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MAGNETIC CLOUDS BETWEEN 2-4 AU: VOYAGER OBSERVATIONS

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SUBMITTED TO: Solar Physics

ABSTRACT

Magnetic clouds were observed in the solar wind between 2-4 AU by Voyagers 1 and 2, indicating that they are stable enough to persist without major changes out to such distances. The average size in radial extent of the clouds observed at these distances was $\sim$ 0.47 AU, compared to 0.25 for clouds observed at 1 AU. Assuming that these numbers are representative, we estimate that the clouds were expanding at a speed of the order of 45 km/s. This is consistent with the expansion speed derived from the difference of the speeds of the front and rear boundaries of the clouds, $\sim$ 33 km/s. The average Alfvén speed at the front and rear boundaries was 104 km/s, so our estimated expansion speed is nearly half of the Alfvén speed, consistent with an earlier estimate of the expansion speed of clouds between the sun and 1 AU. The magnetic field configuration cannot be determined uniquely, but it is highly ordered and consistent with the passage of some kind of loop. The simple model of a magnetic tongue with magnetic field lines in planes, e.g., meridian planes, is not consistent with the data.

1. Introduction

The existence of ordered interplanetary field configurations with a radial dimension of the order of 0.25 AU at 1 AU, characterized by higher than average field strengths and a rotation of the field vectors parallel to a plane, was demonstrated by Burlaga and Klein (1980) and Burlaga et al. (1981) who called them "magnetic clouds" following an idea proposed by Morrison (1954). A statistical study of magnetic clouds at 1 AU showed that during the period from 1967 to 1978 they occurred at the rate of at least one every three months and that their average radial dimension was 0.25 AU (Klein and Burlaga, 1981).

In magnetic clouds at 1 AU the pressure, principally due to the high magnetic field strengths, is generally higher than the ambient pressure, suggesting that they might be expanding as they move away from the sun. In fact, Klein and Burlaga (1981) argued that between the sun and 1 AU magnetic clouds expand at a rate of approximately one-half of the local Alfvén speed in the directions transverse to $\underset{\sim}{B}$. If this expansion continues beyond 1 AU, one should find that the radial dimension of magnetic clouds beyond 1 AU should be larger than 0.25 AU, assuming that clouds are stable enough to maintain their identity beyond 1 AU. This paper will show that magnetic clouds can persist out to at least 4 AU, and that they probably do expand for some distance beyond 1 AU. The specific configurations of the magnetic field in a magnetic cloud cannot be determined unambiguously with observations from only 1 or 2 spacecraft, but we shall show in section 4 that the data are consistent with some kind of a loop, although not the simple "tongues" suggested by Gold (1959).

We shall discuss data from the GSFC magnetometers and MIT plasma analyzers on Voyagers 1 and 2. The principal investigators of these experiments are N. F. Ness and H. S. Bridge, respectively. We consider the period from launch (September 5, 1977 for Voyager 1 and August 20, 1977 for Voyager 2) to approximately October 1, 1978, during which these spacecraft moved from 1 to $\sim$4 AU. Five magnetic clouds were selected for study (see Table 1), based on completeness of the plasma and magnetic field data sets for Voyagers 1 and 2. Four of these are "typical" magnetic clouds and are described in section 2. The fifth is anomalous in that it occurred behind a stream interface, and it is discussed separately in section 3.

2. Four Magnetic Clouds Between ~2 to ~3.5 AU

Since detailed observations of magnetic clouds have already been published, we shall show a complete set of data for only one of the events, that of February 8-10, 1978, which is representative of the other three. The magnetic field and plasma parameters are shown as a function of time in Figure 1. Magnetic field directions are shown in heliographic (HG) coordinates based on an orthogonal $\hat{R}$ $\hat{T}$ $\hat{N}$ system in which $\hat{R}$ points radially away from the sun, $\hat{T}$ is parallel to the solar equatorial plane pointing in the sense of the motion of the planets, and $\hat{N}$ completes the triad; the angle $\delta = \sin^{-1}(B_N/B)$ and $\lambda = \tan^{-1}(B_T/B_R)$, where $B = |\underset{\sim}{B}|$ and B_N, B_T, B_R are the components of $\underset{\sim}{B}$.

The magnetic cloud is identified by the shaded region in Figure 1, in which δ changes from a large southern direction to a large northern direction, B is higher than the ambient field strength, and the temperature is relatively low. It is generally difficult to identify the front and rear boundaries of a magnetic cloud; in this paper we have chosen them such as to set a lower limit on the size of the cloud when there was any ambiguity. The position in time of the front boundary of the cloud in Figure 1 was selected primarily on the basis of $\delta(t)$; it is the time at which $\underset{\sim}{B}$ began its rotation from an extreme southern direction ($\delta = -63°$) to an extreme northern direction. This point also coincides with the arrival of a large filament in $\lambda(t)$, with a drop in density, and with a drop in temperature. Similarly, the rear boundary was selected as the time at which $\underset{\sim}{B}$ reached its northernmost direction (88°). This time was followed by a 7-hr data gap, after which δ remained large for at least 12 hours, so one could argue that the cloud was larger than we have assumed, but our identification procedure at least gives a lower limit on the cloud size, and it is self-consistent, as will be shown below.

The speed of the magnetic cloud in Figure 1 is approximately the same as that of the ambient medium ahead of the cloud on February 7, indicating that the cloud was not moving relative to the ambient solar wind. On the other hand, the vertical dashed line near the end of February 7 suggests the presence of a shock, since across it B, n, V, and T all increase. This identification is not unambiguous, owing to a data gap, but if it is correct one must consider the possibility that near the sun the cloud moved fast enough relative to the ambient wind to produce a shock. If so, the observation that at 1 AU the cloud is not moving relative to the surrounding medium implies that it decelerated somewhere between the sun and 1 AU.

The remarkable order of the magnetic field directions which is characteristic of magnetic clouds is best illustrated by plotting components of $\underset{\sim}{B}$ in a "minimum variance" coordinate system, as illustrated in Figure 2 for the February, 1978, event. The method of Sonnerup and Cahill (1967) is used to find a plane which best-fits the vectors $\underset{\sim}{B}_i - \langle\underset{\sim}{B}\rangle$, i.e., a direction $\hat{z}$, (normal to the plane) in which the component of $\underset{\sim}{B}$ is minimal. An eigenvalue ratio $E_2/E_3 > 2$ (where E_2 and E_3 are the intermediate and minimum eigenvalues, respectively) generally indicates the difference vectors lie close to a plane. Figure 2 shows that for the February, 1978, event there was possibly a small, constant component of $\underset{\sim}{B}$ along $\hat{z}$, while the other component changed by rotating with its tip tracing an arc as the cloud was convected past the spacecraft. The direction of minimum variance, $\hat{z}$, is given by the angles $\lambda_n = 7°$, $\delta_n = 25°$ for Voyager 1 and $\lambda_n = -1°$, $\delta_n = 15°$ for Voyager 2. Since the uncertainties are typically of the order of 10° for $E_2/E_3 > 2$, we conclude that the two spacecraft observed essentially the same magnetic field configuration. Their separation was relatively small (< 0.14 AU).

