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Abstract

A correlative survey of magnetometer (MAG) and Planetary Radio Astronomy (PRA) 1.2 kHz continuum radiation measurements from Voyager 2 provide evidence for at least eight distant Jovian magnetotail sightings occurring about once a month over the first 2/3 of 1981 at distances of ~ 5,000 to ~ 9,000 R_J. The occurrences of these events are in good agreement with prior Plasma Wave Science and Plasma Science identifications. Observations of these distant magnetotail, or tail filament, encounters appear most prevalent in both MAG and PRA data sets when the spacecraft was closest to the Jupiter-Sun axis at ~ 6,500 R_J from the planet; the PRA events are also most intense during those times. A specific tail encounter occurring in mid-February 1981 is analyzed and shown to possess a remarkably symmetric magnetic field signature and to have a bipolar field structure in its central region. The bipolarity is characteristic of most of the eight events.

Introduction

Voyager 2 Planetary Radio Astronomy (PRA) and magnetometer (MAG) data were examined for approximately the first eight months of 1981 in order to provide possible evidence for the existence of an extended (distance $\gtrsim$ 9,000 R_J) Jovian magnetotail; R_J=71,372 km is Jupiter's radius. Examples of distant Jovian tail encounters have been recently cited by members of the Voyager Plasma Wave Science (PWS) and Plasma Sciences (PLS) teams, e.g., see Kurth et al., 1981 and Scarf et al., 1981. The possibility that Voyager 2 would encounter Jupiter's tail at distances of the order of 6,000 R_J was pointed out by Scarf (1979). He also called attention to the interesting possibility of Voyager 2 encountering Saturn at a time when that planet was immersed in the Jovian tail.

In this paper we survey data from the lowest frequency channel of PRA (Warwick et al., 1977), centered at 1.2 kHz, as well as data from the sensitive low field MAG (Behannon et al., 1977) onboard Voyager 2. The initial purpose was twofold: (1) to search for a correlation between the PRA and MAG data, especially for times when the MAG data indicated the maximum likelihood of the presence of a tail field (Jupiter-spacecraft field alignment) and (2) to examine the structure of the magnetic field for candidate tail sightings as defined by PRA. Only the mid-February, 1981 event reported on by Scarf et al. (1981) will be discussed here with regard to detailed structure. Another important goal was to see how well the PRA-MAG tail identifications agreed with PWS-PLS candidate tail sightings, whose times of occurrence were kindly provided to us by W. Kurth of PWS before our survey commenced (see Kurth et al., 1982).

Survey of Data

One indication of the presence of the Jovian tail is the occurrence of low frequency continuum radiation. Such emissions (PRA observations at $\sim$ 1.2 kHz) are shown in the top panel of Figure 1 in the form of 2-hour averages of the intensity for the first 230 days of 1981 with still unprocessed data shown as gaps. Below the top panel are horizontal bars labeled 1 through 8 identifying intervals in which the intensity of this continuum radiation is significantly enhanced above background noise (10^{-14} V^2/m^2 Hz). Shown below these numbered intervals are the locations (dots) of the center times of tail sightings provided by Kurth; no. 7 is also from Scarf et al., 1982. These continuum emissions are characteristic of ordinary mode, LF continuum radiation found in the nightside tail lobes of Jupiter and are consistent with being strongly left-hand polarized, if they are coming from a source upstream of the spacecraft with respect to the solar wind flow direction.

Another indication of the presence of the Jovian tail is the occurrence of magnetic fields that are nearly aligned with the direction of solar wind flow, which must be close to being parallel to the planet-spacecraft line when such fields are observed at the spacecraft for the times of interest here. We define α as the acute angle between the magnetic field and the Jupiter-spacecraft direction, independent of the sense of the field polarity (see bottom of Figure 1). Hence, we consider that a high percentage of hours in a given day for which α is less than 30° is a good indicator for the possible presence of a tail field. This criterion is obviously motivated by our knowledge of the geometry of near-planet tail fields generally (Behannon, 1968, Ness, 1969, and Ness et al., 1979b) as well as that of the distant (> 1,000 earth radii) tail field of the earth (Ness et al., 1967). The $\alpha < 30^{\circ}$ criterion is an especially good discriminator between tail and interplanetary magnetic fields (IMF) for the period of interest, since the IMF is most likely to be approximately perpendicular (i.e. $\alpha \simeq 90^{\circ}$) to an expected tail-like field (where $\alpha \simeq 0^{\circ}$ is most likely) at the spacecraft's distance from the sun. The percentage of hours in a day with $\alpha < 30^{\circ}$ is shown in the bottom panel of Figure 1 for each of the 230 days in the period.

