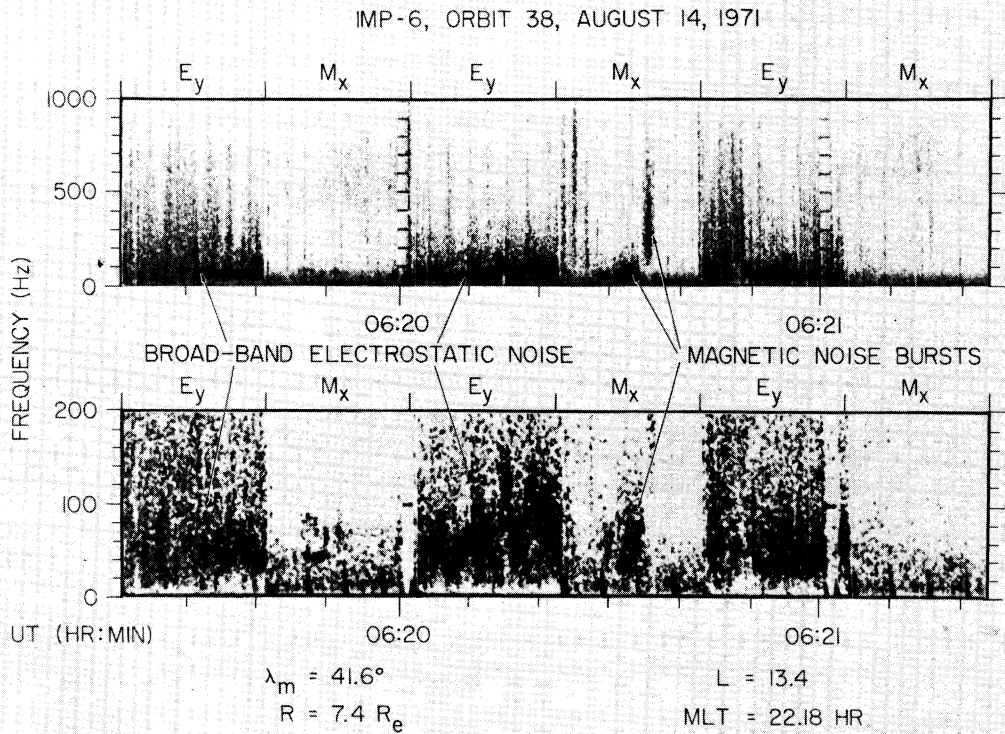


Fig. 5. A similar spectrogram as in Figures 3 and 4 for a terrestrial observation of BEN by the Imp 6 satellite. The location is on nightside auroral field lines. This figure may be compared with the spectrograms of the Jovian waves in Figures 3, 4, and 6.

about inbound and outbound, the reader will find it convenient to remember that the trajectories appear as 'sinusoids' in the figure and the inbound leg is always shifted to the right by an amount ($\sim 90^\circ$) from the outbound leg.

We begin by noting the significant day/night asymmetry in the magnetic field configuration. At comparable radial distances, the field is much more blunted (i.e., pointing north-to-south) on the dayside than the nightside in order to standoff the dynamic pressure of the solar wind [Wolfe *et al.*, 1974]. On the nightside leeward of the planet the field more nearly parallels the magnetic equator beyond about $20 R_J$. At a sufficiently large distance away from the planet, a fully developed magnetotail should form when complete control passes from the planet to the solar wind [Ness *et al.*, 1979b] although modulation effects inherent to the rotation of the planet and cen-

trifugal effects may still be apparent at intermediate distances [Smith *et al.*, 1974; Barbosa *et al.*, 1979; Carbary, 1980]. The periodic alternation of the sign of B_ϕ is synchronized nicely with B_p at large distances but not so well closer to the planet.

