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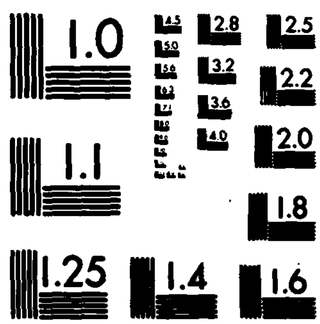

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Voyager Observations of Jupiter's Distant Magnetotail

by

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ABSTRACT

Observations of nonthermal continuum radiation by Voyagers 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. One viable explanation of the observations is that the Jovian tail consists of filamentary structures, some of which extend to large distances in the pre-dawn direction. 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.

I. 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 a third of an 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 anti-solar direction. 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 Pioneer 8 through the tail region at about 500 R_E in January, 1968 [Intriligator et al., 1969; Mariani and Ness, 1969; Scarf et al., 1970; Siscoe et al., 1970; Bavassano et al., 1971; and Scarf, 1971]. 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 observations 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.

Pioneer 7 afforded another set of data from the geomagnetic tail at $\sim 10^3$ R_E. Ness et al. [1967] reported filamentary structures with an aberration angle of $3° - 5°$ which were connected to the Earth. In addition, Ness et al. suggested 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 tail-like characteristics in the magnetic field and plasma. Fairfield [1968] compared observations of tail encounters at ~ 1000 R_E by Pioneer 7 with solar wind observations by Explorers 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 ~ 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.

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, 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 anti-solar direction. In fact, these rays have been observed to fold back from a near solar direction to the anti-solar 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 anti-solar 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. Kennel 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 ~ 4000 R_J ≈ 2 AU. Scarf [1979a] used scaling arguments based on the Earth's tail and arrived at a length of at 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 ~ 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 tail-like structure in the near pre-dawn sector [see, for example, 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. [1981]. 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].

II. 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, 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 - August 10, 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-minute intervals. The distance between two adjacent channels' baselines represents about 5 orders of magnitude or 100 db. A broadband event ($0.311 \lesssim f \lesssim 10$ kHz) commences near the end of day 219 (August 7) and shows considerable variation in the lower frequency cutoff over the next ~ 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, 1981b]. The dashed line, labelled 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 cm^{-3} to as low as ~ 10^{-3} cm^{-3}. (See Gurnett et al. [1981b] for a discussion of the lower continuum radiation cutoff as a density diagnostic.) The periodic spikes in the 100 - 311 Hz channels are interference from the low energy charged particle detector's stepper motor and the semi-periodic, 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 [c.f., Gurnett et al., 1981a]. These bursts lie at the local electron plasma frequency in the solar wind, and indicate an electron density of about 0.1 cm^{-3}. The unimpressive but obvious broadband spike at ~ 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 identification 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 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 re-entries 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 both events. 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. The event shown in Figure 1 shows 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.

Plasma observations made during the event shown in Figure 2 show evidence for a bow shock occurring during the data gap of ~ 1630 - 1900 UT on day 258. During the data gap the density increased by a factor of ~ 2, the bulk speed decreased and the flow angle underwent a large deviation. Corresponding to the plasma wave observations, one of several magnetopause crossings associated with this event was detected by the plasma instrument at ~ 0100 UT on day 259. At this time the density decreased to about 2 x 10^{-2} cm^{-3} which is in general agreement with the onset of continuum radiation in the 1.78-kHz channel. An outbound magnetopause crossing characterized by an increase in density and magnetosheath-like flows occurred at about 0520 - 0530 UT on day 260 followed by a bow shock occurring between 0700 and 0720 UT on the same day. The Voyager 2 magnetometer provided evidence of a bow shock during the data gap on day 258 and evidence of tail-like fields thereafter (R. P. Lepping, personal communication, 1980). These 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 a third of an 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 ~ 900 R_J is given in Figure 3. This illustration is organized in a Jupiter-centered coordinate system. The plane shown is the plane of the Voyager 2 trajectory and the $\hat{X}$ 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 compared 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 3 is a model magnetopause for the Voyager 2 encounter which is taken from Ness et al. [1979b] in the range $X \gtrsim -240\ R_J$. The asymptotic tail width of about 380 R_J is based mainly on Dungey's [1965] tail length-to-width ratio of ~ 30 and a length estimate of ~ 10^4 R_J [Scarf, 1979a]. The tail is shown with an aberration angle of about 2°.

The most surprising result shown in Figure 3 is the large distances in the $-\hat{Y}$ 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 two 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 3 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 3, several 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 3 (as distant as 2000 R_J) and also by Voyager 1 to distances as large as 5818 R_J or ~ 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 4 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 is an obvious increase in the radiation intensity at points where the density decreases. Voyager 2 detected a similar continuum radiation event during January 31 - 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 5 is a 48-second frame of that 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 nonthermal continuum radiation. The cutoff frequency (at f_p^-) corresponds to an electron density of 0.045 cm^{-3}. The plasma observations yield the same density based on measurements in the same region.