There is remarkable agreement betweeen the periods of PRA continuum intensity enhancements and those days with a high percentage of fields with $\alpha < 30^{\circ}$. Furthermore, in all cases where information exists, the PWS tail encounter times are in good agreement with these PRA-MAG event times. It should be pointed out that over the interval shown there are no significant MAG data gaps, i.e., a value of 0% for a given day faithfully represents a condition in which there were no hours during that day in which the average field direction satisfied $\alpha < 30^{\circ}$. Notice that the period during which a high percentage of $\alpha < 30^{\circ}$ cases occurred, from $\sim$ day 47 to 145, corresponds to that of the most intense PRA events: 2 through 5. The middle of this region is day 96. Closest approach (C.A.) to the sun-Jupiter axis occurred on day 77, only $\sim$ 2-1/2 weeks away from this mid-point day. Finally, we note that the eight events occurred quasi-periodically with an average separation of about one month.

The Voyager 1 magnetic field was examined for the first 200 days of 1981 to determine the percentage of hours in a day for which the field was aligned, within 30°, with the sun-Voyager 1 line, in order to compare the results with the MAG-panel of Figure 1. Preliminary Voyager 1 data was used, but for only about 20 percent of the time did significant data gaps exist; the gaps occurred over the last quarter of the 200-day period where the probability of a tail encounter for Voyager 2 was low according to Figure 1. The comparison showed a striking contrast to the Voyager 2 results: "radial" fields at Voyager 1 occurred only about one-sixth as often as at Voyager 2, there was no apparent monthly quasi-periodicity, and even after a delay correction of about one week the occurrence pattern did not resemble the Voyager 2 continuum radiation occurrence pattern. Jupiter's distant tail was probably not seen at Voyager 1 for this period in 1981, and this contrast in observations strengthens the case for identifying the 8 events of Figure 1 as Jupiter tail encounters, and not as interplanetary events.

The spatial locations of the Voyager 2 tail-crossings relative to the Jupiter-Sun line (X-axis) are shown in Figure 2. The trajectory of Voyager 2 is plotted in cylindrical coordinates for the period October 1980 to late August 1981. Distances are given in units of $R_o = 75\ R_J$, which is the average subsolar magnetopause distance at Jupiter based on Pioneer 10,11 (Smith et al., 1976) and Voyager 1, 2 (Ness et al., 1979 a,b) observations. Events 1 through 8, as given in Figure 1, are shown on the trajectory, as well as the positions of earlier apparent tail sightings (K) of October, November, and December 1980 (W. Kurth, private communication). At the C.A. point the trajectory is as much as 4.3 R_o (or 320 R_J) off the sun-Jupiter axis. Notice how events 2, 3, and 4 closely group around C.A.; all are within $\sim 3.5^{\circ}$ of the X-axis. All eleven events occur within 12° of the X-axis, with number 8 occurring about one week before the spacecraft reached closest approach to

Saturn'. It should be noted that the aberration of the tail in the ecliptic plane due to planetary motion for a solar wind speed of 400 km/s is expected to be only 1.8°.

Structure of Mid-February 1981 Event

The mid-February 1981 event (no. 2) observed in the PWS and PLS data of Voyager 2 has been discussed by Scarf et al. (1981) and will be examined here in terms of its PRA and MAG features. In particular, an attempt is made to understand its magnetic field structure. Figure 3 shows the field (15-min averages) in the bottom three panels (dark curve) for 8 days. Because of an obvious symmetry in the field data centered late on day 50, we also show the field data plotted with time going backward (light curve) such that it agrees in time with the forward running data at the point 1700 UT on day 50 ("CENTER" in Figure 3). This mirror symmetry point was determined by optimally correlating the cartesian components of the field as well as its magnitude for the forward and backward running data; all quantities reached a maximum correlation simultaneously. The top panel shows the associated 1.2 kHz PRA data which is asymmetric in intensity but is apparently geometrically centered at the field CENTER point. This point is remarkably close to the middle of the first (and larger) of two regions in which Scarf et al. (1981) estimate the electron density to fall below $\sim 10^{-2}$ cm^{-3}, within a few hours at each end point. This region, henceforth called the core region, lies between the vertical lines shown in the B-panel (see the larger crosshatched bar). It lasts about 2-1/8 days, from hour 17 of day 49 to hour 20.5 of day 51, and is located within the overall $\gtrsim$ 11-day tail/wake identification of Scarf et al.; the core start/stop times are given by Kurth et al., 1982.