We see three choices for what we may identify as the actual 'magnetic equator' for the presentation in Figure 9: $B_\phi = 0$, $B_p = 0$, or $|\mathbf{B}| = \text{minimum}$ along the trajectory. The intersection of the trajectory with the abscissa is an idealized model equator that lies in the neighborhood of all three alternatives and would suffice if all things were perfect. The first choice is clearly unsatisfactory. The second and third choices are approximately equivalent, although there is some slight discrepancy. The point to be made is that the ECH events denoted by the tacks lie very close to the equator defined by $B_p = 0$ in Figure 9 and within the uncertainty inherent in the overall

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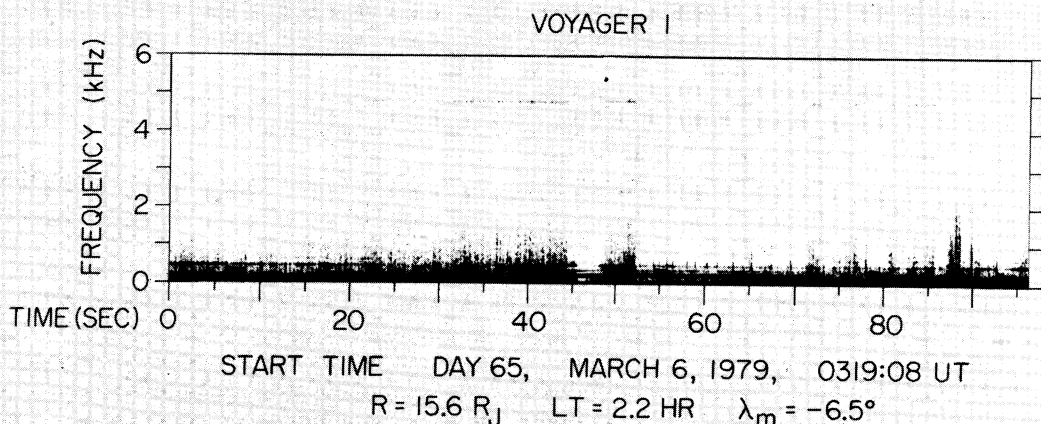


Fig. 6. Voyager 1 outbound spectrogram of BEN.

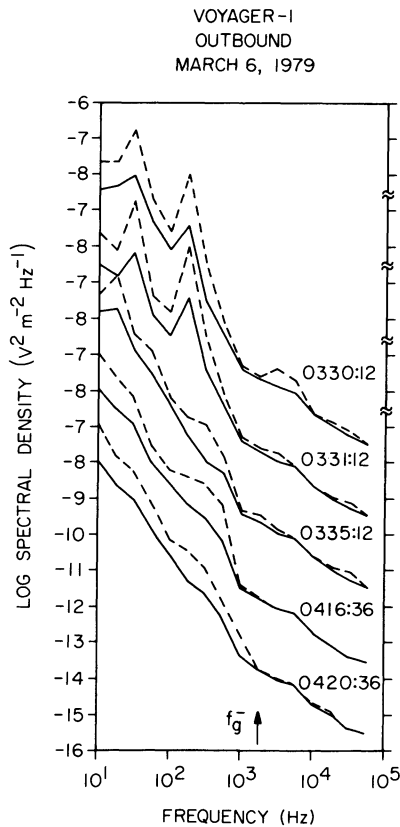


Fig. 7. Energy spectra for five consecutive samples of BEN. The solid lines are averages over 1-min intervals and the dashed lines are the peak values in that same interval. A noticeable break in the spectra appears at 1 kHz. The noise below this frequency is identified as BEN, and the higher frequency noise with the flatter spectra are not identified as yet.

analysis very close to the minimum $|\mathbf{B}|$ surface. This class of waves is thus seen to be a very good probe for the instantaneous magnetic equator [Barbosa, 1980a; Barbosa and Kurth, 1980]. Geos observations have already suggested this on a statistical basis [Christiansen et al., 1978] for the earth. A preliminary survey of the Isee data by one of us (DDB) has confirmed this result although a detailed correlative study with magnetic field data should be undertaken.

