

# Voyager Observations of Jupiter's Distant Magnetotail

W. S. KURTH,<sup>1</sup> D. A. GURNETT,<sup>1</sup> F. L. SCARF,<sup>2</sup> R. L. POYNTER,<sup>3</sup> AND J. D. SULLIVAN<sup>4</sup>

Observations of nonthermal continuum radiation by Voyager 1 and 2 at large distances from Jupiter have led to the identification of brief encounters with the Jovian magnetosphere at distances greater than  $700 R_J$  and in directions substantially far from the Jupiter-sun line. In addition, a number of examples of continuum radiation apparently trapped in local density depressions in the solar wind are observed. Simultaneous measurements by the Voyager plasma instrument have verified the distant magnetotail crossings and are used to correlate the occurrence of trapped continuum radiation events within solar wind density rarefactions. The Voyager observations of the distant Jovian magnetotail are compared with observations in the distant terrestrial magnetosphere and also with observations of the plasma tails of comets. Viable explanations of the observations are that the Jovian tail consists of filamentary structures, some of which extend to large distances in the predawn direction, or that the Jovian tail may be offset in the dawn direction by a combination of corotation angular momentum and forces associated with high-speed streams in the solar wind. The observations of continuum radiation trapped in low-density regions of the solar wind suggest that Voyager may at times be connected to the distant tail by a low-density trough which acts as a wave guide and allows radiation from the tail to reach the spacecraft. This may provide an indirect method of detecting the tail extending more than 2 AU downstream from Jupiter.

## INTRODUCTION

Voyager 2 left Jupiter at a local time of about 3 hours, with the final conspicuous magnetopause crossing occurring at about 0754 on day 215, 1979, at a radial distance of 279.4 Jovian radii ( $R_J$ ) [Bridge *et al.*, 1979a]. Since that time, however, evidence of additional, more distant encounters with the Jovian magnetotail has been gained by plasma wave measurements at radial distances of more than  $700 R_J$ , or about  $\frac{1}{2}$  AU. Simultaneous measurements by the Voyager plasma analyzer have unambiguously identified a few of these encounters as entries into the Jovian tail. Other events appear to be solar wind density rarefactions in which Jovian continuum radiation has been trapped. In this paper we report observations of locally trapped nonthermal continuum radiation and distant encounters with the Jovian magnetotail and attempt to deduce information on the morphology of the distant tail of Jupiter.

Our knowledge of the physics of distant magnetotails is severely limited largely because the total number of observations made in the distant downstream tail region of any of the planets is small. The Voyager missions to Jupiter and beyond afford the possibility of additional input on the subject. Scarf [1979a] has assessed the possibility of Jovian tail crossings by Voyager 2 at distances of 7000–8000  $R_J$  in the spring and summer of 1981. The interim period, after the Jupiter encounter and prior to mid-1981, was not considered to be particularly interesting in terms of the Jovian magnetotail because of the relatively large azimuthal angles the Voyager trajectories make with respect to the Jupiter-sun line. Voyager 1 receded from Jupiter at a local time of about 4.3 hours and Voyager 2 at about 3 hours. It is somewhat surprising then that we are able to report the entry of Voyager 2 into the Jovian tail during this interim period, and we hope to use these observations

to enrich our understanding of the structure of the distant Jovian magnetotail.

A substantial fraction of the observations of the earth's distant magnetotail were gained by the passage of Pioneers 7 and 8 through the tail region at about  $1000 R_E$  in September 1966 (Pioneer 7) [Ness *et al.*, 1967; Fairfield, 1968; Walker *et al.*, 1975; Villante and Lazarus, 1975] and at about  $500 R_E$  in January 1968 (Pioneer 8) [Intriligator *et al.*, 1969; Mariani and Ness, 1969; Scarf *et al.*, 1970; Siscoe *et al.*, 1970; Bavassano *et al.*, 1971; Scarf, 1971]. Ness *et al.* [1967] reported filamentary structures observed with Pioneer 7 with an aberration angle of  $3^\circ$ – $5^\circ$  which were connected to the earth. In addition, Ness *et al.* suggested that some of the observations could be explained by a neutral sheet. Further details of the Pioneer 7 observations of the distant magnetotail are described by Walker *et al.* [1975] and Villante and Lazarus [1975]. These papers present measurements of proton fluxes in the tail, sometimes with a double-peaked velocity distribution, radial to antiradial field reversals, and general taillike characteristics in the magnetic field and plasma. Fairfield [1968] compared observations of tail encounters at  $\sim 1000 R_E$  by Pioneer 7 with solar wind observations by Explorer 28 and 33 and showed evidence of disconnected features in the interplanetary field convecting past the spacecraft. Intriligator *et al.* [1979] have reported intermittent intervals of extremely low fluxes of plasma ions in the tail region at  $\sim 3100 R_E$  and interpreted these as tail-related phenomena on the basis of comparison of data from Pioneer 7 and concurrent upstream solar wind observations from Prognoz 5.

Intriligator *et al.* [1969] reported the presence of rapidly fluctuating ion spectra which were often different from typical solar wind spectra and also time periods when there was a complete absence of measurable plasma while Pioneer 8 was in the earth's magnetospheric wake region. Possible explanations of the observations included the presence of a turbulent downstream wake, filamentary structures in the tail, or disconnected 'bundles' of the tail traveling past the spacecraft. Scarf *et al.* [1970] reported a correspondence between the ion plasma dropouts discussed by Intriligator *et al.* and decreases in broadband electric field strengths. In addition, the intervals of depressed broadband field strengths were bounded by enhanced 400-Hz activity. Scarf *et al.* discussed these observa-

<sup>1</sup>Department of Physics and Astronomy, University of Iowa, Iowa City, Iowa 52242.

<sup>2</sup>TRW Defense and Space Systems Group, Redondo Beach, California 90278.

<sup>3</sup>Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109.

<sup>4</sup>Center for Space Research, Massachusetts Institute of Technology, Cambridge, Massachusetts 02139.

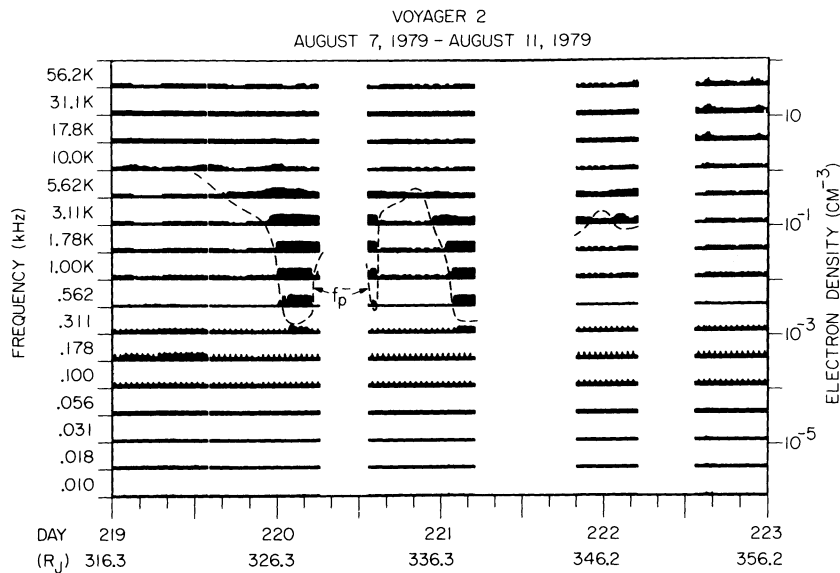


Fig. 1. Plasma wave spectrum analyzer data showing nonthermal continuum radiation within the Jovian magnetosphere at  $\sim 335 R_J$ . The low-frequency cutoff indicated by the dashed line is at the local electron plasma frequency and hence provides a profile of the electron density throughout this event.

tions as evidence for passage into the geomagnetic tail with the boundaries of the tail passages marked by the enhanced 400-Hz noise. Observations by *Mariani and Ness* [1969] provided an estimate for the diameter of the geomagnetic tail of about  $40 R_E$  at distances of about  $470 < R < 580 R_E$ .