Parameters describing some dynamical characteristics of the February 1978 magnetic cloud are shown in Figure 3. The pressure, $P_T = B^2/(8\pi) + nkT_p$, shown in the middle panel is higher inside the cloud than in the ambient medium which passed the spacecraft on February 7, suggesting that the magnetic cloud might still be expanding even at $\sim$ 2 AU. The pressure which drives the expansion is principally magnetic pressure, as indicated by the lower panel of Figure 3 which shows $\beta = nkT_p/(B^2/(8\pi))$. The momentum flux in the cloud was for the most part lower inside the cloud than outside (top panel in Figure 3), consistent with our earlier suggestion that the cloud might have decelerated as it moved through the solar wind. The momentum flux is low because the density in the cloud is low. Near the sun the speed and density of the cloud might have been high relative to the ambient medium, but expansion would reduce the density and hence the momentum flux, and the stream would then decelerate until its relative motion was zero.

Three other magnetic clouds, observed between ~ 2 AU and ~ 3.5 AU, are shown in Figure 4. The common features are the south to north variation of $\underset{\sim}{B}$ and the relatively high field strengths. As was the case for the February 7 cloud, the front boundary was chosen as the time at which the field left its southernmost direction, and the rear boundary was chosen as the time at which the field arrived at the northernmost direction. One could argue that some of the clouds are larger than indicated, but our definition is at least consistent for all the events, and it gives a lower limit on the radial extent of each cloud.

The positions of the front and rear boundaries of the four magnetic clouds described above are shown in Figure 5, as well as that of an additional cloud which was observed in September 1978 and is discussed in the next section. Each event is shown as a snapshot at the indicated time, which is the time (t_1) that the front boundary passed Voyager 1. The radial position (R_2) of the front boundary at the longitude of Voyager 2 was determined from its arrival time (t_2) at the spacecraft and its measured speed (V); in particular, it was plotted on the sun-Voyager 2 line at a distance $R_1-V(t_2-t_1)$ from the sun, where R_1 is the radial distance of Voyager 1 at t_1. The positions of the rear boundaries in Figure 5 were computed similarly from the times that they passed the spacecraft and from the measured speeds.

The radial extent (ΔR) of each cloud, i.e., the distance between the front and rear boundary, is given in Table 1, which shows three results:

1) there is good agreement among the Voyager 1 and 2 results for ΔR, the difference being 0.06 AU on average and less than < 0.15 AU in every case;

2) no value of ΔR is $\leq$ 0.25 AU, the smallest being 0.34 AU; and

3) the average ΔR = 0.47 (± 0.06) AU.

Thus, these magnetic clouds are larger than the average ΔR measured at 1 AU by Klein and Burlaga (1981), viz. 0.25 AU, and we may conclude that, if our sample is representative, magnetic clouds do expand beyond 1 AU.

Taking the average position of the four clouds as 2.5 AU, and the mean speed as 484 km/s (the average of the speeds at the front and rear boundaries), and assuming that their average size at 1 AU was 0.25 AU, we estimate that their expansion speed in the radial direction was of the order $V_e \sim 45$ km/s. If the center of a cloud moves at a speed V_0 and it expands radially at a speed V_e, then one might expect the speed of the front boundary ($V_f = V_0 + V_e$) to exceed that of the rear boundary ($V_r = V_0 - V_e$). This is the case for the clouds we are considering, the average V_f being 517 km/s and the average V_r being 451 km/s. The difference should be $\sim 2\,V_e$, which gives a second estimate of the expansion speed, viz. $V_e \sim 33$ km/s, which compares favorably with the estimate of 45 km/s based on cloud size and transit time. The average Alfvén speed at the front and rear boundaries is 104 km/s. Thus expansion speeds estimated are close to half of the average Alfvén speed. This is consistent with the result of Klein and Burlaga (1981), who estimated that the characteristic expansion speed between the sun and 1 AU is of the order of $V_A/2$.

The observations in Figure 5 place some weak constraints on the shapes of the clouds. A lower limit on their longitudinal extent, a few degrees, is given by the separation of the radial dashed lines in Figure 5. Information about the orientations of the front and rear boundaries is given by the solid line segments connecting the Voyager 1 points with the Voyager 2 points. One sees that the front and rear boundary surfaces may be inclined appreciably with respect to the radial direction, either eastward or westward.

3. Magnetic Cloud Following an Interface

Klein and Burlaga (1981) found that ∼ 30% of the magnetic clouds at 1 AU were associated with corotating stream interfaces. These clouds were all ahead of the interface, never behind, suggesting that they are transient events, possibly swept up by streams, rather than features of stationary corotating streams. However, Voyagers 1 and 2 observed one magnetic cloud behind what appears to be an interface; that cloud is the subject of this section.

The event is shown in Figure 6 where data are from both Voyagers are plotted with a small time shift relative to one another, determined by looking for a "best-fit" of $\delta(t)$ and $\lambda(t)$ between the two spacecraft, which is consistent with the corotation delay. The feature that we identify as a stream interface is shown by the vertical dashed line on September 23 in Figure 6. It unfortunately occurs in a data gap, but we infer the presence of an interface in the gap on the basis of the high magnetic field strengths on either side, the decrease in density and the increase in temperature. This identification is strengthened by the observation of a reverse shock behind the interface, for reverse shocks are usually associated with an interface and corotating stream beyond ∼ 2 AU, and they are rarely associated with the transient flows. There is also evidence of a forward shock ahead of the interface (although this is in a data gap), which is expected to occur in front of a corotating flow with a reverse shock and an interface. It is of interest to note that the reverse shock observed by Voyager 1 appears to be farther from the interface than that observed by Voyager 2, consistent with the fact that Voyager 1 was farther from the sun than Voyager 2.

The magnetic cloud is indicated in Figure 6 by the shaded area in the $\delta(t)$ profile, demonstrating the familiar south to north variation over nearly 5 days. A minimum variance analysis showed a well-defined minimum-variance direction (see Table 2), and the magnetic field rotated smoothly in the maximum variance plane. The field strength in the cloud is high with respect to that observed ahead of the interaction region. The density is lower inside the cloud than ahead of the interaction region, but the temperature is not low. Thus, except for the temperature, the shaded region in Figure 6 looks in every respect like a magnetic cloud, even though it seems to occur in a stream behind an interaction region bounded by forward and reverse shocks and containing an interface.

The presence of a magnetic cloud behind a stream interface presents a problem, since corotating streams are stationary or at least quasi-stationary, implying that the magnetic field should be directed along a spiral in the equatorial plane ($\delta = 0$), whereas the magnetic field in the cloud is directed out of the plane for the most part. The discrepancy could be explained in at least two ways. One might imagine that the stream producing the interaction region was sharply bounded in latitude, lying slightly above (or below) the latitudes of Voyagers 1 and 2. The interaction region and shocks, being pressure waves, might still be observed since they can propagate away from the stream. In particular they might propagate into a cloud with an origin independent of that of the corotating flow. Another possible explanation of the occurrence of cloud behind an interface is that there is only one flow, a corotating flow, but reconnection has occurred in the stream giving the "loop-like" configurations that is obseved. Both of these suggestions are speculative, and one might imagine other explanations as well.