With regard to the continuum radiation, we note that at 3.11 kHz (0.12 cm^{-3}) the density contours tend to align with the direction of the magnetic field. The nightside magnetoplasmaidisc has a well-ordered coherent structure to it, although it may exhibit significant dynamical effects. Structural variability is most evident at very low densities higher into the lobe where large scale flutes and corrugations form, some of which seem to persist for more than a planetary rotation. One example is the dropout of continuum at $\approx 1920 \text{ UT}$ in Figure 2. While we cannot rule out the possibility that this might be simply an ethereal 'cloud' of low-density plasma floating by, there are many examples where a bifurcation of the continuum is preserved over a rotation giving credence to the picture of a structural deformation of the low density edges of the plasma sheet. In fact, if the reader refers to Figure 1 of Barbosa et al. [1979], the remnant of the bifurcation in Figure 2 is still evident in the succeeding lobe excursion at 0650 UT, March 7 for frequencies $f \leq 178 \text{ Hz}$. The lower density contours are more variable as to their distances above the sheet for the second lobe excursion. This is directly evident in Fig-

ure 2 as the second lobe exhibits a tapering-off (filled-in 'V' appearance) going to lower frequencies but the first lobe shows a sharp discontinuous onset at almost all frequencies.

The last point to make in Figure 9 concerns the P-11 observation of field-aligned currents based on large transverse perturbations in the magnetometer data [Kivelson and Winge, 1976]. The location of their FAC event is indicated as the crossed square that occurred at roughly 0800 LT on the approach leg. Allowing for the distension of the field lines we find that this location, when mapped to the plasma sheet, is compatible with our observations of BEN, and we indirectly confirm the Kivelson-Winge FAC observation. However, Kivelson and Winge reported that they were not able to detect FAC anywhere else and we would have expected a magnetic signature in the northern hemisphere pass when the spacecraft again crossed field lines that map to the middle magnetosphere. It may be that the northern hemisphere FAC was imperceptible, since the observed base field $B_0 \gg 500 \text{ nT}$ and the strength of the Kivelson-Winge perturbation was $B_p \sim 50 \text{ nT}$.

3. CONCLUDING REMARKS

On the basis of an assumed BEN/FAC association, we have given evidence (albeit indirect) for a large-scale system of field-aligned currents linking the rotating ionosphere of Jupi-

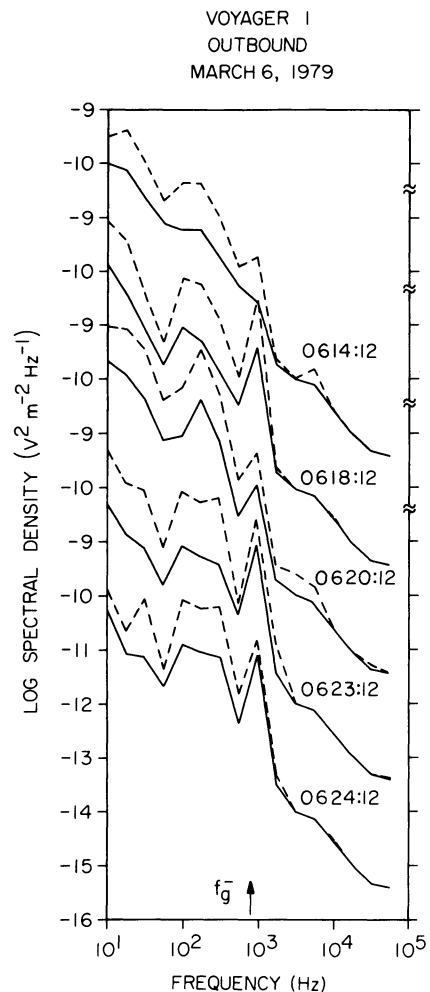


Fig. 8. Same format as in Figure 7. These are spectra taken inside the plasma sheet during a nightside ECH event that appears as the spectral peaks above the gyrofrequency.