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 km/sec during this time period, but the structure most likely has a nonzero group velocity in the rest frame of the interplanetary 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.

III. DISCUSSION

We have presented observations of the magnetospheric tail at large distances from Jupiter and in directions far from the anti-solar 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.

A. 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 3 could reasonably be explained by a simple expansion of the magnetosphere in response to varying solar wind dynamic pressure. Scarf [1979a] suggests the linear dimensions of the magnetosphere might vary by a factor of two if the subsolar magnetopause distance is a reliable scaling parameter. (More recently Goodrich et al. [1980] predict the standoff distance of the Jovian bow shock may vary as much as a factor of three.) The event shown in Figure 2 and labeled B in Figure 3, might be explained by a simple expansion of the magnetosphere, but the dimensions involved are almost unreasonable. It is perhaps appropriate, then, to draw upon our knowledge of the gross structures in cometary plasma tails for an alternative solution to this problem.

Of the various cometary plasma tail structures and phenomena reviewed in the Introduction, the tail rays or filaments offer the most likely explanation of tail-like structures at large angles with respect to the anti-solar direction. While the cometary tail rays ultimately align close to the anti-solar direction, they apparently first appear at large angles with respect to that direction, sometimes in the solar direction and then fold back toward the anti-solar 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 ~ 20 to ~ 40 keV ions in the Jovian tail (called the magnetospheric wind) not in the anti-solar direction, but ~ 20° from the anti-solar 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 towards the local early morning sector producing filaments at relatively large angles to the anti-solar direction.

Figure 6 is a sketch of a model magnetosphere with filamentary structures directed towards 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 tail-like 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 anti-solar 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 anti-solar 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 expect filaments to be a general feature of extended magnetotails.

For the event of days 259 - 260 shown in Figure 2, the low energy charged particle detector observed flows of 20 keV electrons, 30 - 80 keV ions, .5 MeV protons, α-particles, etc., presumably of solar origin, but also $Z \geq 6$ ions which could conceivably originate in the Jovian magnetosphere. The flow direction suggested a combination of both a solar and Jovian source. These observations are not those of the magnetospheric wind reported by Krimigis et al. [1979] but are more suggestive magnetospheric plasma which has been torn from the magnetosphere by an interplanetary disturbance if, indeed, some of the plasma does originate at Jupiter (S. M. Krimigis, personal communication, 1980). This brings to mind the plasma tail disconnection events associated with solar wind sector boundary crossings as prototypes to explain the Voyager observations. 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 [1980] 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 anti-sunward 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 anti-solar direction before the disruption event takes place. Detailed studies of the day 259 - 260 event may provide further insight on the structure of this portion of the tail and hence more information on which to base an explanation. We do not propose to provide a definitive solution to the problem of the September magnetosphere crossing shown in Figure 2. We have, however, suggested some ideas borrowed from cometary plasma tail studies as possible solutions.

B. Interpretation of Locally Trapped Continuum Radiation Events in the Solar Wind

The class of events represented in Figure 3 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 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. Except for the waves upstream of the September event in Figure 2 electron plasma oscillations are not observed in connection with the events studied in this paper. In fact, the preliminary Voyager plasma wave observations indicate that interplanetary shocks and the Jovian bow shock are perhaps the only sources for plasma oscillations at large distances from the sun ($\gtrsim$ 5 AU).

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 compared to the Debye length, λ_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, 4 and 5 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} fall off 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 7 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. Secondly, 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 7 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 4 provide indirect evidence of an extended Jovian magnetotail at least 2 AU in length.

IV. 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 anti-solar direction. One possible explanation for such an extreme geometry is a filamentary structure similar to that seen in cometary plasma tails and also suspected in the terrestrial magnetotail. 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 require 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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FIGURE CAPTIONS

Figure 1 Plasma wave spectrum analyzer data showing nonthermal continuum radiation within the Jovian magnetosphere at ~ 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.

Figure 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).

Figure 3 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.

Figure 4 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.

Figure 5 A wideband frequency-time spectrogram taken by Voyager 2 during the event shown in Figure 4. 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 cm^{-3}.

Figure 6 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 3.

Figure 7 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 trapped continuum radiation events allow indirect measurements of the Jovian magnetotail at distances well over 2 AU from Jupiter.