4. Magnetic Field Configuration

Although we cannot uniquely determine the global magnetic field configuration in a magnetic cloud with data from just two spacecraft, we can put some strong constraints on the possible patterns. Near the front of the cloud, the field is directed southward at a large angle with respect to the equatorial plane while near the rear of the magnetic cloud, $\underset{\sim}{B}$ is directed northward at a large angle as represented schematically by the top panel in Figure 7. The field vector rotates parallel to the plane as the cloud moves past the spacecraft, and at some point it is parallel to the equatorial plane. The relative position of this point is shown in Figure 5 as an open circle. The dotted line joining the corresponding open circles for Voyagers 1 and 2 is approximately parallel to the actual field directions, and this is represented schematically in the bottom panel of Figure 7. Finally, the minimum variance directions given in Table 2 and shown by the arrows in Figure 5, are normal to the planes in which $\underset{\sim}{B}$ rotates. Figure 7 shows that these planes tend to be parallel to the front and rear boundaries of the magnetic clouds, and they are inclined with respect to the meridional planes.

Hypothetical magnetic loops are often drawn as curves in meridional planes, but, this configuration is not consistent with the above observations. Referring to Figure 8a, one sees that it implies a minimum variance direction perpendicular to the radial direction ($\hat{R}$) whereas it is observed to be more nearly along $\hat{R}$. Moreover, this picture implies that $\underset{\sim}{B}$ should be nearly along $\hat{R}$ when it is parallel to the equatorial plane, whereas Figure 5 shows that it is more nearly orthogonal to $\hat{R}$.

One magnetic field configuration that is consistent with the observations is shown in Figure 8b. In this picture the magnetic field lines remain connected to the sun, and any given field line lies in a plane, but different field lines lie in different planes. One can also imagine a magnetic field configuration with no connection to the sun, in which each field line is closed and lies in a plane, with different field lines in parallel planes whose normals are nearly (but not exactly) along $\hat{R}$ (Figure 8c).

5. Summary and Conclusions

Magnetic clouds, initially studied at 1 AU, have been observed and analyzed at greater heliocentric distances using observations from Voyagers 1 and 2 at distances of 2-4 AU. The clouds observed by the Voyager spacecraft were found to have the same well-order variation in field direction as those previously studied. As in the 1 AU investigations, the clouds were identified by a rotation of the field nearly parallel to a plane from an extreme southward to an extreme northward orientation or vice versa. The five Voyager cases studied all had south to north variations. The clouds are defined on the basis of a large rotation of field direction, and Figure 2 suggests that, in some cases at least, the rotation might be greater than 180° (see Voyager 2 data).

The clouds in this study were found to be characterized, as before, by higher than ambient (pre- and post-cloud) field strengths and generally lower than ambient plasma density, temperature and momentum flux. These observations, together with the estimates of the radial extent of the clouds, suggest that the clouds were continuing to expand, even at distances of 2 AU or greater. The average radial size was estimated to be 0.47 AU, compared with 0.25 AU at 1 AU. The expansion speed was estimated to be nearly half the average Alfvén speed, consistent with the 1 AU results. One of the five clouds studied was located behind a stream interface, suggesting that it had been swept up by a corotating stream.

It is not yet clear what sort of large-scale field geometry to attribute to the magnetic clouds. Some possibilities are shown in Figure 8. The cloud observations to date tend to indicate a remarkable uniformity of structure among magnetic clouds, whereas possible source structures observed near the sun in association with mass ejection events suggest a variety of initial field configurations, as previously summarized by Klein and Burlaga (1981). These include magnetic loops which maintain their connection to the sun (Gosling et al., 1974) and can appear as a group of loops that begin as a canopy over a prominence and subsequently expand and accelerate upward through the outer corona (Rust and Hildner, 1976); loops in which the outer extremity becomes detached, forming a separate bubble (only a few cases actually observed) (Rust et al., 1979); and confinement of ejecta by helical fields in flux tubes that expand away from the sun (Rust et al., 1979). An understanding of how such magnetic field configurations evolve in the solar wind may be necessary for the correct interpretation of the field structure in magnetic clouds.

Acknowledgments

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Sonnerup, D. U. O., and Cahill, L. J.: 1967, J. Geophys. Res., 72, 171.

TABLE 1. MAGNETIC CLOUDS, 1978

NAME	S/C	START TIME DAY, HR	END TIME DAY, HR	"SIZE" ΔR (AU)
A	V1	39,20	41,19	0.42
	V2	39,20	41,11	0.43
B	V1	66,8	68,11	0.51
	V2	66,2	68,2	0.49
C	V1	121,11	123,4	0.59
	V2	121,5	122,20	0.53
D	V1	153,18	155,7	0.39
	V2	153,4	154,15	0.37
E	V1	267,13	272,2	1.03
	V2	266,7	270,14	1.03

TABLE 2. MAGNETIC CLOUDS - MINIMUM VARIANCE RESULTS

NAME	S/C	E_2/E_3	B_z/B	$\hat{n}_\lambda$	$\hat{n}_\delta$
A	V1	6.7	0.34	7°	25°
	V2	26.6	0.23	-1°	15°
B	V1	10.2	0.12	-10°	-19°
	V2	5.3	0.23	-20°	-15°
C	V1	7.7	0.27	21°	-14°
	V2	6.1	0.52	28°	-29°
D	V1	8.4	0.08	2°	9°
	V2	4.2	0.16	-12°	16°
E	V1	7.9	0.27	-10°	-7°
	V2	1.7	0.09	16°	-21°

FIGURE CAPTIONS

FIGURE 1 Magnetic field and flow parameters associated with a magnetic cloud observed by Voyager 2. The extent of the cloud, as indicated, is defined by the systematic variation of the latitude angle, δ, of $\underset{\sim}{B}$ from large negative values to large positive values. The cloud is colder and less dense than surrounding flows.

FIGURE 2 The variation of $\underset{\sim}{B}$ in the magnetic cloud shown in Figure 1, as seen at both Voyager 1 (left) and Voyager 2 (right). The data are plotted in the principal axis coordinate system, where Z is along the direction of minimum variance, and X and Y define the plane of maximum variance. The rotation of the field through a large angle in this tranverse plane is shown in the upper panels, while the small and relatively constant component of $\underset{\sim}{B}$ along the Z-axis is given below. Also given are the inclusive day-of-year numbers with start and stop hours at each spacecraft, and the longitude λ_n and latitude δ_n of the minimum variance direction at each relative to heliographic coordinate axes.

FIGURE 3 Additional parameters relating to cloud dynamics for the cloud shown in Figure 1. Shown are the momentum flux (top), total pressure (middle) and plasma beta (lower panel) (see text).