*Intriligator et al.* [1969] concluded that the geomagnetic tail underwent significant changes between  $80 R_E$ , where the tail is well ordered [*Wolfe et al.*, 1966; *Gringauz et al.*, 1966; *Ness*, 1965; *Ness et al.*, 1967], and  $500 R_E$ , where an unambiguous understanding of the wake-associated turbulence was not possible. The Pioneer 8 observations could be considered consistent with a filamentary structure of the tail or disconnected bundles, possibly evidence of gas accelerated following a magnetic merging process occurring earthward of the spacecraft. *Siscoe et al.* [1970] investigated these wake effects as detected by the various Pioneer 8 experiments and characterized the wake as a region of reduced density and/or increased temperature and with flow speeds not unlike upstream solar wind values. The wake could be reasonably well described by wave drag effects.

As pointed out by *Scarf* [1979b], the physics of planetary magnetotails is similar in several respects to the physics involved in the formation and dynamics of cometary Type I (plasma) tails. What is most tantalizing about the probable generalization of tail dynamics in magnetospheres and comets is the global nature of observations of comet tails. While the study of an extended planetary magnetotail via in situ observations provides essential information about microprocesses in the various structures, the temporal and spatial effects cannot be easily sorted out, and large structural forms cannot be discerned without multipoint observations. Cometary plasma tails, on the other hand, are easily studied remotely and on a global basis due to the luminosity of the molecular ions in the tail. An extensive review of the plasma processes active in comets and in particular interactions with the solar wind is given by *Brandt and Mendis* [1979].

Several phenomena have been noted in the morphology of comet tails which may prove to be applicable to the study of distant magnetotails. These include filamentary structures evidently associated with bundles of magnetic field lines [*Lüst*,

1962; *Wurm and Mammano*, 1972] and the disruption (or disconnection) of plasma tails [*Niedner et al.*, 1978; *Niedner and Brandt*, 1978; *Ip and Mendis*, 1978]. While there is no direct evidence for cometary magnetic fields and hence magnetospheres, observations of filamentary structures strongly suggest that molecular ions are confined by a magnetic field [*Lüst*, 1962], and the wind sock theory of cometary plasma tails [*Brandt and Rothe*, 1976] based on *Alfvén's* [1957] theory of the capture of solar wind field lines by cometary ionospheres offers simplified explanations of how a magnetized comet tail might arise, even without an intrinsic field in the nucleus.

As noted above, the Alfvén model provides a vehicle by which bundles of magnetic field lines may coalesce in a direction close to the antisolar direction. In fact, these rays have been observed to fold back from a near-solar direction to the antisolar direction in a relatively uniform manner which has been described as a folding-umbrella motion. This offers the possibility of finding rays at rather large azimuthal angles with respect to the antisolar direction and will be drawn upon below as a possible explanation of encounters with the Jovian tail at large azimuthal angles.

*Niedner and Brandt* [1978] provide a concise review of *Alfvén's* [1957] theory of cometary plasma tails and use this model to explain observations of the disconnection of the tail of comet Kohoutek 1973f. In this case the passage of a magnetic field sector boundary was well correlated in time with the disruption of the tail. It is thought the sector boundary crossing resulted in magnetic field line reconnection. These cometary observations provide vivid evidence that the formation of tail filaments and disconnection events can and do take place in astrophysical settings and should be considered when studying distant planetary magnetotails.

Very little is presently known about the distant Jovian magnetotail. *Kenel and Coroniti* [1977, 1979] have speculated on the form of the tail and have drawn upon *Dungey's* [1965] estimate for the length of the terrestrial magnetotail as the basis for estimating the Jovian tail's length. This gives an estimated length of  $\sim 4000 R_J \approx 2 \text{ AU}$ . *Scarf* [1979a] used scaling arguments based on the earth's tail and arrived at a length of at

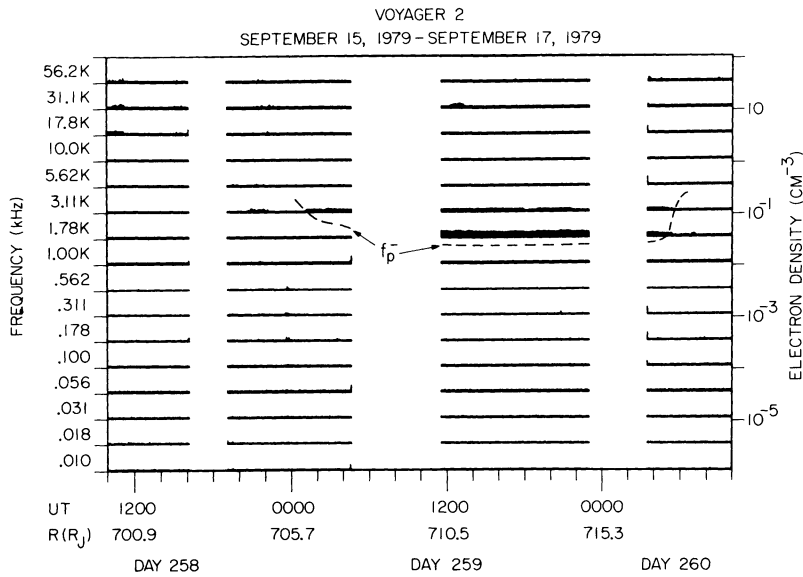


Fig. 2. A second, more distant encounter with the Jovian magnetotail at a distance of more than  $700 R_J$ . The magnetosphere encounter is preceded by a bow shock during the data gap on day 258 as determined by the plasma and magnetic field measurements (see text).

least  $9000 R_J$  for the Jovian tail. A detailed calculation of the Jovian magnetosphere and its interaction with the solar wind was carried out by *Dryer et al.* [1973]; however, they did not directly address the structure of a distant tail. *Wolfe* [1976] has reported intermittent depressed levels of plasma flux when Pioneer 10 was  $\sim 5$  AU downstream from Jupiter, and given that these are not merely solar wind density rarefactions, these are evidently the only observations of the distant Jovian tail to date. Voyager observations have established the existence of a taillike structure in the near predawn sector [see *Ness et al.*, 1979a; *Gurnett et al.*, 1980]. The current paper is the first of what will hopefully be a series of observations of the distant Jovian tail by the Voyager spacecraft, if the predictions of *Scarf* [1979a] are correct.