TABLE 1

OBSERVATIONS OF CONTINUUM RADIATION BY THE VOYAGER PLASMA WAVE INSTRUMENTS DURING THE OUTBOUND TRAJECTORIES FROM JUPITER

Start-Stop (DAY/HRMN)		$R(R_J)$	ϕ(DEG)+	Region*
Voyager 1				
1979	74/1640 - 75/0030	163	244.5	Ms
	116/0500 - 117/1400	726	244.5	SW
	218/0630 - 218/1400	2077	236.7	SW
	218/1630 - >218/1830	2082	236.7	SW
	226/0330 - 226/0530	2180	236.1	SW
	358/0240 - 358/0555	3929	224.6	SW
1980	32/1630 - 33/0520	4465	221.1	SW
	33/0750 - 34/1100	4473	221.0	SW
	75/0945 - 76/0050	5053	217.1	SW
	129/1450 - 129/2100	5818	212.2	SW
Voyager 2				
1979	206/0030 - 206/0410	184	224.1	Ms
	208/1830 - >212/1800	212	224.9	Ms
	213/0820 - 214/0720	259	225.8	Ms
	215/0630 - 215/0750	279	226.0	Ms
	219/1630 - >222/0500	313	226.3	Ms
	<230/2000 - >230/2400	434	226.5	SW
	<237/1230 - 238/0400	498	226.4	SW
	241/2100 - >241/2400	541	226.3	SW
	259/0100 - 260/0520	706	225.5	Ms
	263/1445 - 263/1800	750	225.3	SW
	263/2130 - >263/2245	752	225.3	SW
	270/0500 - 270/1830	813	225.1	SW
	271/1340 - 271/1620	825	225.0	SW
	353/0420 - 353/0650	1600	219.0	SW
	353/1830 - 354/1420	1606	219.0	SW
1980	31/0400 - >31/2400	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 radiaton was being detected. However, times given here are determined by the detection of continuum radiaton and are not, therefore, necessarily the times of magnetopause crossings as determined by plasma or magnetic field observations.

