(NASA-TM-80668) MAGNETIC CLOUDS IN THE SOLAR WIND (NASA) 17 p HC A02/MF A01 CSCL 03B

N80-22221

Unclas
G3/92 18129

NASA

Technical Memorandum 80668

Magnetic Clouds In The Solar Wind

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MARCH 1980

National Aeronautics and
Space Administration

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MAGNETIC CLOUDS IN THE SOLAR WIND

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Submitted to: Geophysical Research Letters

ABSTRACT

Two interplanetary "magnetic clouds", characterized by anomalous magnetic field directions and unusually high magnetic field strengths with a scale of the order of 0.25 AU, are identified and described. As the clouds moved past a spacecraft located in the solar wind near Earth, the magnetic field direction changed by rotating $\approx 180^\circ$ nearly parallel to a plane which was essentially perpendicular to the ecliptic. The configuration of the magnetic field in the clouds might be that of a tightly-wound cylindrical helix or a series of closed circular loops. One of the magnetic clouds was in a cold stream preceded by a shock, and it caused both a geomagnetic storm and a depression in the galactic cosmic ray intensity. No stream, geomagnetic storm or large cosmic ray decrease was associated with the other magnetic cloud.

Introduction

The existence of unusual magnetized clouds of plasma emitted by the active sun was proposed by Morrison (1954) as a cause of world-wide decreases in cosmic ray intensity, lasting for days and correlated roughly with geomagnetic storms. Cocconi et al. (1958) proposed that the magnetic field in such a cloud has the form of an extended loop, the field lines being anchored in the sun, and they called such a loop an "elongated tongue" and a "magnetic bottle". A similar concept was discussed more quantitatively by Piddington (1958), who also considered the additional possibility that a loop could become detatched from the sun by magnetic field reconnection, forming closed magnetic field lines in the solar wind (a magnetic "bubble"). Gold (1959) proposed that the magnetic loop might be preceded by a shock wave (see also Gold, 1955). All of these authors envisaged that the magnetic cloud is formed by motion of plasma ejected from a flare or some other transient solar disturbance. None of these authors was very specific about the 3-dimensional configurations of the loops or bubbles.

Direct evidence for magnetic loops or bubbles has been elusive (see Hundhausen, 1972). Indirect, statistical evidence suggestive of closed magnetic field lines (i.e., magnetic bubbles) behind shock waves was presented by Montgomery et al. (1974) and Gosling et al. (1973). This was based on the observation of low temperatures behind shocks; they presented no magnetic field observations. Statistical evidence for magnetic loops behind shocks was presented by Pudovkin et al. (1977, 1979) based on the magnetic field data compiled by King (1977); however, they did not consider the plasma observations. In a different kind of statistical study, Rosenberg and Coleman (1980) suggested that a magnetic "loop" might be formed in the interaction region between shock pairs in front of a stationary, corotating stream. Similarly, Akasofu (1979) suggested that large north-south components of $\underset{\sim}{B}$, like those associated with magnetic loops, could be produced by the distortion of sector boundaries ahead of stationary corotating streams. It is likely, however, that the data of Rosenberg and Coleman (1980) and Akasofu (1979) included transient as well as corotating flows. Bobrov (1979) noted that in some flare-associated streams one component of $\underset{\sim}{B}$, viz. that parallel to the earth's geomagnetic equator, varies systematically in a way which he suggested is consistent with a closed magnetic loop in that plane.

The purpose of this letter is to present direct evidence for the existence of a class of magnetic clouds in which the magnetic field vector rotates nearly parallel to a plane. We consider all components of $\underset{\sim}{B}$, and we determine the orientation of the cloud plane by a minimum variance analysis. Both magnetic field and plasma observations for two such planar magnetic clouds are presented, and it is shown that magnetic clouds can occur in the absence of fast streams.