Our current work presents observations of distant tail encounters by Voyager 2 at distances greater than  $700 R_J$ , and a number of events from Voyager 1 and 2 at distances greater than 2 AU which we believe to be indirectly associated with the distant Jovian tail. We shall draw mainly from observations of nonthermal continuum radiation detected by the plasma wave instruments on Voyager described by *Scarf and Gurnett* [1977]. Summaries of the plasma wave observations from Jupiter are given by *Scarf et al.* [1979a], *Gurnett et al.* [1979], and *Scarf et al.* [this issue]. Supporting observations included herein are from the Voyager plasma science investigation, whose instrumentation is described by *Bridge et al.* [1977]. Overviews of the plasma science Jupiter observations are given by *Bridge et al.* [1979a, b].

#### EVIDENCE FOR THE DETECTION OF THE DISTANT JOVIAN MAGNETOTAIL

*Gurnett et al.* [1980] described the outbound legs of the Voyager 1 and 2 Jupiter encounters with particular emphasis on the detection of Jovian nonthermal continuum radiation trapped within the magnetosphere. Gurnett et al. used the low-frequency cutoff of continuum radiation as a measure of the electron plasma frequency and hence density and found regions of very low density identified as tail lobes, the relatively high density plasma sheet, and also evidence for a boundary layer just inside the magnetopause. Like Gurnett et

al. we base the present observations of the Jovian tail on the detection of nonthermal continuum radiation.

Figure 1 is an example of an encounter with the Jovian magnetosphere at about  $335 R_J$  during the period August 7 to August 11, 1979, by Voyager 2. Displayed are the average electric field strengths detected in the 16 spectrum analyzer channels of the plasma wave receiver as a function of time. The height of the black areas for each channel is proportional to the logarithm of the electric field strength averaged over 6.4-min intervals. The distance between two adjacent channels' baselines represents about 5 orders of magnitude, or 100 dB. A broadband event ( $0.311 \leq f \leq 10$  kHz) commences near the end of day 219 (August 7) and shows considerable variation in the lower-frequency cutoff over the next  $\sim 2$  days. We identify the smooth, nearly time-invariant character and broad spectral nature of this radiation with the continuum radiation reported by *Gurnett et al.* [1979], *Barbosa et al.* [1979], and *Gurnett et al.* [1980, this issue (b)]. The dashed line, labeled  $f_p^-$ , is an estimate of the plasma frequency derived from the lower-frequency cutoff of the radiation and shows excursions in the local electron density  $n_e$  from nearly  $1 \text{ cm}^{-3}$  to as low as  $\sim 10^{-3} \text{ cm}^{-3}$ . (See *Gurnett et al.* [this issue (b)] for a discussion of the lower continuum radiation cutoff as a density diagnostic.) The periodic spikes in the 100- to 311-Hz channels are interference from the low-energy charged particle detector's stepper motor and the semiperiodic, step-level changes in the upper 8 channels are related to a failure in the Voyager 2 flight data system.

A second example of trapped continuum radiation is presented in Figure 2. This event took place during September 15–17, 1979, at a distance of over  $700 R_J$  from Jupiter. The narrowband burst of noise in the 3.11-kHz channel at about 2100–2300 on day 258 is very reminiscent of Langmuir waves often detected upstream of the earth and Jupiter's bow shock [cf. *Gurnett et al.*, this issue (a)]. These bursts lie at the local electron plasma frequency in the solar wind and indicate an electron density of about  $0.1 \text{ cm}^{-3}$ . The unimpressive but obvious broadband spike at  $\sim 2330$  UT on day 258 below 1 kHz is characteristic of the Jovian bow shock [*Scarf et al.*, 1979b], although this example is particularly weak and its identifica-

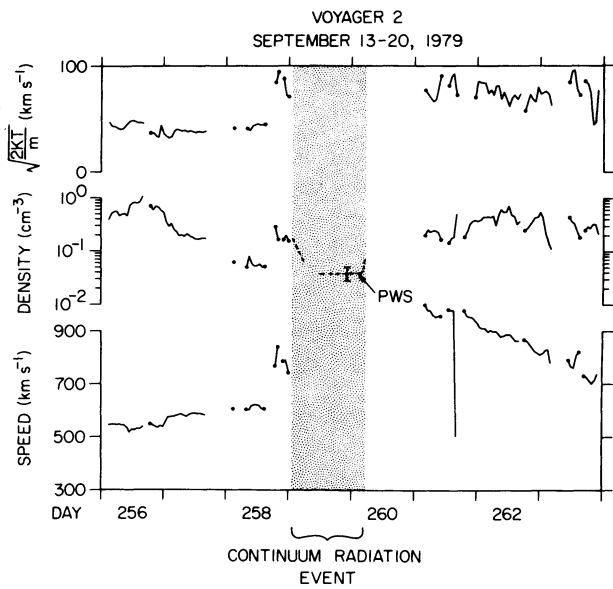


Fig. 3. Preliminary hourly averages of the bulk speed, density, and thermal speed of solar wind protons from the Voyager 2 plasma science investigation. The dashed line labeled PWS is the density inferred from the low-frequency cutoff of continuum radiation detected by the plasma wave science instrument.

tion as an actual shock is questionable. Nonthermal continuum radiation is detected starting at about 0100 UT on day 259, 1979. We would tentatively associate this time with an inbound magnetopause crossing. The outbound magnetopause crossing probably coincides with the abrupt cessation of the

continuum radiation at ~0520 UT on day 260. In this case the electron density varies very little and is near  $0.04 \text{ cm}^{-3}$  for the duration of the event after ~1130 UT on day 259. As in the previous example, the temporal character of the radiation is very smooth.

On the basis of the similarity of these two events with continuum radiation detected within the Jovian magnetosphere, we suspected both of these events as possible reentries of Voyager 2 into the Jovian magnetotail. Observations by the plasma science instrument on Voyager 2 independently verified that the spacecraft was indeed embedded in magnetospheric plasma during the first event, and probably also in the second. The plasma observations which lead to a determination that the spacecraft did penetrate the magnetosphere involve the transition from a normal, cold solar wind plasma spectrum dominated by protons to a hot, higher-density plasma in the sheath with decreased bulk velocities followed by a dramatic decrease in the density as the spacecraft penetrates the magnetopause. The bow shock is usually accentuated by rotations in the bulk flow direction. Plasma data (not shown) for the event displayed in Figure 1 reveal probable bow shock and magnetopause signatures at 1930 UT and 2300 UT, respectively, on day 219, and the spacecraft evidently left the tail region during the data gap on day 222. Other magnetopause crossings occur during the interval of days 220 and 221, consistent with the plasma wave observations of large increases and decreases in  $f_p^-$  as seen in Figure 1.