C-G80-528

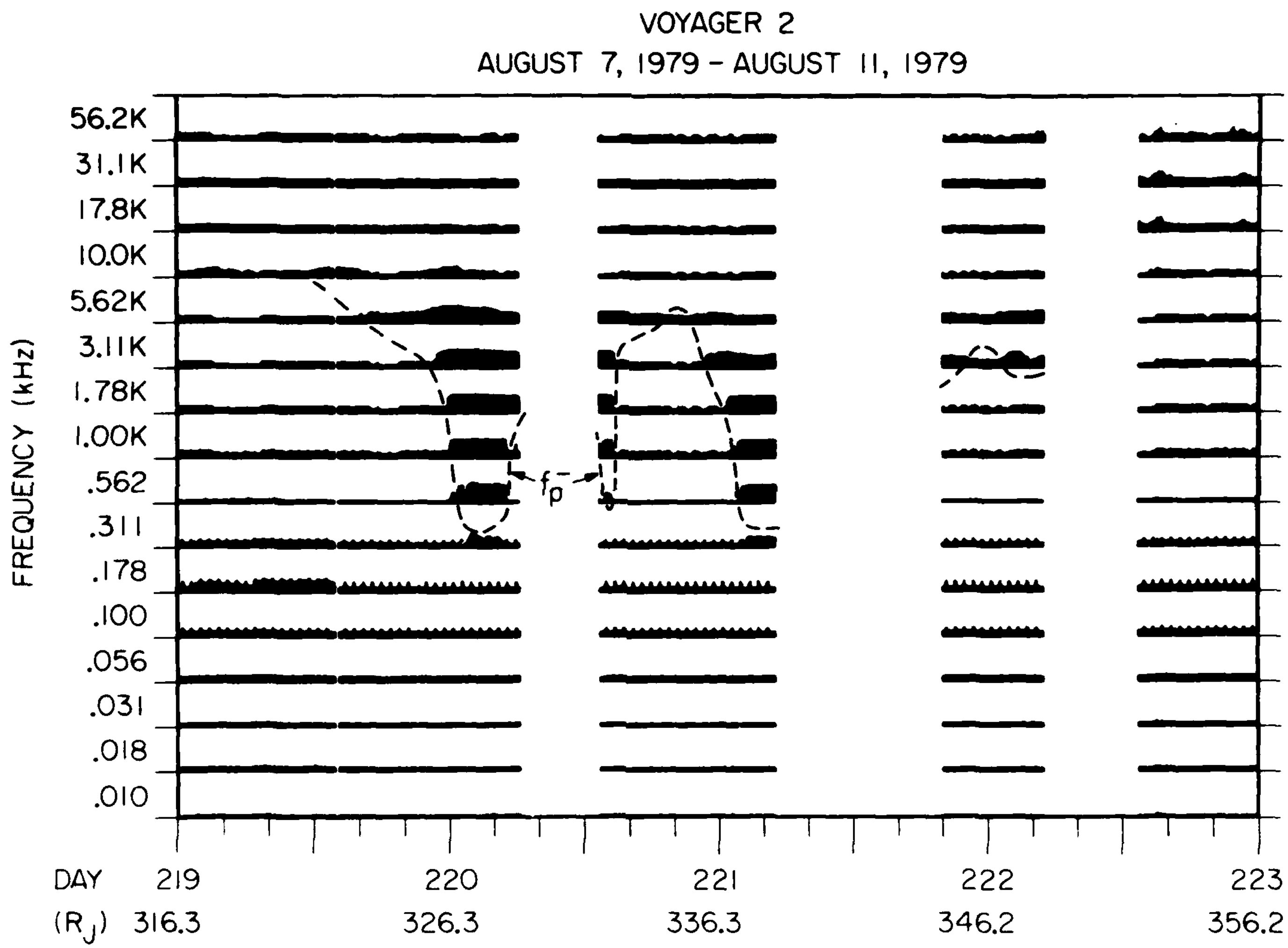

Figure 1

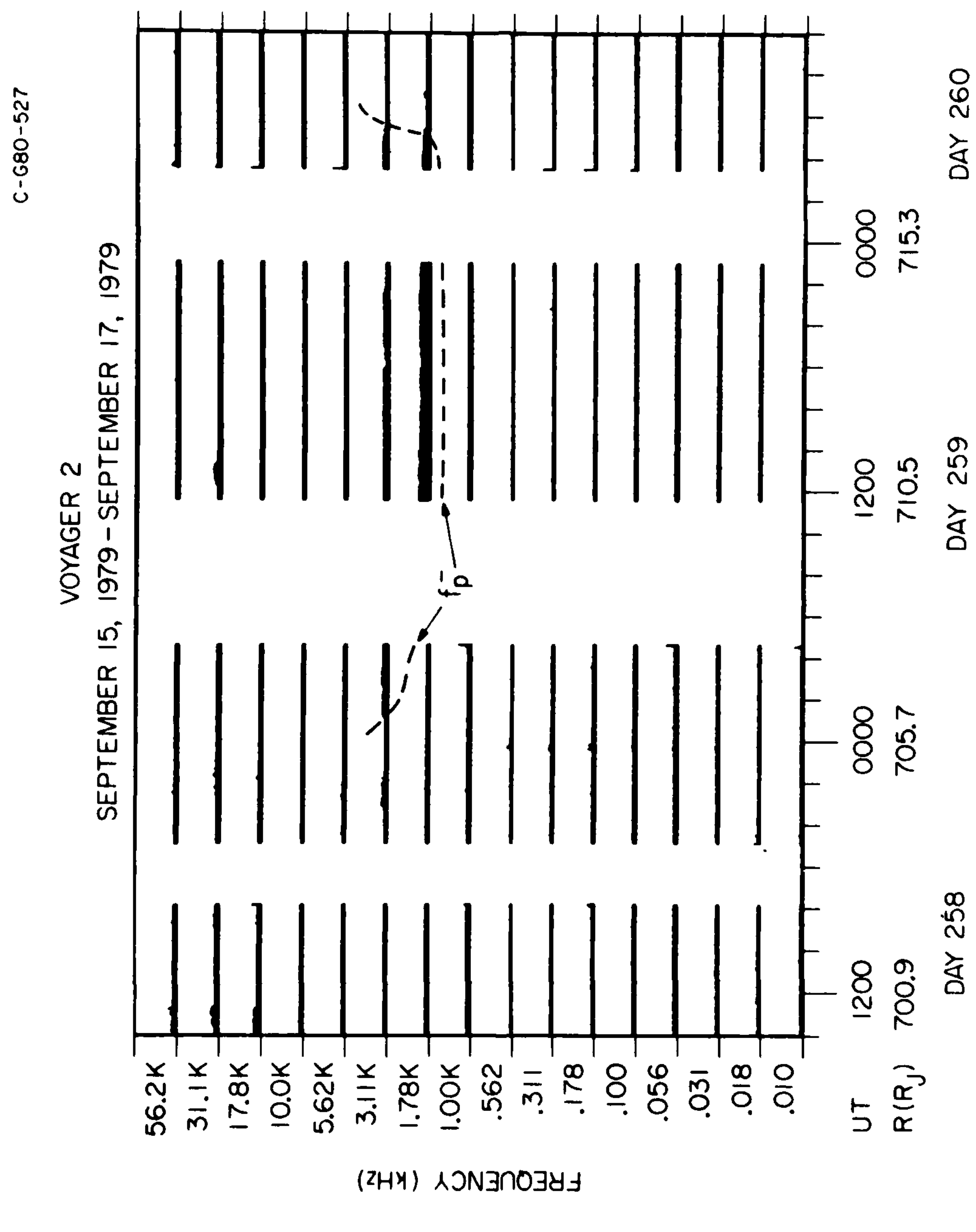
C-G80-527
VOYAGER 2
SEPTEMBER 15, 1979 - SEPTEMBER 17, 1979
FREQUENCY (KHz)
56.2K
31.1K
17.8K
10.0K
5.62K
3.11K
1.78K
1.00K
.562
.311
.178
.100
.056
.031
.018
.010
UT
R(RJ)
1200
700.9
0000
705.7
1200
710.5
0000
715.3
DAY 258
DAY 259
DAY 260
fp