The core region shows a distinct mirror symmetry about the CENTER point in all three parameters B, λ, and δ, although the δ symmetry is of lower quality. Immediately bracketing this core region, for about 3/4 day on each side, the field maintains a clear mirror symmetry in δ but shows an $\sim 180°$ flip in longitude (λ), as denoted in Figure 3; this difference is, in fact, one of the main reasons for choosing the specific boundaries of the core region. (Even the RMS deviation, not shown, ates a rough symmetry for $\gtrsim$ 6 days around day 50, corresponding to the 6 days of the enhanced 1.2 kHz continuum

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radiation). A proposed model, given in the next section, will attempt to explain these symmetric features. First, we point out some specific characteristics of the core and external regions separately.

Probably the most outstanding feature of the core region is the bipolarity of the field: $\lambda \approx 180^\circ$ on average around the CENTER of the core for $\approx$ 12 hours (i.e., for the latter half of day 50) and $\lambda \approx 0^\circ$ on either side for $\approx$ 12 hours each. The magnitude of the field differs significantly between these two regions of opposite polarity with the region with $\lambda \approx 0^\circ$ having a significantly higher magnitude than either the central region or the external regions immediately outside the 2-1/8 day core region, on either side. Notice also that where λ is $\approx 0^\circ$, δ is on average -25° to -30°, and that where λ is $\approx 180^\circ$, λ is on average $\approx 30^\circ$. This correspondence indicates that the bipolar fields are close to being truly antiparallel. Another interesting characteristic of the core region is the interval between hour 17 of day 49 and hour 0 of day 50 where $\lambda \sim 90^\circ$ and δ is very southward which violates the symmetry seen elsewhere and appears to be a boundary effect.

The 3/4-day external intervals bordering the core region (where λ flipped by $\approx 180^\circ$) do indeed appear to be outside of the magnetotail proper (or tail filament) in that they have the appearance of near-magnetopause southward draped magnetosheath fields. Such near-magnetopause field line draping is commonly seen in sheaths around all known magnetospheres. Scarf et al. (1981) point out that during days 43 through 48 (i.e., just prior to the core region) the spacecraft appears to have been in a region of streaming low-density solar wind, or possibly a wake region around a tail filament (See Siscoe et al., 1970).

What appears to be a brief filament encounter (or re-encounter), identified by "MAG" in the λ-panel, occurs approximately from hour 18 of day 52 to hour 6 of day 53, the early part of which coincides with the second (shorter) crosshatched bar from Scarf et al., (1981). In the "MAG" interval the magnitude of the field is slightly greater than in the adjacent regions. Again both polarities appear, with $\lambda = 0^\circ$ predominating. Also on day 48, hours 7 to 12, another brief encounter may have occurred but for $\lambda \approx 0^\circ$ only.

The lateral extent of the overall wake/sheath has not been determined, since no distant planetary bow shock has been identified. This should not be surprising, since any bow shock which might exist at these distances would be very weak and probably very distant from the Sun-Jupiter axis and possibly would not be encountered at all during 1981. It is interesting that Pioneer 7 observations made in the distant tail of earth (~ 1,000 earth radii) also did not reveal distant bow shock signatures, although magnetotail or wake identifications at that distance are well known (Wolf et al., 1967, and Villante, 1977); see Scarf (1979) on the issue of comparing the earth's tail length to that of an expected Jovian tail in terms of a day-side magnetosphere size, as we did in Figure 2 by using units of R_o.

A Model of the Mid-February Event

Here we give two versions of a model of the mid-February event. We will refer to the core region as a tail filament, keeping in mind that it conceivably could be the tail itself, since we do not have direct knowledge of its cross-sectional size. Figure 4 shows two sketches, both representing simplifications of what Voyager 2 appeared to observe during part of this event (i.e., for $\gtrsim$ 4 days centered around hour 17 of day 50); there is one for each of two types of filament motion. The upper sketch (TIME SYMMETRY) represents the cross-section of a bipolar magnetotail filament which moves relative to the spacecraft in an approximately oscillatory manner, so that the spacecraft appears nearly to retrace its path. The cross-sectional plane is perpendicular to the local axis of the filament, but the axis is inclined by ~ 30° with respect to the orbital plane of Jupiter, being higher behind the figure and lower in front, as δ in Figure 3 indicates for both "lobes." The projection of this filament axis on the orbital plane is, however, closely aligned with the Jupiter direction. The spacecraft spends about 2/3 of its time in the upper lobe where $\lambda \simeq 0°$, and about 1/3 of its time in the lower lobe where $\lambda \simeq 180°$. Outside of the boundary of the filament and close to it the draped, "external" (i.e., sheath/wake) field lies approximately in the plane of the figure and parallel to the boundary. The flip of $\simeq$ 180° in longitude of this external field is then apparently due to the change in the slope of the field lines as a result of curvature of the boundary between the entrance and exit points.