FIGURE 4 Magnetic field characteristics of three additional magnetic clouds observed by both Voyagers 1 and 2 during March (top), May (middle) and June (bottom), 1978. Note the similar variations of $\underset{\sim}{B}$ and δ in particular, which help to define the clouds and their extent.

FIGURE 5 Minimum estimated radial extent of five magnetic clouds observed by Voyagers 1 and 2 in 1978. The locations of the front and rear boundaries of the clouds in the heliographic equatorial plane on the given dates are illustrated. Also given are the minimum variance directions for each cloud and spacecraft at the times that $\underset{\sim}{B}$ was parallel to the equatorial plane. The average radial size of a cloud at 1 AU is also shown for comparison.

FIGURE 6 Magnetic field and flow parameters for a magnetic cloud observed by Voyagers 1 (solid curve) and 2 (dashed curve) behind a stream interface. This was the only cloud of the five studied which was located in the vicinity of an interface.

FIGURE 7 Schematic representation of the observed magnetic field characteristics of magnetic clouds.

FIGURE 8 a) and c) Possible field geometries for detached "magnetic bubbles"; b) Possible geometry for extended loops attached to the sun. The configuration a) is not admissible because it requires a normal direction and a field orientation that are not consistent with observations (see text).

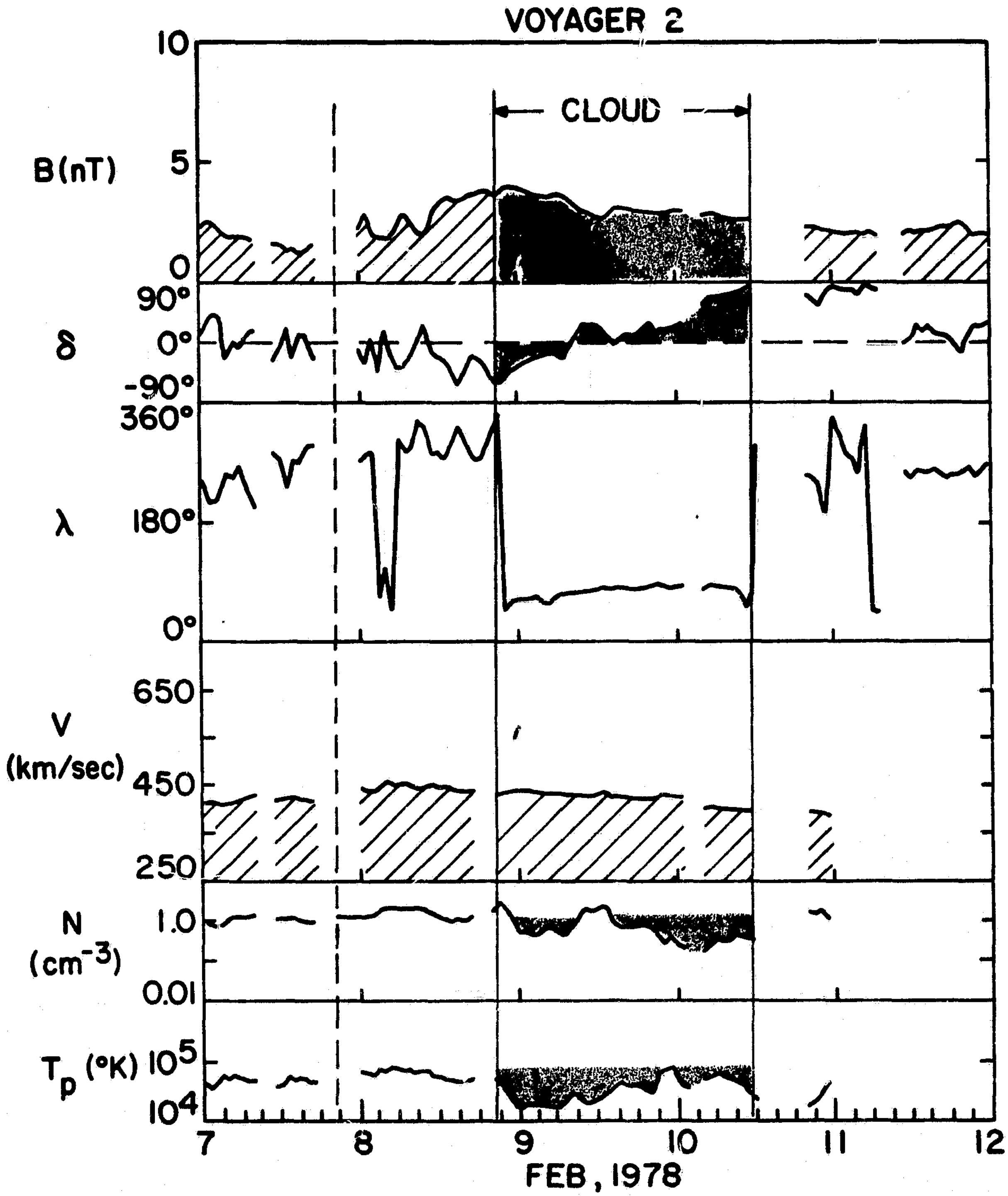

VOYAGER 2
CLOUD
B(nT)
10
5
0
δ
90°
0°
-90°
λ
360°
180°
0°
V
(km/sec)
650
450
250
N
(cm^{-3})
1.0
0.01
T_p (°K)
10^5
10^4
7
8
9
10
11
12
FEB, 1978