The plasma observations made during the event shown in Figure 2 are quite unusual and complex. Using a preliminary analysis based on the method of moments, hourly averages of

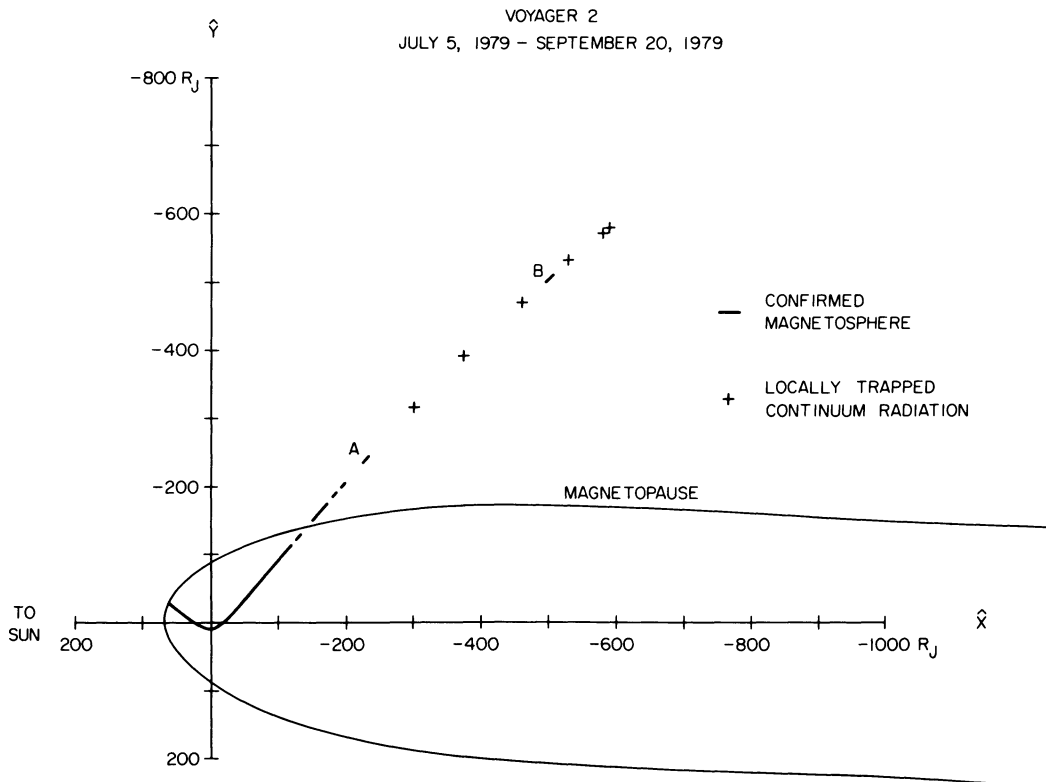


Fig. 4. A summary of the Voyager 2 observations of nonthermal continuum radiation during the outbound leg of the trajectory. The lines indicate times when Voyager was known to be within the Jovian magnetosphere. The events marked A and B are shown in Figures 1 and 2, respectively. The plus signs indicate times when Voyager detected trapped continuum radiation but was not within the magnetosphere. Other events detected by Voyager 1 as well as more distant events observed by Voyager 2 are summarized in Table 1.

TABLE 1. Observations of Continuum Radiation by the Voyager Plasma Wave Instruments During the Outbound Trajectories From Jupiter

Start-Stop, day/UT	$R, R_J$	$\phi^*$ , deg	Region†
<i>Voyager 1</i>			
74/1640-75/0030, 1979	163	244.5	Ms
116/0500-117/1400, 1979	726	244.5	SW
218/0630-218/1400, 1979	2077	236.7	SW
218/1630->218/1830, 1979	2082	236.7	SW
226/0330-226/0530, 1979	2180	236.1	SW
358/0240-358/0555, 1979	3929	224.6	SW
32/1630-33/0520, 1980	4465	221.1	SW
33/0750-34/1100, 1980	4473	221.0	SW
75/0945-76/0050, 1980	5053	217.1	SW
129/1450-129/2100, 1980	5818	212.2	SW
<i>Voyager 2</i>			
206/0030-206/0410, 1979	184	224.1	Ms
208/1830->212/1800, 1979	212	224.9	Ms
213/0820-214/0720, 1979	259	225.8	Ms
215/0630-215/0750, 1979	279	226.0	Ms
219/1630->222/0500, 1979	313	226.3	Ms
<230/2000->230/2400, 1979	434	226.5	SW
<237/1230-238/0400, 1979	498	226.4	SW
241/2100->241/2400, 1979	541	226.3	SW
259/0100-260/0520, 1979	706	225.5	Ms
263/1445-263/1800, 1979	750	225.3	SW
263/2130->263/2245, 1979	752	225.3	SW
270/0500-270/1830, 1979	813	225.1	SW
271/1340-271/1620, 1979	825	225.0	SW
353/0420-353/0650, 1979	1600	219.0	SW
353/1830-354/1420, 1979	1606	219.0	SW
31/0400->31/2400, 1980	2011	215.5	SW

\*Azimuthal angle in a Jupiter-centered system based on the instantaneous plane of the sun, Jupiter, and spacecraft measured in the right-hand sense from the solar direction.

†Plasma science observations identify the spacecraft to be in SW, the solar wind, or Ms, the magnetosphere, during the time continuum radiation was being detected. However, times given here are determined by the detection of continuum radiation and are not therefore necessarily the times of magnetopause crossings as determined by plasma or magnetic field observations.

the bulk speed, density, and thermal speed of protons in the solar wind have been computed. These averages of the preliminary analysis values are plotted for an 8-day period in Figure 3. From the speed profile it is apparent that a very high speed solar wind event occurred during this time interval. Before the tracking data gap on day 258 at  $\sim 1650$  UT, normal solar wind is observed; after the gap ( $\sim 1900$  UT) the flow speed has increased and has a positive azimuthal component, and the plasma appears shocked. At  $\sim 0100$  UT on day 259 the density drops abruptly to the noise level of the instrument in this operating mode. The apparently shocked nature of the plasma observed after the day 258 data gap coupled with the increase in flow speed is consistent with the near-coincident passage of a bow shock and high-speed stream during the data gap. The abrupt drop in density would be characteristic of a magnetopause crossing, although a reverse shock with a bulk speed of  $\gg 1000$  km/s cannot be ruled out on the basis of the ion data alone.

On day 260 and following, the solar wind is observed to come into the instrument energy per charge range from above, indicating that the solar wind speed was appreciably greater than 1000 km/s. Subsequently, the decay phase of this impulsive event was observed. This event was also seen on Voyager 1 after an appropriate time delay. However, no feature in the plasma data analogous to day 259/260 was observed, even

though the bulk speed did again exceed the range of the instrument for a short time.

The Voyager 2 magnetometer provided evidence of a bow shock during the data gap on day 258 and evidence of taillike fields thereafter (R. P. Lepping, personal communication, 1980). The plasma and magnetic field observations do not support the identification of upstream electron plasma oscillations between 2100 and 2300 UT on day 258 or the possible shock signature at 2330 UT suggested by the wave observations. However, all three sets of observations agree that the density depression associated with the continuum radiation seen on days 259 and 260 is almost certainly a traversal of a magnetospheric region. We point out that this traversal occurs at a distance of about  $\frac{1}{2}$  AU from Jupiter. The event shown in Figure 2 has proven to be quite complex and interesting from the point of view of the plasma and magnetometer investigations and is the subject of further study.