The lower sketch (SPACE SYMMETRY) represents a similar cross-section of a tail filament but which moves approximately along a straight line relative to the spacecraft, so that the spacecraft appears to observe a spatial profile of the filament. Otherwise most comments made above for the time-symmetry sketch hold (e.g., filament inclination, lobe - durations, external field characteristics, etc.). Here, however, the λ-change of the external field must be due to an IMF polarity change (which we explicitly show by the dashed vector projections onto the Jupiter orbital plane) that occurred over the 2-1/8 day period of filament passage. Such a sector change is not unlikely based on inspection of plots of many 25-day cycles of the IMF; these λ-changes were common at the same phase of the other cycles.

In the lower lobe of the filament, where $\vec{B}$ is toward Jupiter ($\lambda \simeq 180^\circ$), i.e., for ± 6 hours around the CENTER, recall that the field drops to about 1/3 to 1/2 of its value in the upper lobe. Figure 3 strictly shows that around hours ∼20-24 of day 50 weak fields exist during a transition of λ: from $\sim 180^\circ$, through $\sim 0^\circ$, to -180°, and finally back to $\sim 0^\circ$. Although it favors the lower lobe, the low-field region occurs mainly around the transition region from one lobe to the other, as the dashed curve in Figure 4 indicates and, in fact, resembles a plasma sheet. If there exists a plasma sheet, as yet undetected, in this transition region, its presence could explain the lower field observed there. If the plasma in such a layer were subsonic, or if it were flowing well outside of the antisolar direction, it might be difficult to detect. This low-field region cannot easily be explained by a sudden expansion of the tail field, since then it would be expected that the outbound passage through the upper lobe would show a lower B value also, and it does not.

To explain the apparent brief filament encounter, approximately delineated by the second (shorter) crosshatched bar in Figure 3, we can imagine that both lobes of a second (possibly thinner) filament were observed, consistent with the spirit of the bottom sketch of Figure 4. Alternately, the brief encounter may have been a return visit by the same "core" filament, in the spirit of the upper sketch of Figure 4. Similar explanations may be used for other possible brief encounters.

A preliminary review of the field structures of all of the events shown in Figure 1 indicates that these structures are complex and do not generally show such striking symmetry as the mid-February event. They do, however, reveal the bipolar field characteristic in most cases, and some events show a persistent field polarity for long periods, with brief moments of opposite polarity. Event 5, for example, had $\lambda \simeq 180^\circ$ persistently for over 3 days (141, 142, 143+) and only very brief durations of $\lambda \simeq 0^\circ$ during earlier and later periods. There is a tendency for events 2, 3, and 4 to favor the $\lambda = 0^\circ$ lobe and for events 5, 6, 7, and 8 to favor the $\lambda = 180^\circ$ lobe.

The monthly quasi-periodicity [213 days/(8-1) events = 30 days, average period from Figure 1] implies that the tail is apparently driven longitudinally by solar wind (stream) pressure gradients; the solar rotation period of 25 days (for a negligible longitudinal spacecraft speed) is close to this quasi-period. For this reason we stress sideways tail motion, as shown in Figure 4, but the model does not necessarily mean to preclude the possibility or importance of latitudinal tail motions.

Discussion

The combined observations from PWS, PLS, PRA, and MAG onboard Voyager 2 discussed here, or referred to, strongly indicate that the spacecraft encountered Jupiter's magnetotail/wake on numerous occasions in 1981 and late 1980. Also the events were more intense or more probable in the vicinity of the closest approach point to the Jupiter-Sun line. The important question remains: Are these encounters with tail filaments or with the tail itself? The answer is not obvious, but we can infer that the distant tail probably does not have a very large overall crossectional radius (i.e., probably not > 800 R_J) nor consist of numerous fine-scale filamentary structures. The event-signatures (Figure 1) and spatial distribution of events (Figure 2) seem to lead to these inferences.