Figure 1

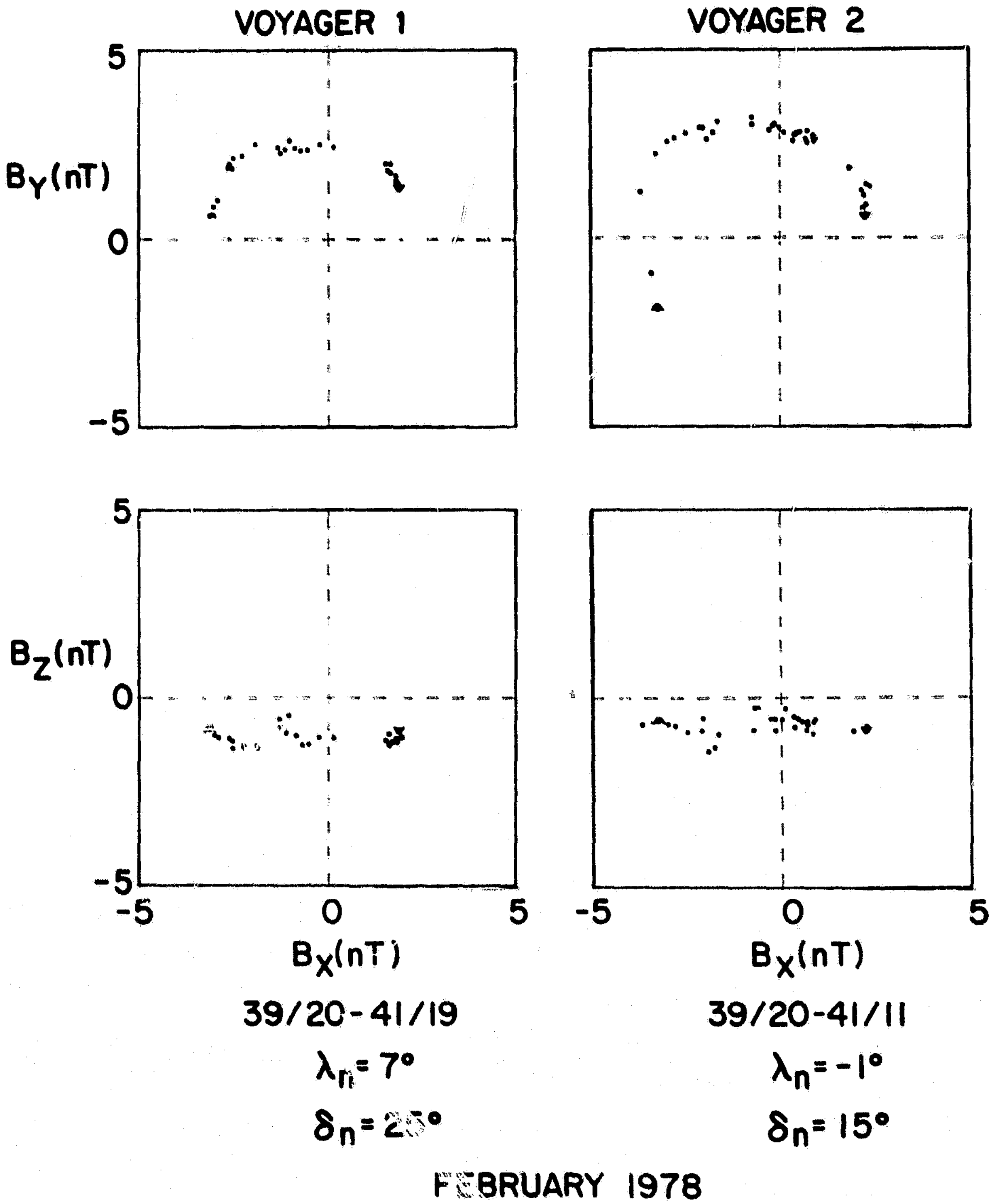