Figure 2

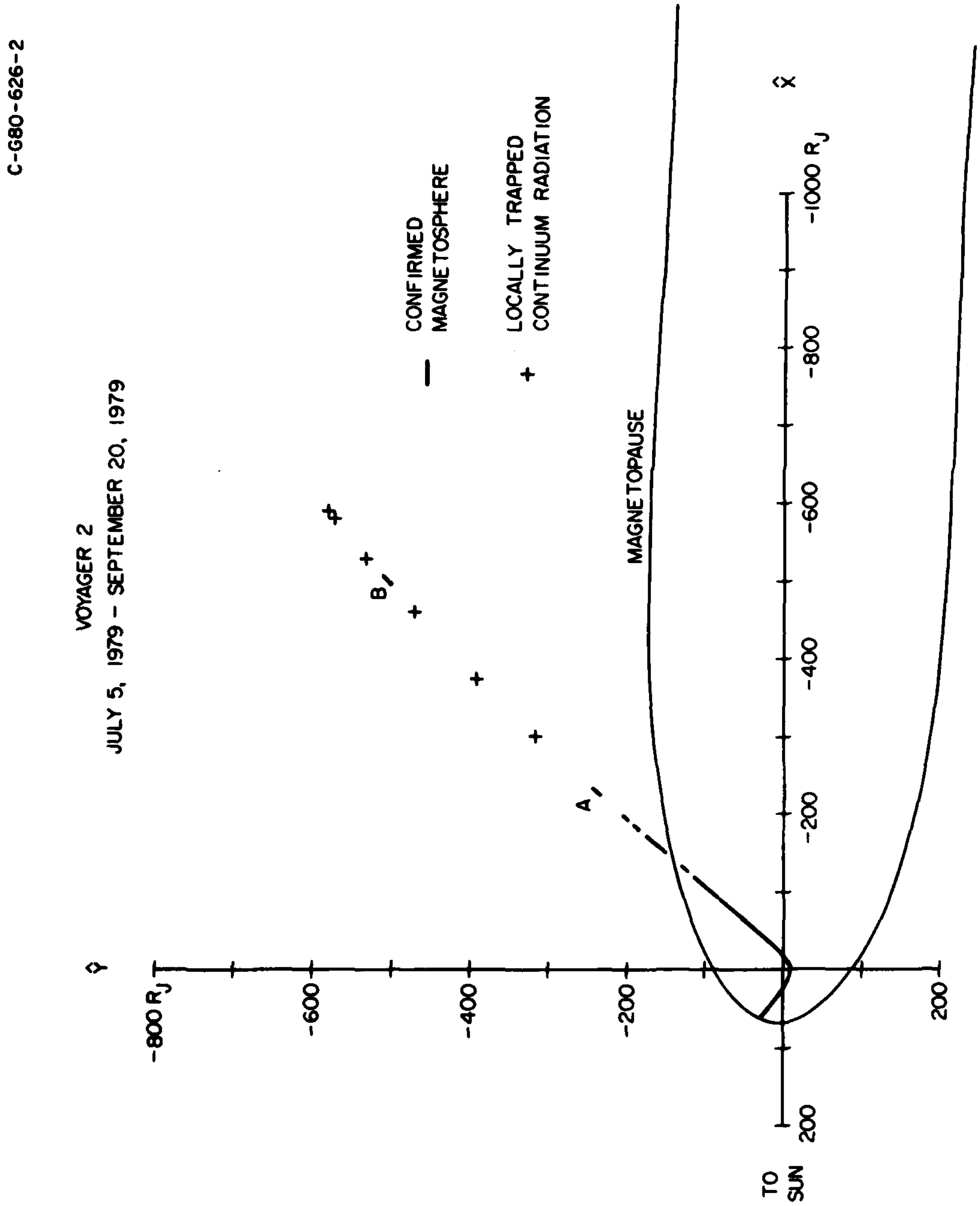
C-G80-626-2
VOYAGER 2
JULY 5, 1979 - SEPTEMBER 20, 1979
CONFIRMED
MAGNETOSPHERE
LOCALLY TRAPPED
CONTINUUM RADIATION
MAGNETOPAUSE
A
B
ŷ
-800 R_J
-600
-400
-200
200
x̂
-1000 R_J
-800
-600
-400
-200
200
TO
SUN