There exist several other examples of apparently trapped continuum radiation detected by both Voyagers as they left Jupiter, although it should be noted that the events in Figures 1 and 2 are among the most impressive examples seen to date and should not be regarded as typical of the other events discussed below. A summary of the events detected by the Voyager 2 instrument out to  $\sim 900 R_J$  is given in Figure 4. This illustration is organized in a Jupiter-centered coordinate system. The plane shown is the plane of the Voyager 2 trajectory, and the  $X$  axis is the projection of the Jupiter-sun line in that plane. Since the plane has only a small inclination with respect to the ecliptic, an ecliptic plane projection would be very similar. Plotted are the locations of Voyager 2 when it was known to be within the Jovian magnetosphere (lines) and/or when continuum radiation was detected (plus signs). Beyond the first outbound magnetopause crossing, the lines indicate periods when continuum radiation was detected and the spacecraft was known to be imbedded in magnetospheric plasma according to the plasma science instrument. The plus signs indicate positions where continuum radiation was detected but the spacecraft was known to be in the solar wind. The duration of these solar wind events is in all cases small in comparison to the size of the plus sign. The events shown in Figures 1 and 2 are labeled A and B, respectively.

Also shown in Figure 4 is a model magnetopause for the Voyager 2 encounter which is taken from *Ness et al.* [1979b] in the range  $X \geq -240 R_J$ . The asymptotic tail width of about  $380 R_J$  is based mainly on *Dungey's* [1965] tail length-to-width ratio of  $\sim 30$  and a length estimate of  $\sim 10^4 R_J$  [*Scarf, 1979a*]. The tail is shown with an aberration angle of about  $2^\circ$ .

The most surprising result shown in Figure 4 is the large distances in the  $-Y$  direction of most of the events, especially the tail encounter of September 16-17, 1979, labeled B in the illustration. As mentioned by *Scarf* [1979a], the magnetosphere may at times be twice the size of that shown if scaling arguments based on the subsolar magnetopause distance are employed, since a factor of 2 variation in this distance has been observed. A magnetospheric expansion to a scale large enough to encompass event B may be possible but seems somewhat unreasonable. Alternative explanations will be explored in the discussion section.

The events shown in Figure 4 represented by plus signs are all characteristic of trapped continuum radiation. Most of the events show relatively sharp onset and stop times which would be indicative of rather well-defined low-density regions. In addition to those events shown in Figure 4, several

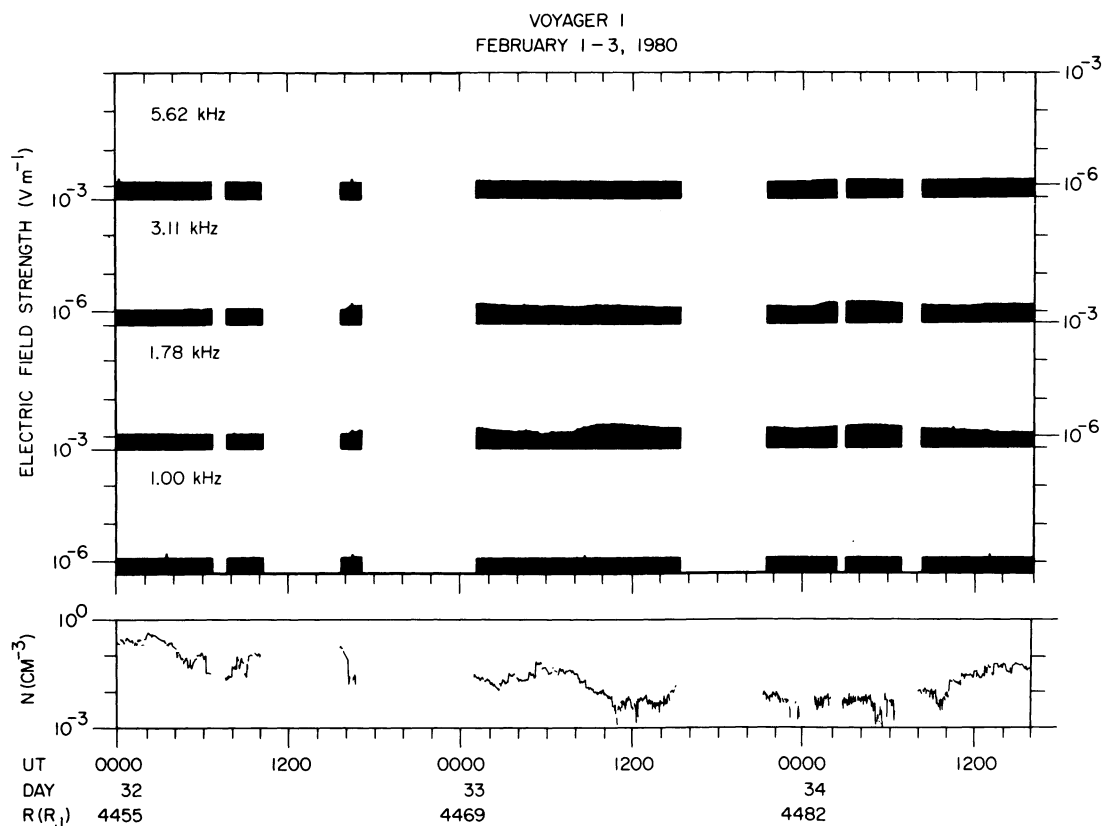


Fig. 5. A trapped continuum radiation event seen by Voyager 1. Shown are both the plasma wave signature and also the density profile of the solar wind as measured by the plasma science instrument. Notice that the intensity of the continuum radiation tends to follow variations in the density.

other examples of continuum radiation trapped in low-density regions in the solar wind were detected by Voyager 2 beyond the region of space shown in Figure 4 (as distant as  $2000 R_J$ ) and also by Voyager 1 to distances as large as  $5818 R_J$ , or  $\sim 2.8$  AU from Jupiter. Table 1 summarizes the times and locations of additional trapped continuum radiation events observed by Voyagers 1 and 2 and whether the event occurred in the solar wind or was associated with the magnetosphere directly. (In the cases where the plasma instrument provides the determination that the spacecraft is imbedded in the magnetosphere, it does not necessarily follow that the times of the continuum radiation event listed correspond to magnetopause crossings. The boundary defined by the radiation is defined simply by a density gradient and may not correspond to the well-defined magnetopause as determined by plasma and magnetic field signatures. Also, there exists the possibility that numerous magnetopause crossings may have been encountered during a single continuum radiation interval listed in the table.)

Simultaneous plasma observations during the greater majority of the trapped continuum radiation events on both Voyager 1 and 2 show well-correlated density depletions which support the interpretation of low density regions in the solar wind as derived from the plasma wave observations. Figure 5 shows plasma and plasma wave data from Voyager 1 from February 1-3, 1980, which show the correspondence between the occurrence of continuum radiation and local depletions of the solar wind plasma density. There are obvious increases in the radiation intensity at points where the density decreases. Voyager 2 detected a similar continuum radiation event during January 31 to February 1, 1980 (see Table 1); however, the event is somewhat obscured by the effects of a failure in the

spacecraft flight data system. Fortunately, however, wideband waveform data were obtained for a short time on February 1, 1980. Figure 6 is a 48-s frame of those data showing the continuum radiation unimpaired by the failure. Shown is a plot of the intensity of waves as a function of frequency and time, with the darker regions representing greater intensities. The narrow lines at 2.4 and 4.8 kHz are interference from the spacecraft power supply, and the 400-Hz plus odd harmonic tones are interference from the plasma science instrument. The diffuse noise with a lower cutoff at 1.9 kHz is the non-thermal continuum radiation. The cutoff frequency (at  $f_p^-$ ) corresponds to an electron density of  $0.045 \text{ cm}^{-3}$ . The plasma observations yield the same density based on measurements in the same region.