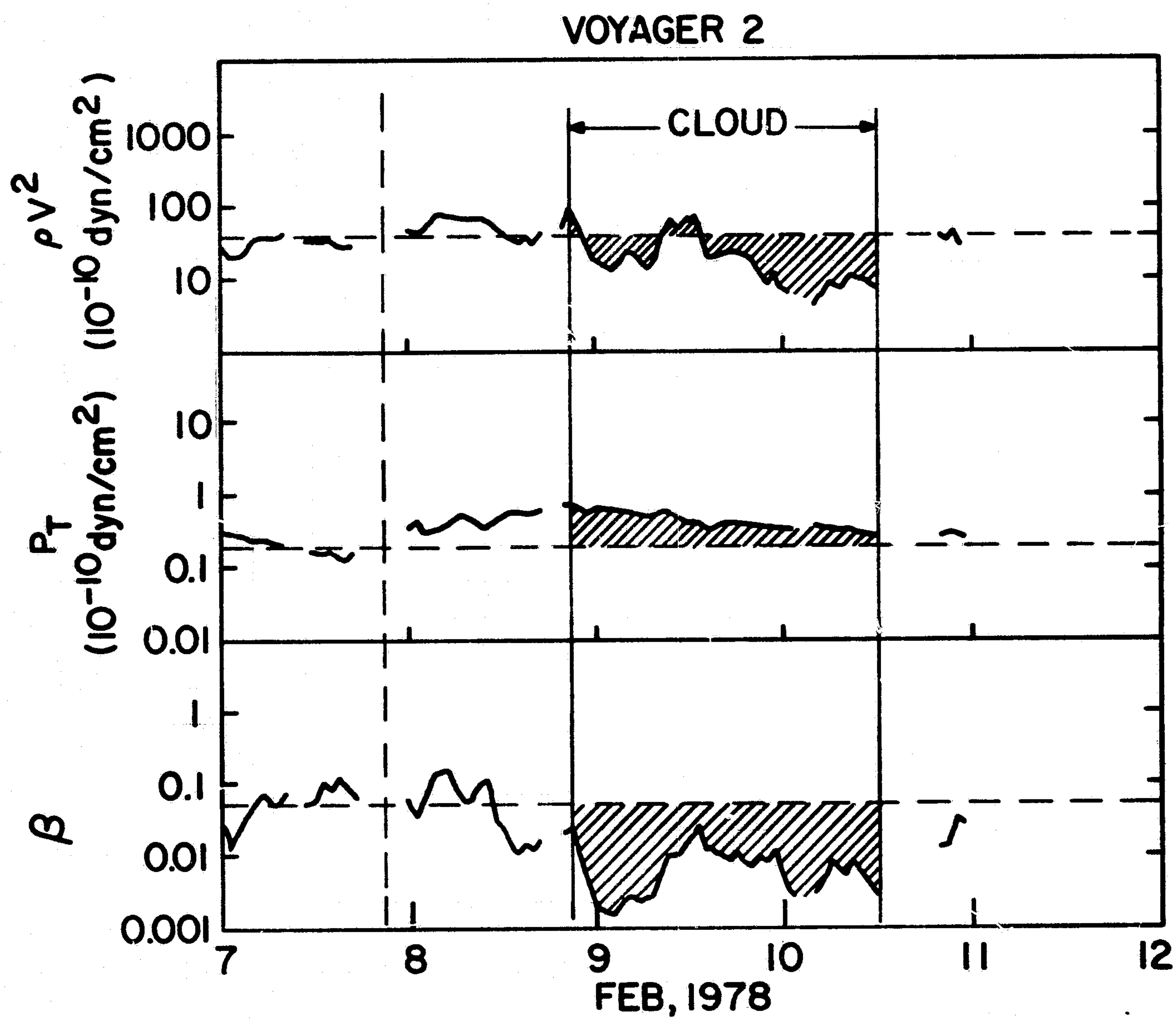
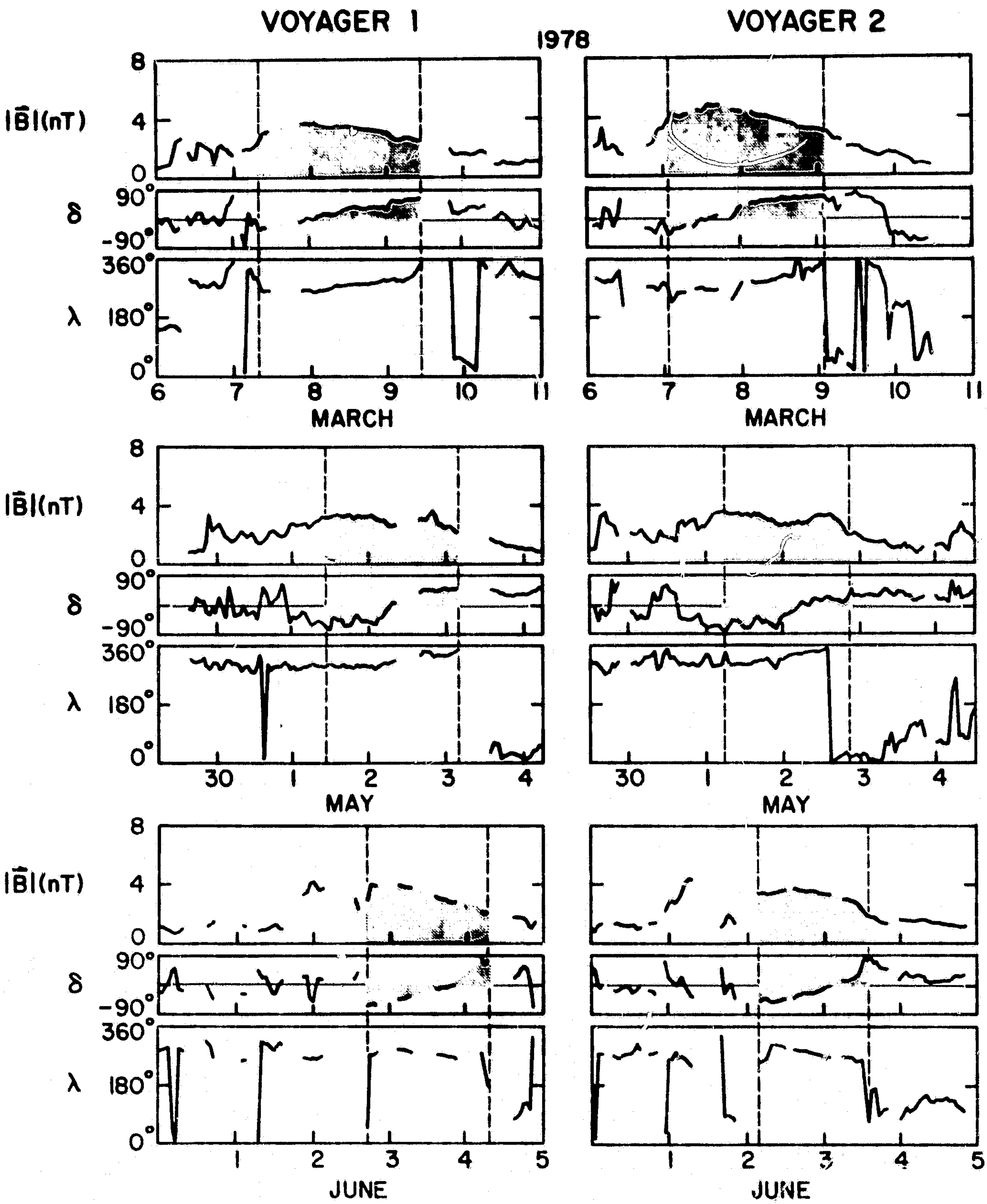