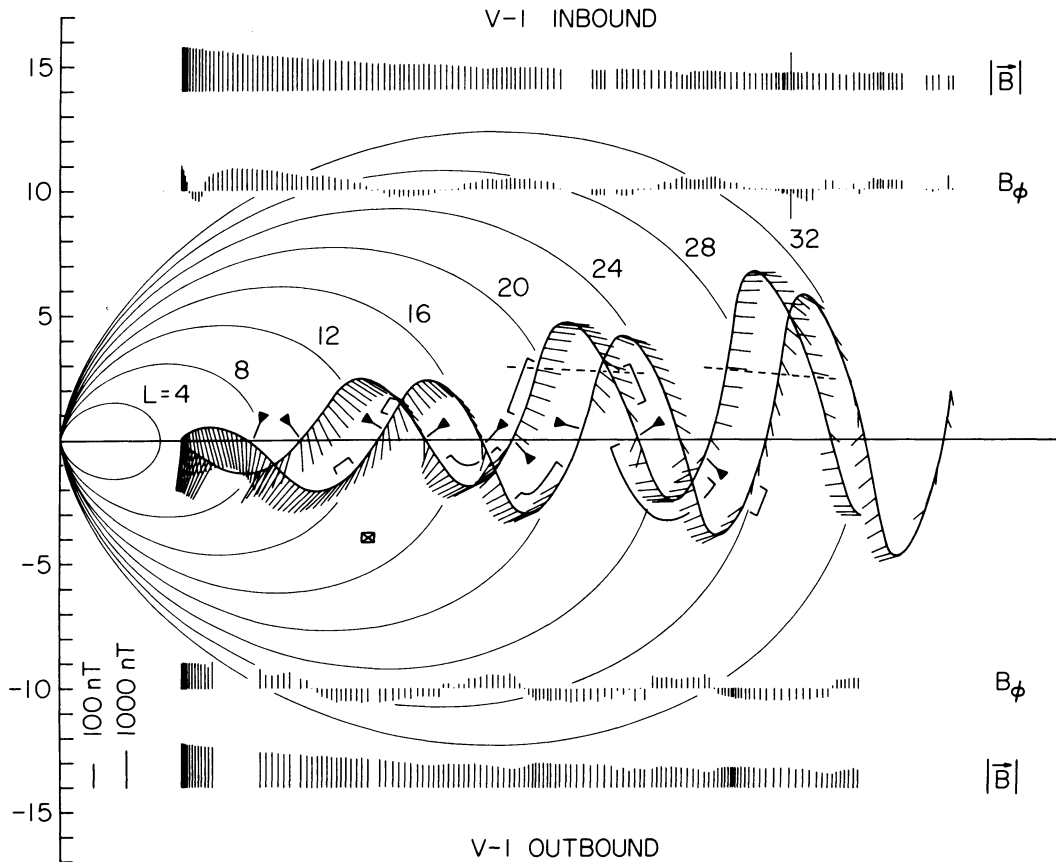


Fig. 9. A magnetic field and plasma wave composite of the Jovian middle magnetosphere. See the text for a detailed explanation of this figure. We see here the transition from the inner to outer magnetosphere involving a global system of field-aligned currents (inferred from our BEN observations) linked to the rotating Jovian ionosphere. This region also involves extensive plasma heating and energetic particle deposition and local acceleration with a focal point of $R = 20 R_J$. A discrete aurora in the Jovian atmosphere is a natural consequence of this system of inferred field-aligned currents. Note also that the low-density tail lobe becomes visible at Voyager 1 spacecraft latitudes for distances beyond $\sim 20 R_J$, where the hot magnetoplasmaidisc has sharp well-defined edges. The reader will also note that the magnetic field parallels the planetary dipole magnetic equatorial plane beyond $20 R_J$ on the nightside, a situation expected for a hot tenuous plasma sheet. At some greater distance not shown, the magnetoplasmaidisc becomes warped in latitude due to a combination of centrifugal and solar wind impressed effects.

ter to the middle magnetosphere $10 \leq R \leq 30 R_J$. There are two pertinent weaknesses in our case as such: (1) instrumental—the absence of a magnetic loop antenna to detect magnetic noise bursts that usually accompany BEN contributes to the ambiguity of our identification, and (2) observational—the foundation of a firm BEN/FAC empirical relationship has not been established on a statistical basis at earth, although isolated cases have been published. The first point will be remedied by future missions to the outer planets such as Galileo, and the second point can be investigated presently by Isee and Open in order to verify the results of this paper a posteriori.