Virtually all of the continuum radiation events detected in the solar wind are directly associated with density rarefactions. It is not the case, however, that all density rarefactions detected by the plasma science investigation contain trapped continuum radiation. It is significant that none of the trapped continuum radiation events were detected upstream from Jupiter. Some escaping continuum radiation was detected upstream but always at frequencies much greater than the local solar wind plasma frequency, implying that the upstream events were freely escaping over the high-density barrier formed by the magnetosheath.

The solar wind structure showed striking similarities between the Voyager 1 and 2 events of early February 1980, and it seems clear that the structure propagated from one spacecraft to the other. The solar wind speed averaged  $450 \text{ km/s}$  during this time period, but the structure most likely has a nonzero group velocity in the rest frame of the interplanetary

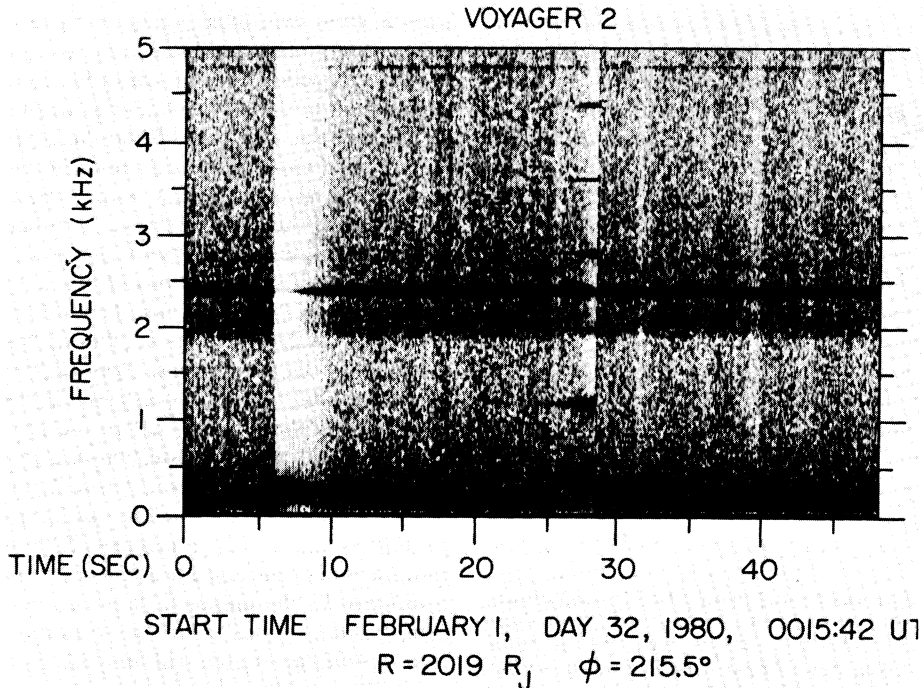


Fig. 6. A wideband frequency-time spectrogram taken by Voyager 2 during the event shown in Figure 5. In this case the event apparently convected from Voyager 2 to Voyager 1. The lower-frequency cutoff at 1.9 kHz corresponds to a local electron density of  $0.045 \text{ cm}^{-3}$ .

medium, so it is not possible to verify a direct connection between the events on the basis of apparent propagation speed alone. The Voyager 2 event of day 353 and Voyager 1 event of day 358 (see Table 1) also appear to have the same structure, which has apparently propagated from one spacecraft to the other. It seems clear then that the structures detected by the plasma wave receiver are low-density regions in the solar wind which trap nonthermal continuum radiation. In the next section we shall discuss the problem of how the radiation became trapped in these solar wind rarefactions.

#### DISCUSSION

We have presented observations of the magnetospheric tail at large distances from Jupiter and in directions far from the antisolar direction, as well as low-density regions in the solar wind which trap nonthermal continuum radiation and may convect over large distances as relatively stable structures. We shall look at these two separate phenomena in turn in an attempt to explain or understand the observations and hopefully derive some insight into the structure of the distant Jovian magnetotail.

#### Implications of Distant Magnetotail Encounters

Using observations of nonthermal continuum radiation, we have identified traversals of the distant Jovian tail which were subsequently verified by the identification of magnetospheric signatures in the plasma detected simultaneously by the plasma science instrument. The event shown in Figure 1 and labeled A in Figure 4 could reasonably be explained by a simple expansion of the magnetosphere in response to varying solar wind dynamic pressure. Scarf [1979a] suggests that the linear dimensions of the magnetosphere might vary by a factor of 2 if the subsolar magnetopause distance is a reliable scaling parameter. (More recently, Goodrich *et al.* [1980] predict that the standoff distance of the Jovian bow shock may

vary as much as a factor of 3.) The event shown in Figure 2 and labeled B in Figure 4 might be explained by a simple expansion of the magnetosphere, but the dimensions involved are almost unreasonable. (Without the benefit of a full-scale, coordinated study of this event by all the field and particle investigations on Voyager, we must allow for the possibility that the identification of the event as a magnetotail encounter is in error; however, all evidence uncovered so far indicates that the spacecraft did indeed reenter the tail, and we proceed on this basis.)

Since the September 16–17 event took place during highly disturbed solar wind conditions ( $V_{sw} > 1000 \text{ km s}^{-1}$ ), we first look at how external pressures on the magnetic tail might move the tail in the dawn direction. Figure 7a is a simplified picture of how a high-speed stream could distort the tail. The key factors include a tail which normally is skewed in the dawn direction a small amount under the assumption that magnetospheric plasma streaming down the tail is likely to carry off some of the corotational angular momentum. The second factor stems from the fact that there will be a net force in an eastward direction as a result of pressure built up ahead of a high-speed stream. This effect is commonly seen when a high-speed stream overtakes a slow stream. For our purposes one can think of the magnetotail as a slow-speed stream. In addition, the flow direction for this particular event is not radial but has a positive azimuthal component. The net result is to temporarily distort the Jovian magnetotail toward the dawn direction as the high-speed stream traverses the magnetosphere.