Figure 3

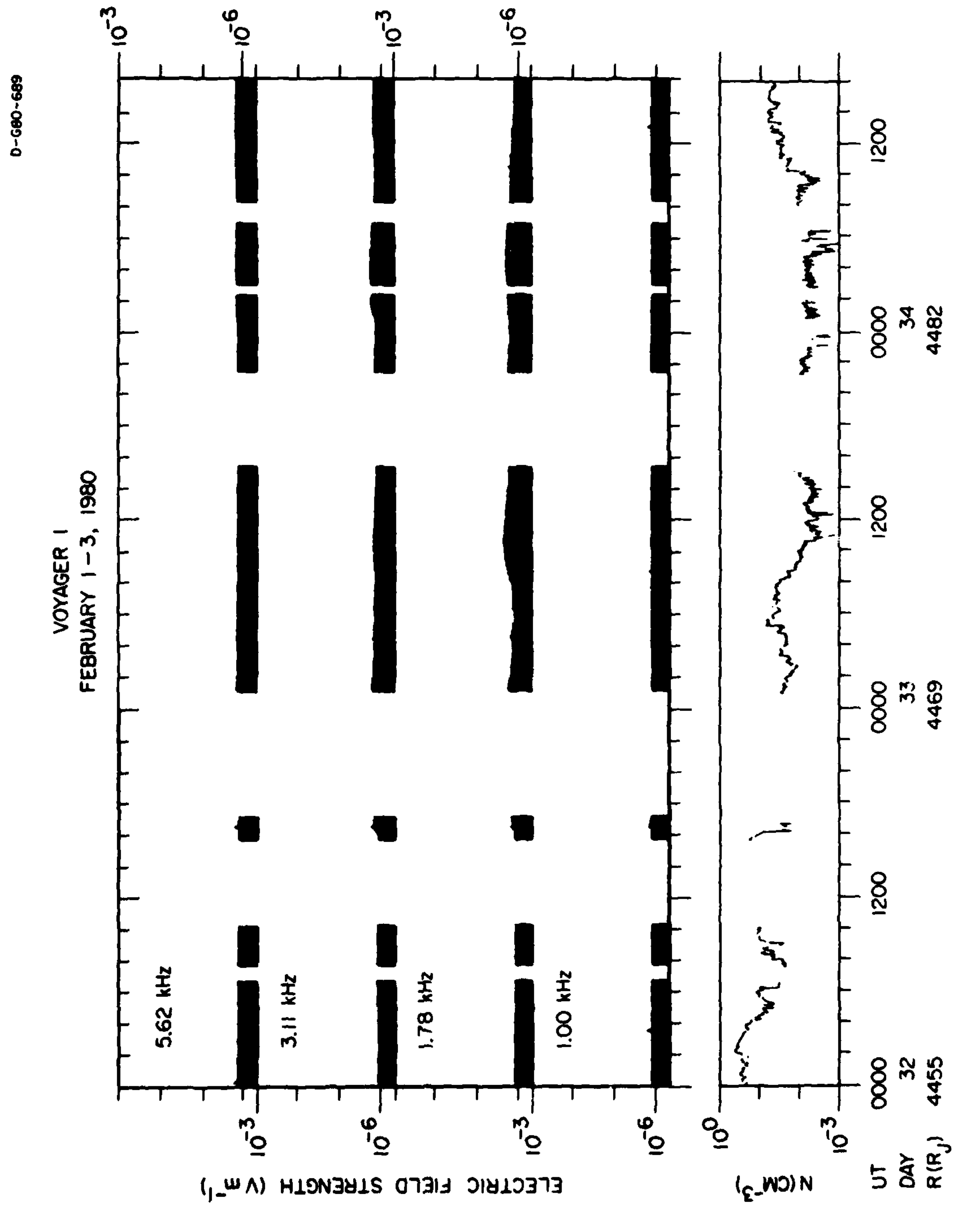
D-G80-689
VOYAGER I
FEBRUARY 1-3, 1980
5.62 kHz
3.11 kHz
1.78 kHz
1.00 kHz
ELECTRIC FIELD STRENGTH (V m^{-1})
10^{-3}
10^{-6}
N(CM^{-3})
10^{0}
UT
DAY
R(R$_J$)
0000
1200
32
33
34
4455
4469
4482