The broadband electrostatic noise has been observed near the edges of the plasma sheet in four inbound and four outbound events of Voyager 1. The intensity decreases with increasing distance beyond $10 R_J$, and the noise was not detected in the outer magnetosphere beyond $30 R_J$. The inner magnetosphere ($< 10 R_J$) was dominated by the presence of whistler mode waves, and if BEN occurs there, it could have been obscured by the whistler noise. Thus we cannot state whether or not field-aligned currents are flowing in the inner magnetosphere based on the observations of BEN; however,

there is positive evidence for FAC in the middle magnetosphere where the eight BEN events were recorded.

4. DISCUSSION

Field-aligned currents to the middle magnetosphere have a number of important implications for Jovian particle dynamics. We have already discussed in the introduction theoretical reasons why such currents are to be expected. Having given evidence for the FAC system, we may now explore the consequences with a mind toward resolving a variety of questions raised not only by the observations of the plasma wave experiment but also by other instruments onboard Pioneer and Voyager spacecraft.

The eight broadband electrostatic noise events have been found on the periphery of the plasma sheet in a broad spatial region extending from $10 \leq R \leq 30 R_J$, which we have referred to as the middle magnetosphere. From an energetic particle viewpoint, Van Allen [1976] and his co-workers singled out this region as one exhibiting significant field-aligned anisotropies manifested as streaming away from the planet at high latitudes (P-11) of both electrons and protons and dumbbell distributions of energetic electrons near the equator (P-

10), peak anisotropy occurring near $20 R_J$ [Trainor *et al.*, 1974]. On the basis of where we observe BEN, this enigmatic middle magnetosphere has all the earmarks of a transition region from inner to outer magnetospheres.

Voyager experiments have reaffirmed this picture of the middle magnetosphere as one of transition. A number of points that have already been made are (1) the plasma sheet pressure is greater than or equal to the magnetic dipole energy density at $R > 17 R_J$ [Barbosa *et al.*, 1979], (2) a distinct change in the plasma sheet density profile occurs with a flatter slope for $R \geq 20 R_J$ [Barbosa and Kurth, 1980], (3) the sharp rise in density also implies a peak occurs in the effective plasma temperature of approximately 20 keV near $R = 20 R_J$ [Barbosa and Kurth, 1980], (4) the distance $R \approx 23 R_J$ marks the change-over between the two classes of current sheet crossings observed by the magnetometer [Ness *et al.*, 1979a], (5) the plasma science team give evidence for a significant departure from corotation occurring from 11–22 R_J for the low energy component of the plasma; a saturation or ‘leveling-off’ of the plasma speed occurs at $R = 18 R_J$ [McNutt *et al.*, 1979].

A few other points can be added to this list: (6) all of the low energy charged particle (LECP) instrument channels show a singularly large flux level for the focal crossing of V-1 outbound at $R \approx 23 R_J$ [Krimigis *et al.*, 1979]; the 53- to 85-keV ion fluxes were more than three times higher than the crossing at $18 R_J$ and more than 20 times higher than the one at $26 R_J$ (see Figure 2 of Carbury [1980]), (7) the LECP experiment also gave evidence for a distinct change in the radial profile of energetic heavy ion abundance ratios at $20 R_J$, (8) the cosmic ray subsystem (CRS) experiment also recorded a large flux for the crossing at $23 R_J$ [Vogt *et al.*, 1979a]; they also report from the Voyager 2 encounter that ‘significant fluxes of energetic sulfur and oxygen nuclei (4–15 MeV per nucleon) of Jovian origin were observed inside $25 R_J$, and the gradient in phase space density at $12 R_J$ indicates that the ions are diffusing inward’ [Vogt *et al.*, 1979b].