On the controversial issue of whether or not Saturn was in Jupiter's magnetotail/wake during the Voyager 2 Saturn encounter, two important points have been put forward (J. Sullivan, PLS, private communication) to argue that such an occurrence probably did not take place: (1) Saturn's magnetosphere, although unusually expanded during the outbound leg of the encounter (Ness et al., 1982), had dimensions within estimated possible limits assuming its expansion was due to a very low solar wind ram pressure (at a 5% probability), and (2) no continuum radiation was observed in Saturn's magnetosphere (puzzling in itself) as would be expected, if the magnetosphere were in the Jovian tail, due to leakage of the radiation from the tail. To these arguments we add another, weaker, one: that the August 1981 event (no. 8 in Figures 1 and 2) occurred one week before Voyager 2 reached closest approach to Saturn as stated earlier, and since the proposed tail-encounters were arriving rather faithfully with a quasi-period of $\sim$ one month, the spacecraft planetary encounter period of $\sim$ 4 days was not expected to occur during a Jovian-tail encounter. (And, in fact, PRA data examined for many weeks post-Saturn encounter reveals no significant continuum radiation.) Furthermore, the lower intensity of the PRA events and lower occurrence probability of the MAG events prior to, and later than, events 2 through 5 (Figure 1) also weakens the credibility of such an occurrence. On the other hand, the PRA investigators (Warwick et al., 1982) report on a dramatic decrease in emission intensity of Voyager 2 Saturn kilometric radiation lasting for about two days, ending at 0800 UT on day 241, 1981. They speculate that it might have been due to the expansion of Saturn's magnetosphere and the possible concomitant diminution of particle population in the cusp regions (probable sources of the emissions), if the expansion was the result of Saturn's immersion in Jupiter's magnetic tail. Obviously, none of these arguments is definitive, and the case for Saturn being in Jupiter's tail during encounter is still open.

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Figure Captions

Figure 1. The results of a survey of Voyager 2 Planetary Radio Astronomy and magnetometer data for the first 230 days of 1981. The top panel shows the intensity of PRA continuum radiation centered at 1.2 kHz, below which prominent events are labeled 1 through 8. The bottom panel shows the percentage of hours in a day for which the magnetic field satisfies $\alpha < 30^{\circ}$, where α is defined by the sketch at the bottom; see text.

Figure 2 The Voyager 2 trajectory in cylindrical coordinates in units of R_o for the period covered in Figure 1 plus several previous months. R_o refers to the average Jovacentric subsolar magnetopause distance. Voyager 2 encounter with Saturn occurred about one week after event 8.

Figure 3 The top panel presents 48-s averages of PRA continuum radiation centered at 1.2 kHz. The bottom three panels (dark curves) show 16 min. averages of the magnetic field in terms of its magnitude (B), longitude (λ), and latitude δ in heliographic coordinates, such that $\lambda = 0^{\circ}$ is antisolarward. The lighter curve is the same field data running backward in time such that the two curves agree exactly at day 50, 1700 UT (CENTER). The two crosshatched bars shown above the B-panel indicated regions in which the electron density has been estimated to be below $\sim 10^{-2}$ cm^{-3} (Scarf et al., 1981).

Figure 4 Two sketches representing variations of a model to explain the main features of the magnetic field signature around day 50, 1981 ± 2 days. The core region is shown enclosed by a boundary, and $\bar{B}_{in}$ and B_{out} are external (i.e. wake/sheath) fields; see text.