Figure 4

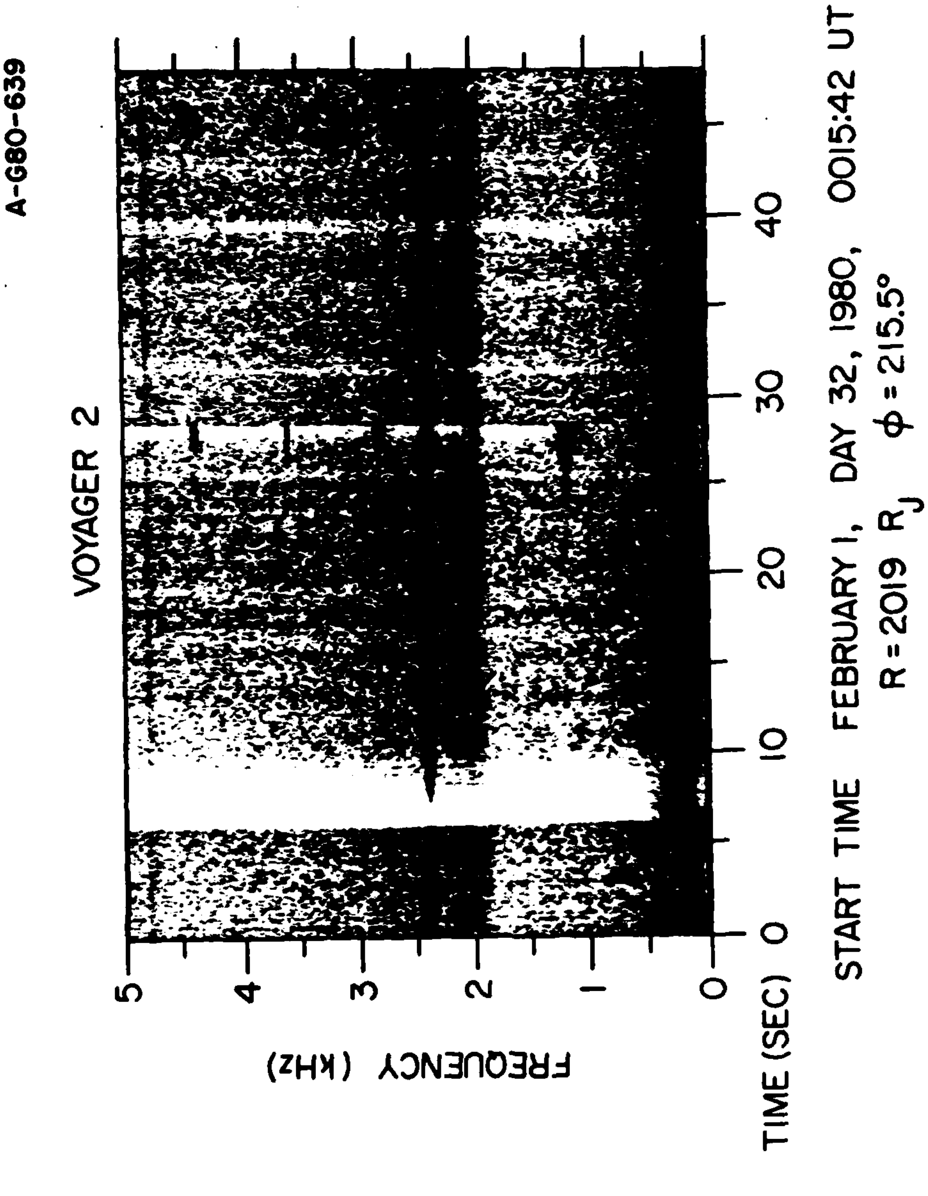
A-G80-639
VOYAGER 2
FREQUENCY (KHz)
5
4
3
2
1
0
0
10
20
30
40
TIME (SEC)
START TIME FEBRUARY 1, DAY 32, 1980, 0015:42 UT
R = 2019 R$_J$ φ = 215.5°