Clearly some local magnetospheric acceleration mechanism must be operating to raise ions of probable ionian origin to cosmic ray energies, and the Voyager observations suggest that this occurs in the middle magnetosphere (or farther out in the magnetodisc). The heavy ions diffuse out and are heated in the process; some are accelerated to very high energies and then diffuse back in resulting in a peculiar phase space density where $\partial f / \partial L_\mu$ changes sign at some intermediate value of the first invariant μ of the ion.

There are conceivably a large number of processes occurring here to energize particles. Local heating and high-energy acceleration mechanisms must be operative in order to account for energetic (>100 keV per nucleon) heavy ions from Io at $R \geq 20 R_J$. Wave-particle interactions of one sort or another are strongly suggested by the Jupiter observations, and Scarf [1976] has discussed their likelihood based on what we know about the earth’s magnetosphere. The Pioneer measurements of 0.2–20 MeV protons [McDonald *et al.*, 1979] have already provided detailed information regarding the characteristics of this high-energy component of the plasma distribution. For stochastic acceleration by Alfvén waves the energy threshold for protons is the Alfvén energy $E_A = B^2 / 8\pi n_0 = kT/\beta$ [Barbosa, 1979c, 1980b], which is easily met in the middle and outer magnetospheres. On the basis of the spectral characteristics and energetics of these protons we then propose this mechanism for high-energy acceleration. We are presently constructing a model to adapt this mecha-

nism to the Jovian environment, but before we can quantitatively assess its merits, detailed studies similar to those of McDonald *et al.* [1979] and Gloeckler *et al.* [1979] are needed.

The character of the low-energy thermal plasma from the Io torus is still not readily understood. For instance Belcher *et al.* [1980] claim that in going from 10 to $20 R_J$ the low-energy (≤ 6 keV) plasma temperature drops. Their observations have indicated that the plasma sheet is differentiated by centrifugal forces and has an ‘undercoating’ of heavy/cool ions. The temperature of the central part of the plasma sheet near the magnetic equator is apparently much higher than that of the plasma sheet edge even for that component below 6-keV energies. Whether the temperature of this component increases with radial distance in the middle magnetosphere must be addressed in order to understand the nature of the transport process. It may be argued that some heating is necessary in order to have a sufficient number of heavy particles at threshold for injection into a second-stage acceleration mechanism [Barbosa, 1979c] to account for the flux levels of the high-energy heavy ions. Our observations of field-aligned currents to the middle magnetosphere suggest that not only does the bulk corotational energy of the plasma increase with distance but also the temperature.

The effective temperature of the plasma however is apparently much larger than the corotational energy and is of the order of 20 keV at $20 R_J$ [Barbosa *et al.*, 1979]. Our previous inference of hot proton plasma is now seen to be quite compatible with the observations of the charged-particle experiments. The reason is that field-aligned currents to the middle magnetosphere indicate the possibility of low-altitude aurorae and concomitant acceleration of particles in the ‘topside ionosphere’ which then travel and disperse in the equatorial plasma sheet. This view differs from that proposed by Sentman *et al.* [1978] in that it is the electrical coupling of magnetosphere to ionosphere that is central here. The myriad complexities of the earth’s auroral field lines are still being sorted out, but the realities of field-aligned potential drops and associated anomalous effects are gaining wide acceptance. Beams of energetic ions of ionospheric origin are known to flow out to the magnetosphere on auroral field lines [Ghielmetti *et al.*, 1978; Kaye *et al.*, 1981, and references therein]. More recently Ghielmetti *et al.* [1979] have suggested that these energetic ions may be a significant component of the total magnetospheric plasma population. We then suggest this phenomenon, previously referred to as ‘strong ionosphere-magnetosphere interaction,’ as a candidate source for ~ 10 -keV protons to the Jovian middle magnetosphere [Barbosa *et al.*, 1979]. Subsequent pitch angle scattering and migration outward in the magnetodisc and inwards to the Io plasma torus can account for the qualitative features of the plasma density and effective temperature profiles of Barbosa and Kurth [1980]. That is, this source will give the flattening of the slope in density beyond $20 R_J$, a peak in effective temperature at $20 R_J$, and a drop in effective temperature at closer distances as the 10-keV protons mix with the heated thermal plasma from the Io torus. Direct evidence for this source may be contained in points 6 and 7 discussed above. Detailed spectral, angular, and composition studies of the Jovian plasma environment are needed to gauge the effectiveness of this source in comparison with rival sources in the Io plasma torus and the solar wind.