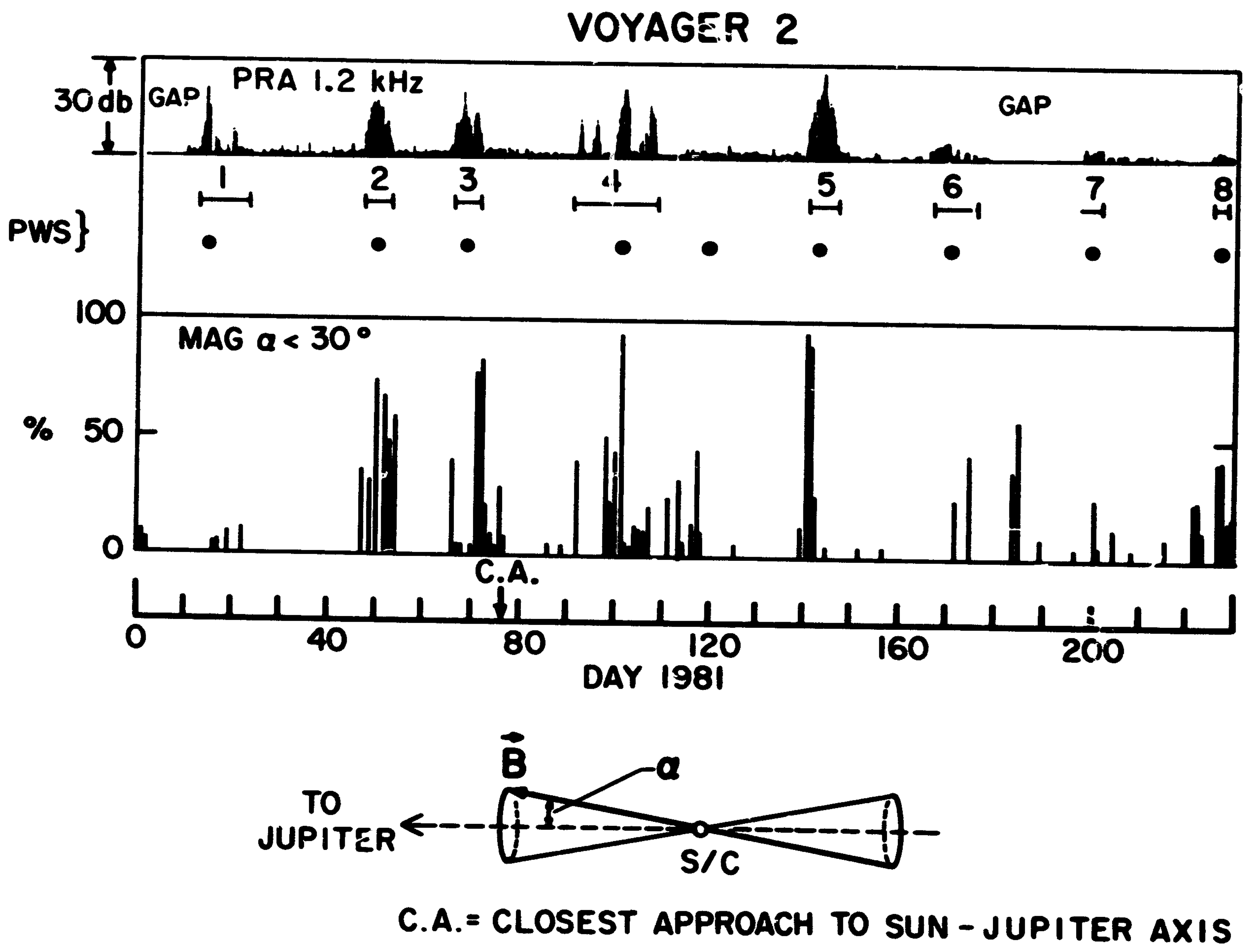
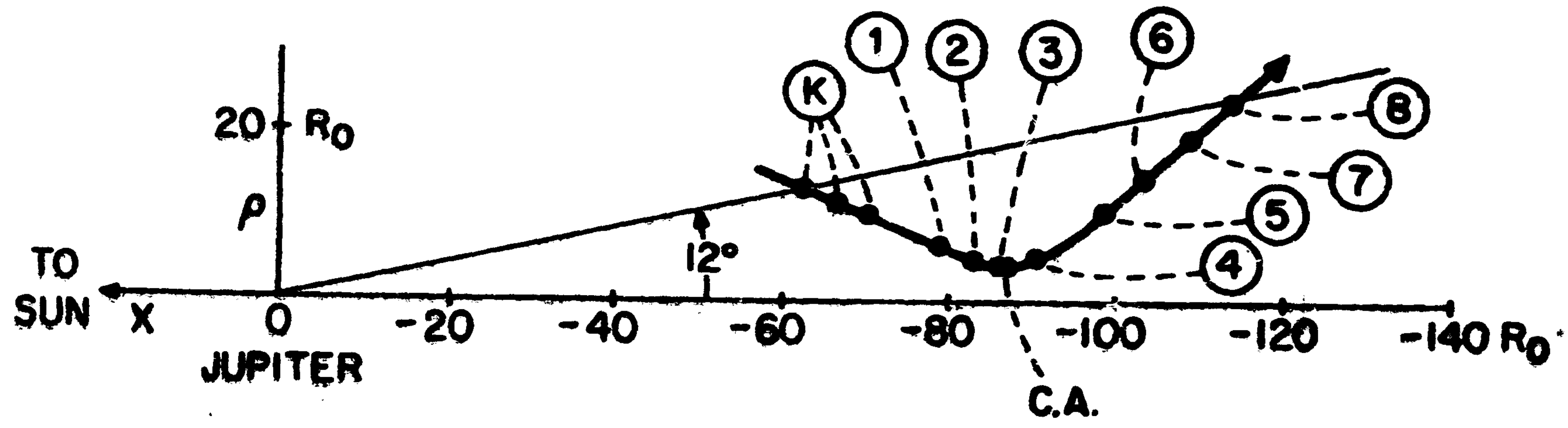