VOYAGER 1
VOYAGER 2
BY(nT)
BZ(nT)
5
0
-5
-5
0
5
BX(nT)
BX(nT)
39/20-41/19
λn= 7°
39/20-41/11
λn= -1°
δn= 15°
FEBRUARY 1978

Figure 2



VOYAGER 2
CLOUD
ρV^2 $(10^{-10}$ dyn/cm$^2)$
1000
100
10
P_T $(10^{-10}$ dyn/cm$^2)$
10
1
0.1
0.01
β
1
0.1
0.01
0.001
7
8
9
10
11
12
FEB, 1978

Figure 3



VOYAGER 1
1978
VOYAGER 2
|B|(nT)
δ
λ
8
4
0
90°
-90°
360°
180°
0°
6
7
8
9
10
11
MARCH
30
1
2
3
4
MAY
1
2
3
4
5
JUNE

Figure 4

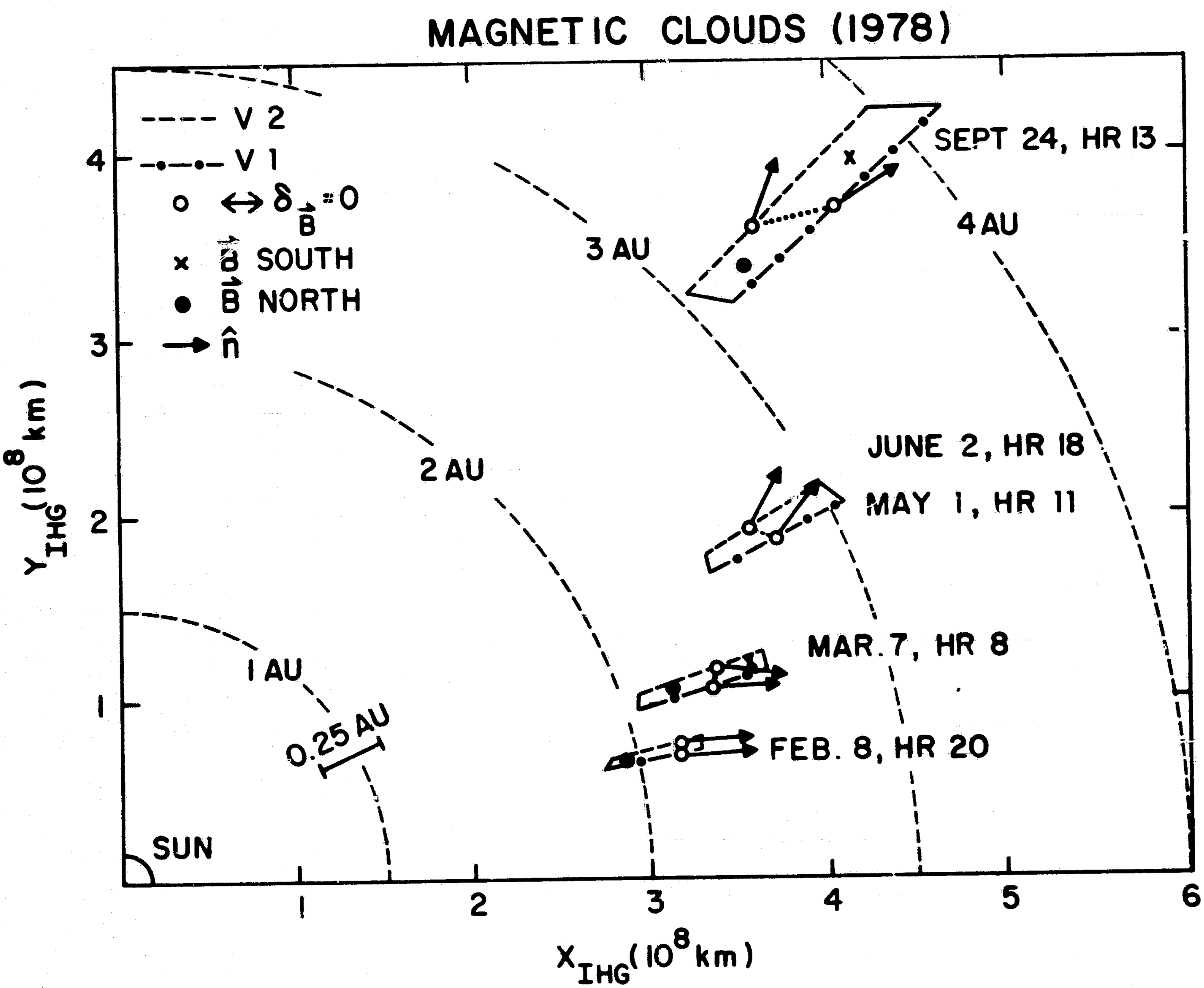

MAGNETIC CLOUDS (1978)
V 2
V 1
$\leftrightarrow \delta_{\vec{B}} = 0$
$\vec{B}$ SOUTH
$\vec{B}$ NORTH
$\hat{n}$
SEPT 24, HR 13
JUNE 2, HR 18
MAY 1, HR 11
MAR. 7, HR 8
FEB. 8, HR 20
1 AU
2 AU
3 AU
4 AU
0.25 AU
SUN
X_{IHG} (10^8 km)
Y_{IHG} (10^8 km)
1
2
3
4
5
6

Figure 5

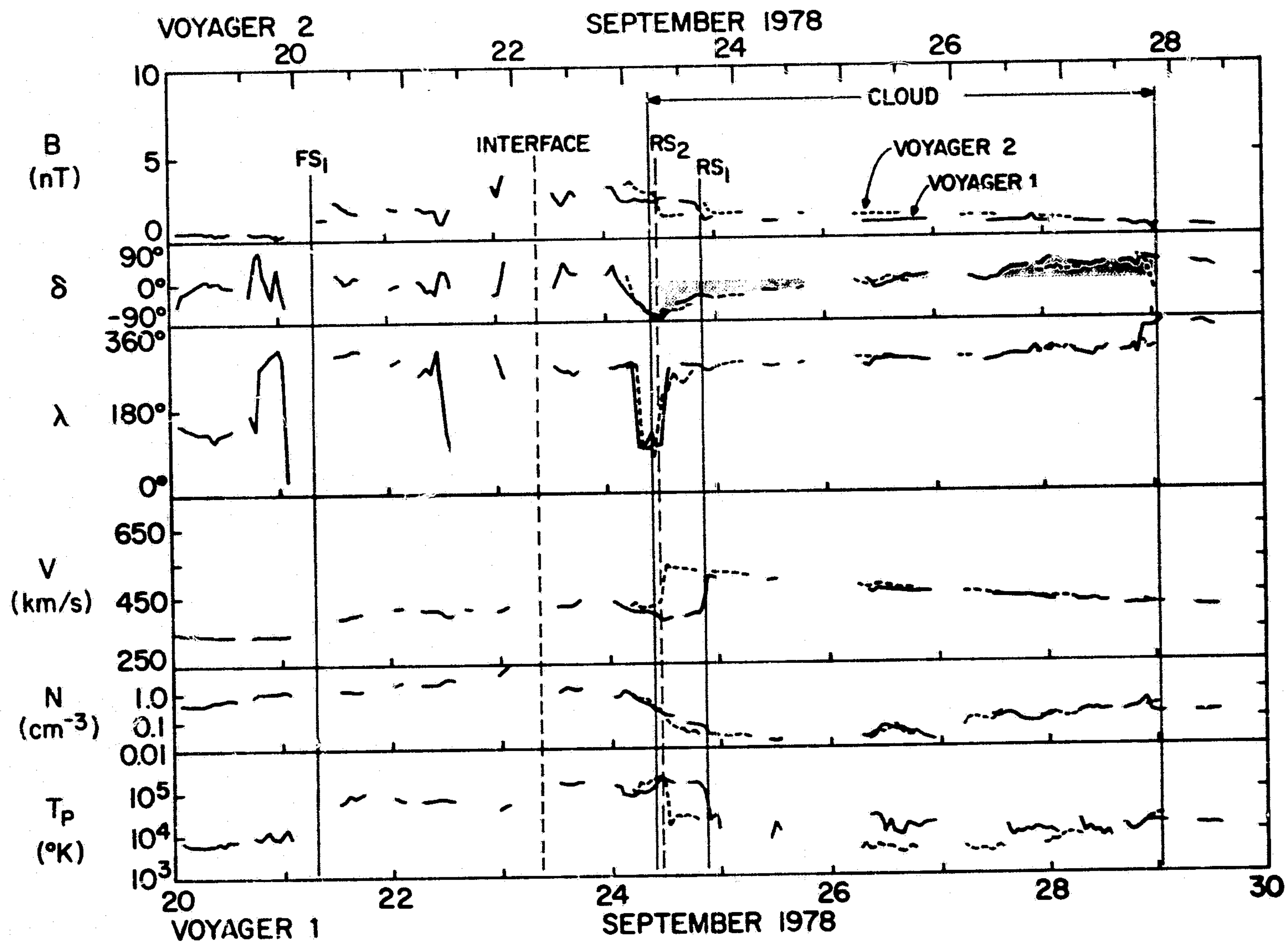

VOYAGER 2
SEPTEMBER 1978
20
22
24
26
28
CLOUD
B
(nT)
10
5
0
FS1
INTERFACE
RS2
RS1
VOYAGER 2
VOYAGER 1
δ
90°
0°
-90°
λ
360°
180°
0°
V
(km/s)
650
450
250
N
(cm-3)
1.0
0.1
0.01
Tp
(°K)
10^5
10^4
10^3
20
22
24
26
28
30
VOYAGER 1
SEPTEMBER 1978