Figure 5

C-G80-629

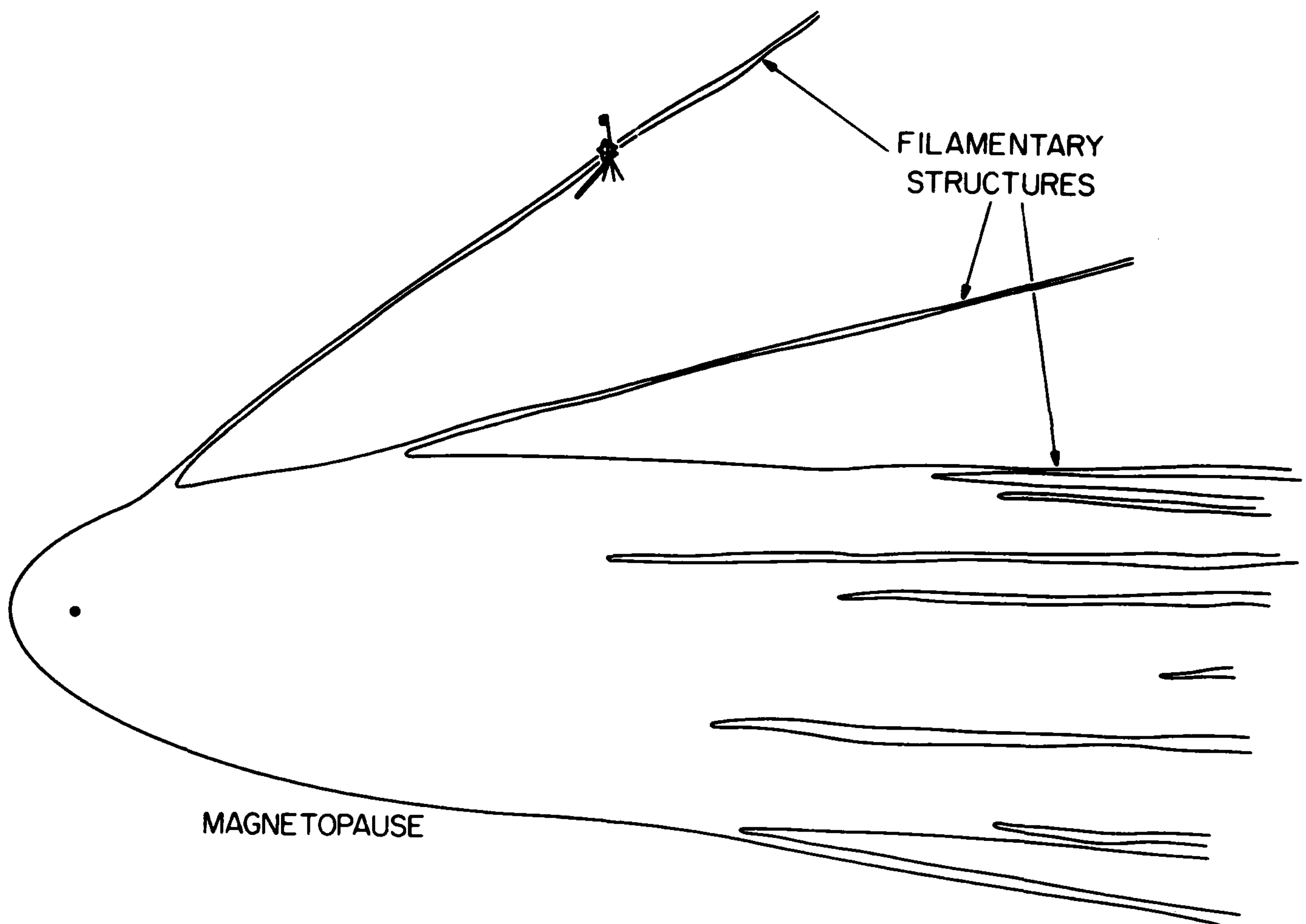

Figure 6

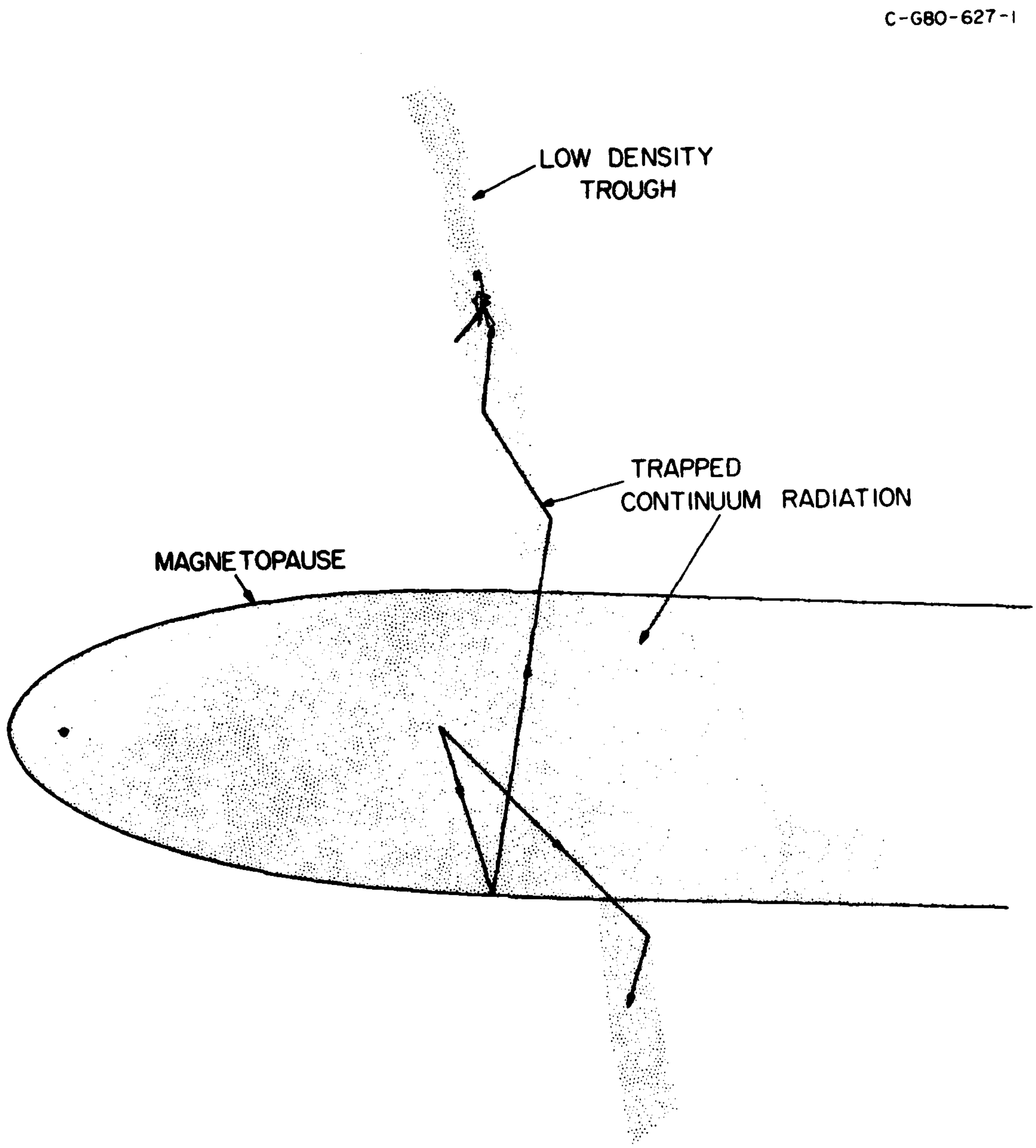
C-G80-627-1
LOW DENSITY TROUGH
TRAPPED CONTINUUM RADIATION
MAGNETOPAUSE

Figure 7