Further support for this source comes from Pioneer 11 at high latitudes where Sentman *et al.* [1978] found field-aligned streaming anisotropies. Although their interpretation was am-

biguous, we note that their streaming index showed three peaks in the northern hemisphere and one peak in the southern hemisphere. This is consistent with the particular P-11 trajectory revisiting a singular set of auroral field lines in the northern hemisphere at, we would suggest, $L = 20$ and gives indirect evidence for our proposition of ionosphere-magnetosphere coupling and FAC.

This scenario embraces a number of other effects that may have observable consequences. *Ness et al.* [1979b] have suggested the tail plasma sheet as a possible source for precipitating electrons and a diffuse aurora. The aspect of magnetosphere-ionosphere electrical coupling provides for another type of electron precipitation akin to the 'inverted-V' structures observed at earth. The result would be a discrete auroral form on field lines that map to the middle magnetosphere with a focal point of $L = 20$ and imbedded in a diffuse aurora caused by scattering of energetic electrons at the equator into the loss cone. It has been known for some time that energetic electrons are lost from the inner magnetosphere, and according to *Sandel et al.* [1979] the dominant source for the EUV aurora is the Io plasma torus, which supplies 10^{14} W of precipitating electron power. This large apparent power requirement, however, might be reconciled with the existence of a field-aligned accelerating agent in the topside ionosphere that directly taps the rotational energy of Jupiter and provides precipitating inverted-V electrons at $L = 20$.

Another aspect that this scenario confronts is the large power output of non-Io-related radio sources. Electrons precipitated from the equator by pitch angle scattering into the loss cone tend to have distribution functions that are stable to various plasma instabilities, and these electrons radiate electromagnetic energy only by relatively inefficient incoherent single-particle mechanisms. The output of a field-aligned potential drop is an energetic electron beam that has the requisite distribution in velocity space to be unstable to a variety of

plasma modes resulting in an effective beam-plasma interaction with maserlike radiative efficiencies [*Barbosa, 1976*].

These are some of the major consequences we envisage of a system of field-aligned currents to the middle magnetosphere and an electrical connection to the ionosphere. We have summarized the contents of our discussion in Figure 10. The scenario has the 'potential' for answering a number of perplexing questions raised by the Voyager observations such as extensive local plasma heating, energetic proton deposition from the ionosphere to the magnetosphere, high-energy tails of protons, ions, relativistic electrons, and high-power electron bombardment of the atmosphere. A detailed examination of the Voyager data should tell us the degree to which these mechanisms are operating at Jupiter.

Note added in proof. We have referred to the distance $R = 20 R_J$ in the equatorial plane as the focal point for middle magnetosphere energization and auroral processes. The precise location of these field lines when mapped to the Jovian ionosphere depends on a magnetic field model that includes azimuthal current sheet contributions and other external currents. *Connerney et al.* [1980] have recently recomputed the location of the Jovian polar cap and the precipitation zone for the plasma sheet. Their results now show a larger, earthlike auroral belt that rivals the locus of field lines threading the Io plasma torus as the source of the very bright EUV auroral emissions. The location of the aurora should be redefined precisely in terms of this new field line mapping [e.g., *Sandel et al.*, 1979] since the reported power requirements (10^{13} – 10^{14} W) are so large and impact greatly any and all models of the Jovian magnetosphere.