Figure 6

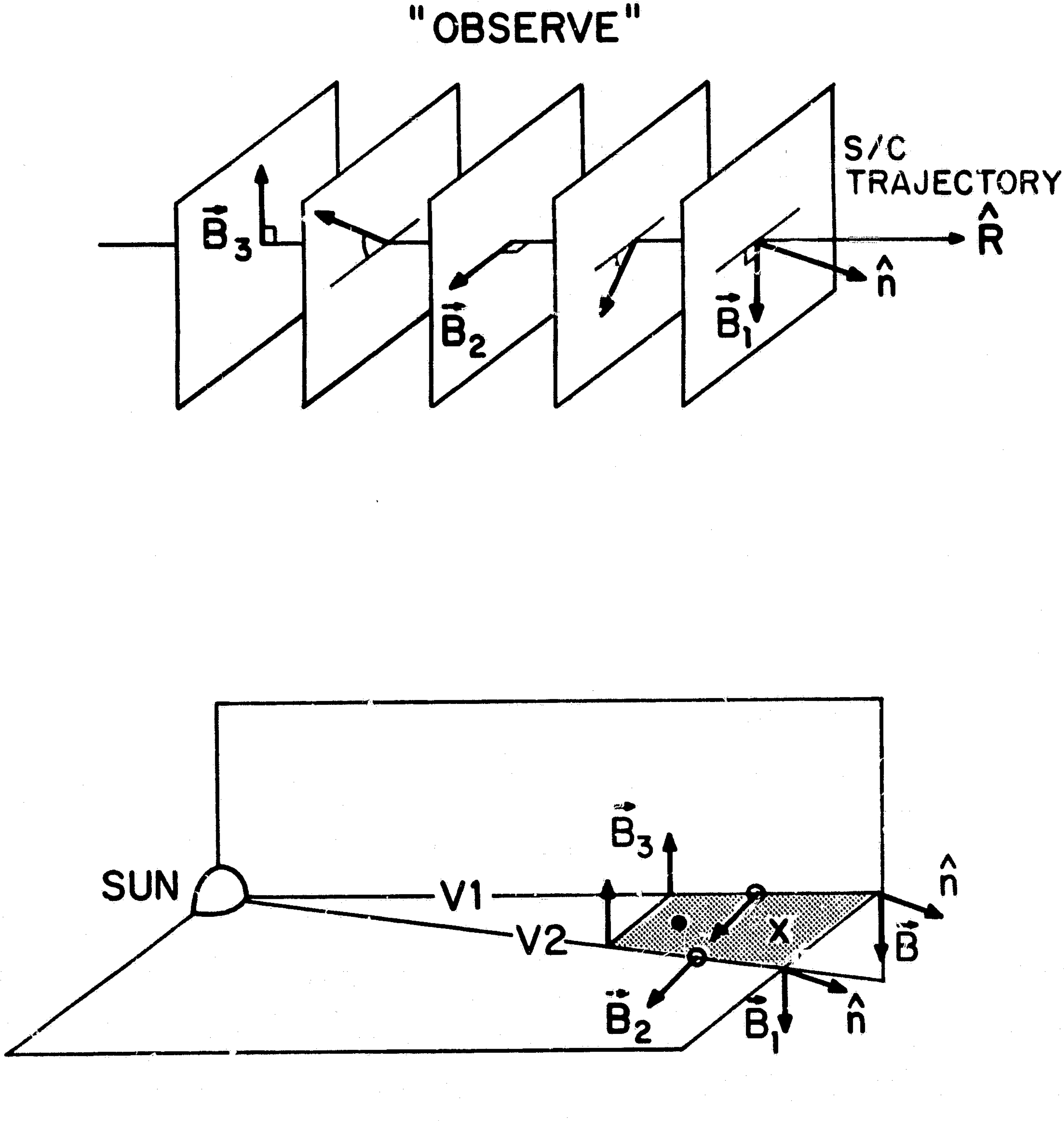

"OBSERVE"
S/C
TRAJECTORY
$\hat{R}$
$\vec{B}_3$
$\vec{B}_2$
$\vec{B}_1$
$\hat{n}$
SUN
V1
V2
$\vec{B}_3$
$\hat{n}$
X
$\vec{B}$
$\vec{B}_2$
$\vec{B}_1$
$\hat{n}$

Figure 7

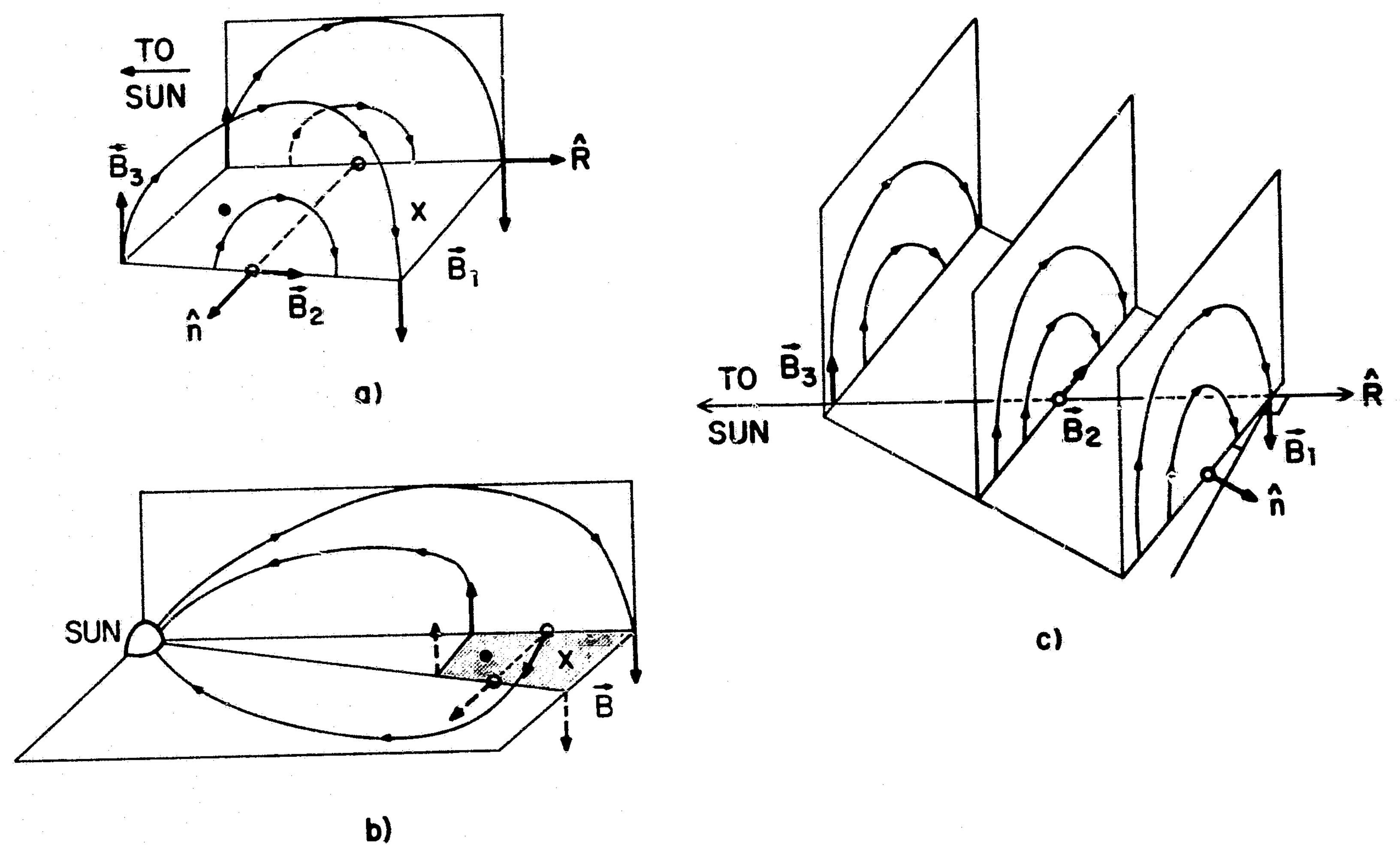

TO
SUN
$\vec{B}_3$
$\hat{R}$
X
$\vec{B}_1$
$\hat{n}$
$\vec{B}_2$
a)
SUN
X
$\vec{B}$
b)
TO
SUN
$\vec{B}_3$
$\vec{B}_2$
$\vec{B}_1$
$\hat{R}$
$\hat{n}$
c)

Figure 8