VOYAGER 2
30 db
GAP
PRA 1.2 kHz
GAP
1
2
3
4
5
6
7
8
PWS}
100
MAG α < 30°
%
50
0
C.A.
0
40
80
120
160
200
DAY 1981
B
α
TO JUPITER
S/C
C.A.= CLOSEST APPROACH TO SUN-JUPITER AXIS

Figure 1

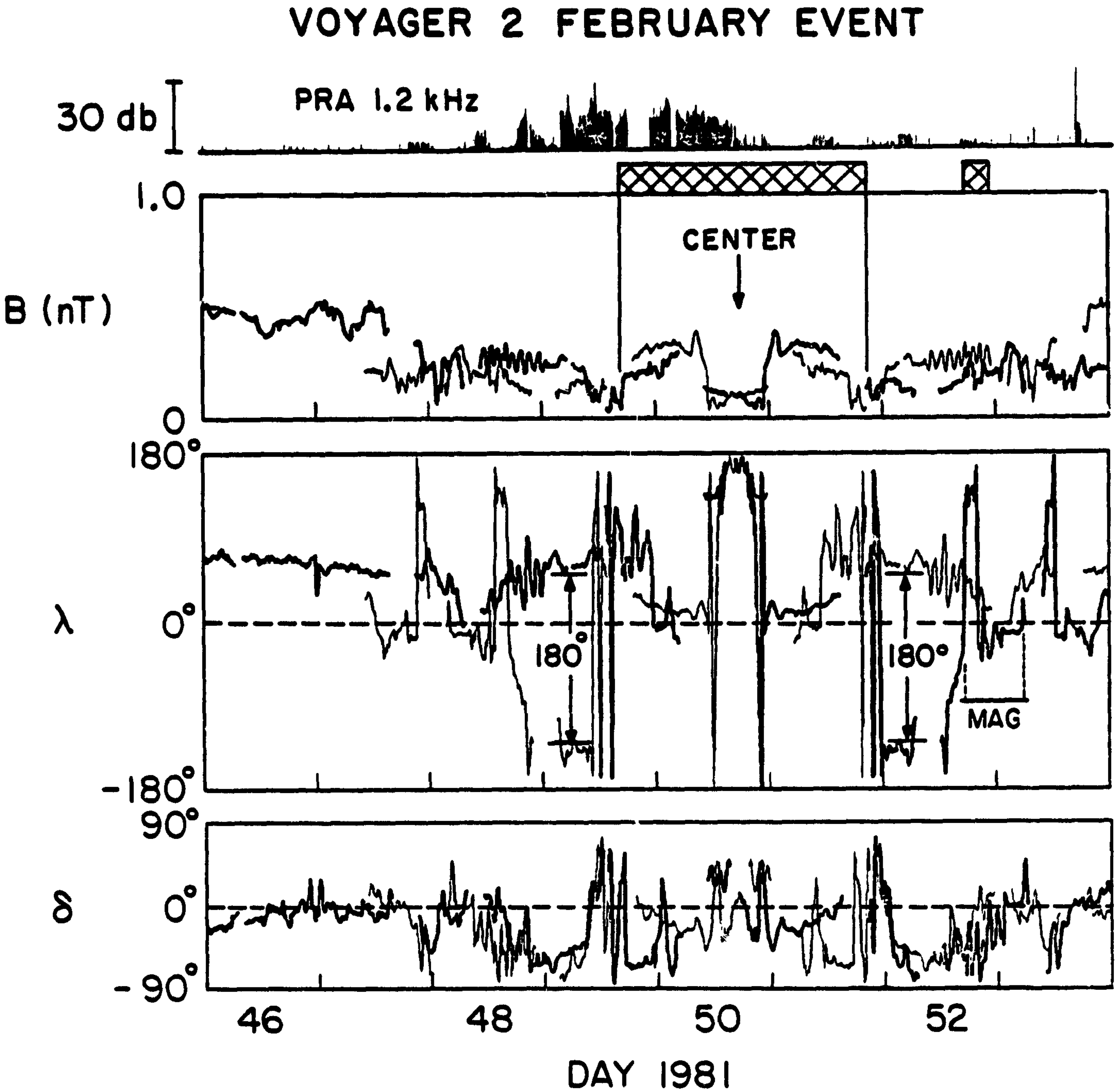
VOYAGER 2 TRAJECTORY



$R_0 = 75\ R_J = 5.4 \times 10^6$ KM

$\rho = \sqrt{Y^2+Z^2} \qquad \rho_{C.A.} = 4.3R_0$