In this regard, recent observations of soft X rays from Jupiter by the Einstein Observatory [*Metzger et al.*, 1980] seem to require also a large amount of power in precipitating electrons. While the spatial resolution is not adequate to distinguish between the footprint of the Io plasma torus and the in-

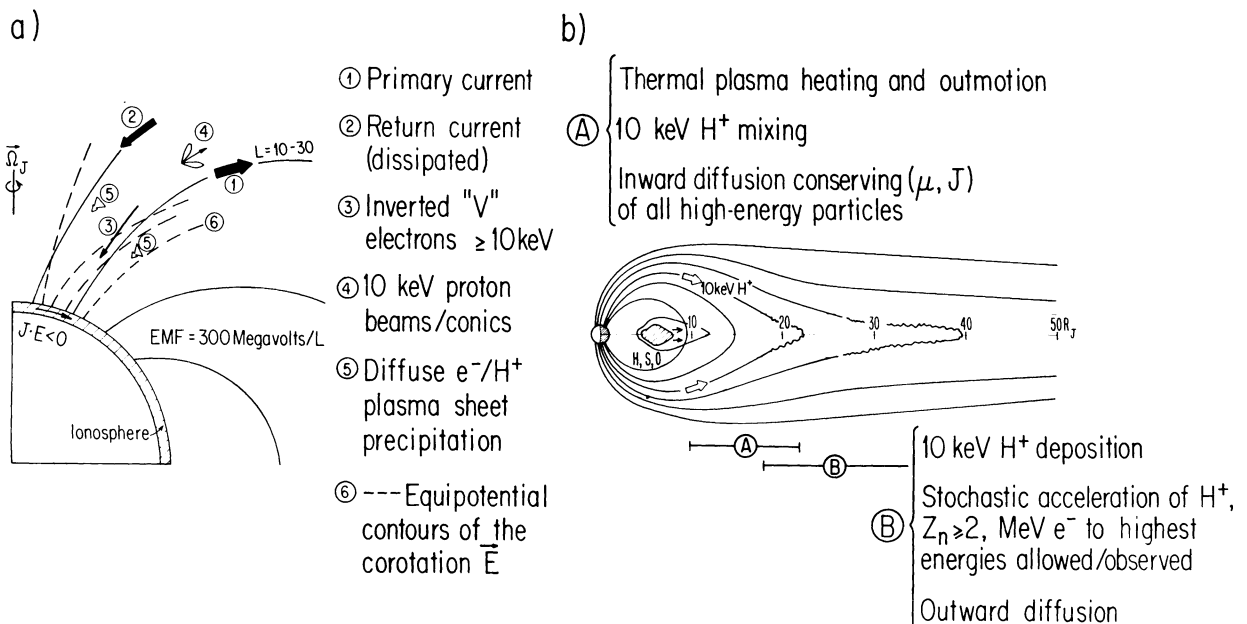


Fig. 10. A summary of the processes inferred to be active at Jupiter. (a) The high-latitude Jovian topside ionosphere is expected to be as busy as the earth's. A component of the corotation electric field dropped along magnetic field lines will result in a high-power electron beam precipitating into the atmosphere and energetic (~ 10 keV) protons injected into the middle magnetosphere to constitute the hot magnetoplasma disc. (b) An equatorial view of the magnetosphere that shows the amalgamation of various plasma and energetic particle populations.

ner edge of the magnetodisc on the planet, they do identify electrons as the dominant precipitating species and support our interpretation of a high-latitude accelerating agent for a discrete aurora. However, evidence at other wavelengths [Tokunaga and Gillett, 1980; Hinson and Tyler, 1980] are also indicative of high-latitude auroral activity.

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