Similar displacements of the earth's tail have been observed. In a heretofore unpublished event, Explorer 35, while in lunar orbit about  $1.7^\circ$  from the sun-earth line, was outside the magnetopause for about 56 min on June 10, 1968. The solar wind speed was approximately 600 km/s as measured by the Explorer 35 plasma instrument. Taking the radius of the

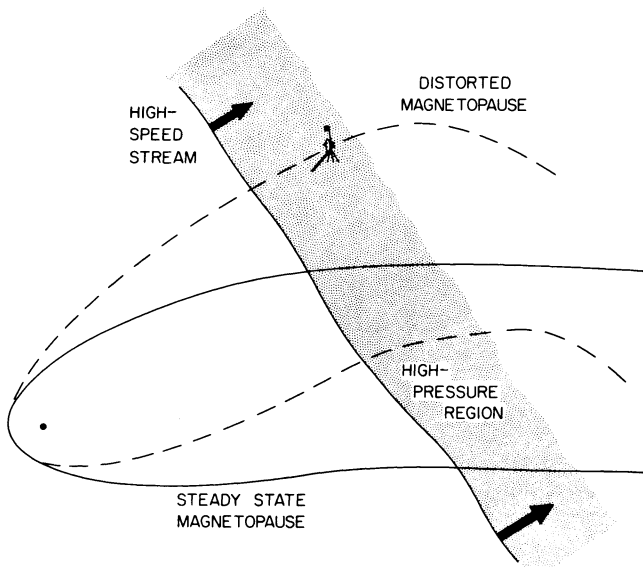


Fig. 7a. A model of the Jovian magnetosphere which is distorted in the dawn direction as a result of forces associated with a high-speed stream in the solar wind coupled with a natural skewing of the tail in the dawn direction resulting from plasma streaming down the tail, carrying away corotational angular momentum.

tail to be  $\sim 28 R_E$  [Howe, 1971], this implies a deflection of the tail of at least  $25^\circ$  in order to leave the spacecraft beyond the magnetopause. Other observations of the motion of the earth's tail have been studied by Howe and Siscoe [1972]. They report magnetospheric displacements of more than  $8^\circ$  from the average boundary positions as measured by Explorer 35 at a distance of  $60 R_E$ . The standard deviation of the deflection angle was found to be  $4.7^\circ$  on the dawnside and was thought to depend somewhat on the magnitude of the solar wind velocity. Considering the remarkably deformable nature of the Jovian magnetosphere, similar deflections of the Jovian tail may be reasonable even though the solar wind is more tenuous at 5 AU.

Alternate explanations for distant tail encounters such as that in Figure 2 may be found by drawing upon our knowl-

edge of gross structures in cometary plasma tails. Of the various cometary plasma tail structures and phenomena reviewed in the introduction, the tail rays or filaments may offer a likely explanation of taillike structures at large angles with respect to the antisolar direction. While the cometary tail rays ultimately align close to the antisolar direction, they apparently first appear at large angles with respect to that direction, sometimes in the solar direction, and then fold back toward the antisolar direction. Wurm and Mammano [1972] argue that all the shifts and motions of the rays are not necessarily in response to solar wind flow conditions but are caused by variations in the emission conditions for the ions at their source close to the nucleus. Krimigis et al. [1979] have reported flows of  $\sim 20$ - to  $\sim 40$ -keV ions in the Jovian tail (called the magnetospheric wind) not in the antisolar direction but  $\sim 20^\circ$  from the antisolar direction in a sense which is consistent with the corotation direction. Krimigis et al. estimate the energy density of the hot ions (assuming protons) is comparable to that in a 5-nT magnetic field and that if a significant fraction of the ions are sulfur or oxygen, the field may be dominated by the plasma. The hot ion energy density is also comparable to typical solar wind pressures reported by Bridge et al. [1979a] at Jupiter. The implication is that ions may be directed toward the local early morning sector, producing filaments at relatively large angles to the antisolar direction.

Figure 7b is a sketch of a model magnetosphere with filamentary structures directed toward the local early morning. Presumably, the filaments consist of magnetospheric plasmas and ion flows consistent with the Krimigis et al. observations. This picture provides a mechanism for projecting low-density taillike structures in the direction of Voyager 2 as it receded from Jupiter in September 1979. Also shown are filamentary structures in the magnetotail proper. No direct evidence of these forms has been observed, but filaments in the antisolar direction would be a natural expectation if filaments were detected in the early local morning sector. The early morning filaments may fold back into the antisolar direction in a manner very similar to cometary tail rays. Also, filamentary structures in the distant terrestrial magnetotail are consistent with the observations of Intriligator et al. [1969], and hence one might

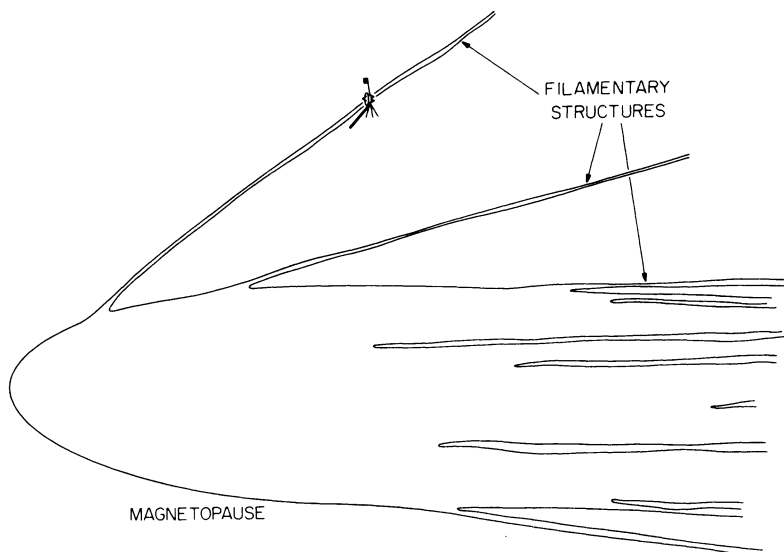


Fig. 7b. A model of the distant Jovian magnetosphere featuring filamentary structures which might extend to large distances in the local morning direction in order to explain the magnetospheric encounter labeled B in Figure 4.



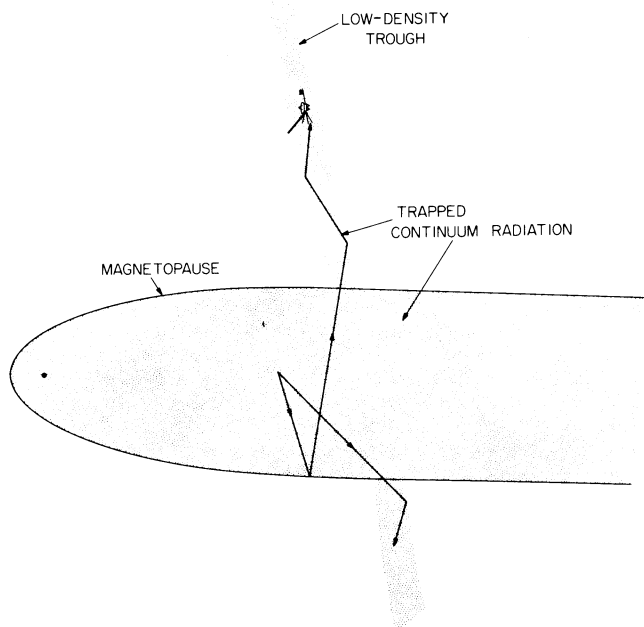


Fig. 8. A model of a low-density trough connecting to the distant magnetotail which serves as a wave guide for low-frequency continuum radiation. If the trough follows the usual garden-hose angle, this model implies that trapped continuum radiation events allow indirect measurements of the Jovian magnetotail at distances well over 2 AU from Jupiter.

expect filaments to be a general feature of extended magnetotails.