Figure 2

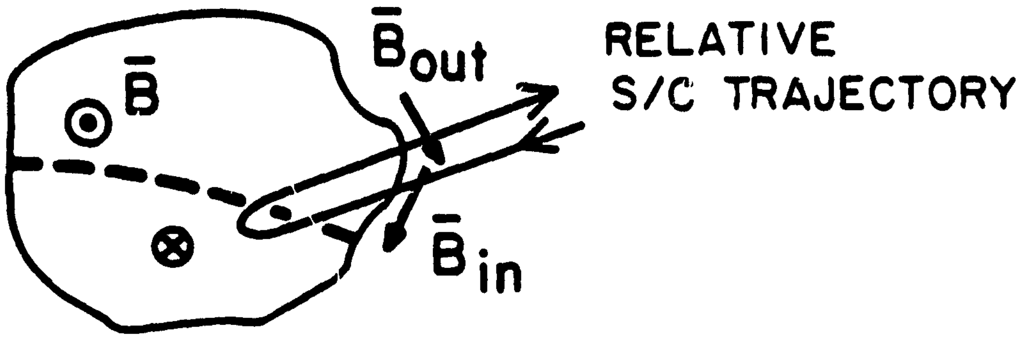


VOYAGER 2 FEBRUARY EVENT
30 db
PRA 1.2 kHz
1.0
B (nT)
0
CENTER
180°
λ
0°
180°
180°
MAG
-180°
90°
δ
0°
-90°
46
48
50
52
DAY 1981

Figure 3

CROSS-SECTION OF TAIL, OR TAIL FILAMENT

TIME SYMMETRY:



(VIEW TOWARD JUPITER)

SPACE SYMMETRY:

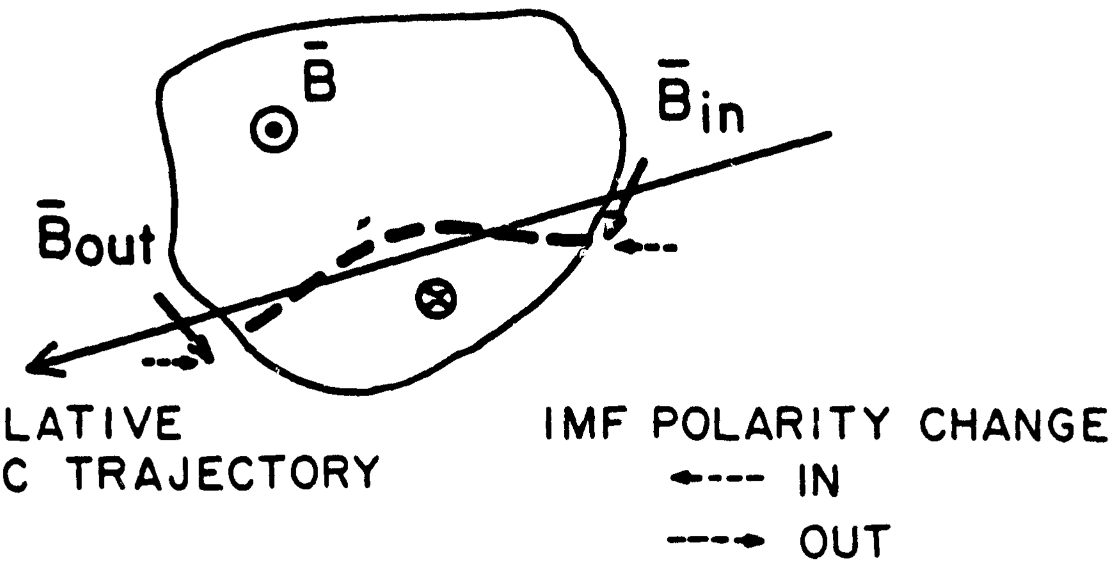


Figure 4