Another scenario is suggested by the cometary plasma tail disconnection events associated with solar wind sector boundary crossings. That is, the distant tail observations might be that of a bubble which has been disconnected from the magnetosphere through some magnetic merging process. *Intriligator et al.* [1969] offered a similar scenario in explanation of observations in the distant tail of the earth, and *Melrose* [1981] has suggested that bubbles of continuum radiation escape from the downstream tail in bubbles of solar wind plasma. The solar wind would convect the disconnected fragment in a more-or-less antisunward direction, but motion in the azimuthal direction may be due to pressure gradients transverse to the radial direction. Alternately, a disrupted fragment might be carried far from the sun-Jupiter line by solar wind flows with a substantial component in the azimuthal direction for an extended period of time. Finally, it may be necessary to return to the former hypothesis of tail rays at large angles with respect to the antisolar direction before the disruption event takes place. One might expect to see a Jovianlike composition of particles in such a bubble or fragment. The low-energy charged particle investigation did indeed measure flow directions, suggesting a combination of both a solar and a Jovian source during the day 259–260 event; however, the composition was similar to the usual solar wind and apparently not Jovian in origin (S. M. Krimigis, personal communication, 1980).

The possibilities discussed above are, of course, highly speculative, and we cannot offer a definitive explanation for the event in Figure 2. A detailed study of the particles and fields measured during the event may help to narrow the field of possible explanations; however, this detailed study is the subject of a future paper and is beyond the scope of the present work.

### Interpretation of Locally Trapped Continuum Radiation Events in the Solar Wind

The class of events represented in Figure 4 by plus signs have the advantage that they are structures in the solar wind and are not actual traversals of the Jovian tail; hence we have only to explain the origin of the trapped waves contained within the density rarefactions without moving the tail into anomalous positions or configurations. We are presented with a situation where both Voyagers have detected trapped nonthermal continuum radiation at large distances from Jupiter, up to 2.8 AU, but the magnetospheres of Jupiter and the earth are the only known sources of nonthermal continuum radiation in the solar system. Hence one must either provide an indirect connection between the solar wind density rarefactions and the Jovian magnetotail or find a mechanism for the generation of continuum radiation in the solar wind.

The only known examples of freely propagating electromagnetic waves generated in the solar wind are the Type III solar radio bursts which are believed to be formed from electron plasma oscillations excited by flare-related energetic electrons streaming through the solar wind. The day 226, 1979, Voyager 1 event which is associated with an interplanetary shock is the only event in Table 1 which is accompanied by electrostatic waves such as plasma oscillations which might be related to the direct generation of the electromagnetic radiation in the solar wind. Preliminary Voyager plasma wave observations indicate greatly reduced occurrence rates of electron plasma oscillations at distances beyond  $\sim 5$  AU and that interplanetary shocks and the Jovian bow shock are perhaps the only sources for plasma oscillations in the outer solar system. It seems unlikely then that any of the events in Table 1 except for the day 226 event can be explained by local generation of electromagnetic radiation in the solar wind.

*Hoang et al.* [1980] have discussed locally generated thermal electrostatic waves seen by ISEE 3 which appear to be very similar to the escaping continuum radiation seen in the vicinity of the earth. We have considered the possibility of this effect appearing in the Voyager observations. Hoang et al. state that for an antenna which is short in comparison to the Debye length  $\lambda_D$ , no low-frequency cutoff (at the local plasma frequency) will be seen in the spectrum of the local electrostatic waves. For most of the Voyager observations used in this paper,  $L < \lambda_D$  is satisfied, where  $L$  is the effective length of the Voyager antenna, 7.07 m. Hence the detection of a low-frequency cutoff such as that shown in Figures 1, 2, 5, and 6 is not consistent with the mechanism studied by Hoang et al. In addition, a calculation of the noise voltage spectral density predicted by Hoang et al. shows the effect to be considerably smaller (by at least a factor of 10) than the Voyager receiver's threshold. We argue that contrary to what one would expect from the Hoang et al. effect, the radiation studied in this paper is not present at all times and the events are normally quite well defined in time. Also, the radiation reported here is often not detected even when the plasma density and temperature are the same or similar to times when the radiation is detected. If the source were a local effect, the same antenna placed in identical plasmas should respond identically. We conclude therefore that the observations discussed in this paper cannot be explained by locally generated electrostatic (thermal) waves as described by *Hoang et al.* [1980].

We can be reasonably sure then that the continuum radiation detected in the distant solar wind must have its source

within the Jovian magnetosphere and the only problem remaining to be solved is to explain how it got from the magnetosphere to the position of Voyager. The simplest explanation is that the radiation has escaped from the magnetosphere and propagated freely to Voyager. The obvious problem with this explanation is that the intensities of many of the events detected at distances of up to 2 AU are much too large to have suffered an  $R^{-2}$  falloff without requiring unreasonable amplitudes in the source region. Also, it is difficult to see how the radiation which is apparently locally trapped when detected could have propagated a great distance in the solar wind without encountering a high-density barrier.

Figure 8 shows a relatively simple model which would allow the detection of continuum radiation at large distances from the magnetosphere without the above mentioned problems. In this illustration we assume that a low-density trough may exist in the solar wind which more or less aligns with the ambient solar wind field direction. If the trough intersected the magnetotail, a low-density path would exist from the magnetospheric cavity to the spacecraft. The trough would act like a wave guide or light pipe connecting the spacecraft to the source of the radiation, and the radiation could reach the spacecraft without the usual  $R^{-2}$  dependence.

Two observations support the 'wave guide' model. First, the majority of events correspond very well with local depressions in the solar wind density which is an obvious requirement of the model. Second, at least two and possibly more of the events appear to have convected from Voyager 2 to Voyager 1 with something like the solar wind velocity. A trough aligned with the ambient magnetic field would be expected to convect radially at the solar wind velocity. On the other hand, the fact that this is not always observed is not surprising, since the structure might disintegrate after a time in the solar wind, or, more likely, if the trough has a finite extent in the direction normal to the ecliptic plane, it is quite possible for the trough to intercept one but not both spacecraft.

Given that the model in Figure 8 is correct in principle, the trapped continuum events provide an indirect means of observing the distant Jovian magnetotail. If the ambient field follows the usually accepted Archimedian spiral direction and the low-density troughs align in the same general direction, then the position of connection of a trough with the tail is at least as distant in the  $-\hat{X}$  direction as the spacecraft itself. Hence the Voyager 1 observations of February 1-3, 1980, shown in Figure 5 provide indirect evidence of an extended Jovian magnetotail at least 2 AU in length.

#### CONCLUSIONS

Observations of nonthermal continuum radiation subsequent to the Voyager Jupiter encounters have yielded the detection of at least one encounter with the Jovian tail more than  $700 R_J$  from Jupiter and at a relatively large angle with respect to the antisolar direction. Possible explanations for such an extreme geometry are that corotation angular momentum and forces associated with high-speed streams in the solar wind may combine to distort the tail in the dawn direction or that filamentary structures similar to those seen in cometary plasma tails and also suspected in the terrestrial magnetotail may extend from Jupiter toward the dawn direction. The unusual orientation of the filaments implied by the Voyager observations may be explained by energetic ion flows or the magnetospheric wind detected by the low-energy charged particle detectors on Voyager in the tail.

Other observations of trapped continuum radiation not in the magnetosphere but in density depressions in the solar wind seem to suggest the existence of low-density troughs or wave guides connecting Voyager to the magnetosphere. This in a sense allows for indirect observations of the tail and provides evidence for a greatly elongated tail (at least 2 AU in length based on most recent observations).

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