A Magnetic Cloud in a Stream Behind a Shock

Figure 1 shows a plot of hour-averages of the magnetic field strength (F), magnetic field latitude (θ) and longitude (ϕ) in solar ecliptic coordinates, bulk speed (V), density (n), and proton temperature (T) versus time for the period February 9 to February 14, 1969. In the middle of this interval (between the lines marked B and D) one can see a distinctive structure with the following characteristics: 1) the magnetic field direction changes slowly from a southward to a northward orientation and it is nearly perpendicular to the nominal spiral direction in the region where $\theta \sim 0$; the magnetic field strength is unusually high for a relatively long time (F > 10 nT for 36 hr) and it is largest near the middle of the structure; 2) the temperature is unusually low; and 3) the speed is relatively high, especially near the front of the structure, indicating the presence of a small stream, and it decreases monotonically in the region between B and D; 4) the density decreases monotonically from higher than average values to unusually low values. This structure resembles some of the CMEs identified by Burlaga <u>et al</u>. (1978) and Burlaga and King (1979). As discussed below, this event is unusual, and it is associated with a decrease in the cosmic ray flux, so it may be called a magnetic cloud as defined by Morrison (1954).

To investigate the geometry of the magnetic field in the cloud, we carried out a minimum variance analysis (Sonnerup and Cahill, 1967, Lepping and Behannon, 1980), i.e., we searched for a plane about which the scatter of $\underset{\sim}{B}_i - \langle\underset{\sim}{B}\rangle$ is minimum (here $\langle\underset{\sim}{B}\rangle$ is the average field in the interval and

$\mathbf{B}_i$ are the individual hour averages of $\mathbf{B}$). The end time for the analysis was taken to be hour 18 on February 12, corresponding to the time when the direction of $\mathbf{B}$ abruptly returned to the spiral direction, the magnitude of $\mathbf{B}$ dropped to $\sim$ 6nT, the temperature and density increased abruptly to normal values, and the stream ended. The appropriate start time for the interval was less certain, so we tried a few different times; the results were not sensitive to these times.

The result of the minimum variance analysis of $\mathbf{B}$ for the interval, hr 9 to hr 18 on February 12 are shown in Figure 2. The bottom panel shows the rotation of the projection of $\mathbf{B}$ in the plane of maximum variance; $\mathbf{B}$ rotates smoothly in this plane, changing direction by $\sim 180^\circ$. The scatter of $\mathbf{B}_i$ with respect to this plane is shown in the top panel of Figure 2. The scatter is small and irregular compared to the change of $\mathbf{B}$ shown in the bottom panel, indicating that a minimum variance direction is well-defined and confirming that $\mathbf{B}$ does indeed tend to rotate nearly parallel to a plane, which we call the cloud plane. The standard measure of planarity is the ratio of the minumum to intermediate eigenvalues, λ_3/λ_2 (Sonnerup and Cahill, 1967). In this case $\lambda_3/\lambda_2 = 7.7$; usually $\lambda_3/\lambda_2 > 2$ is taken to be indicative of a well-determined plane (see Lepping and Behannon, 1980).

The minimum variance direction is the same as the normal to the plane of rotation. For the results in Figure 2 the normal is given by $\theta_n = 16^\circ$, $\phi_n = 148^\circ$, i.e., it is close to the ecliptic and to the nominal spiral direction at 1 AU. (Taking hour 9 for the start of the analysis interval gives $\theta_n = 15^\circ$, $\phi_n = 144^\circ$.) In other words, the normal to cloud plane ($\hat{n}$) is nearly <u>parallel</u> to the spiral direction. The component of $\mathbf{B}$ along $\hat{n}$ is small, $\langle|B_n|\rangle/\langle F\rangle \lesssim 0.26$, indicating that the magnetic field in the cloud is nearly <u>perpendicular</u> to the spiral direction. Clearly, such a magnetic cloud is an unusual interplanetary magnetic field configuration. Variance analysis of several shorter intervals within the 'cloud' gave nearly the same results for the normal. This can be taken as evidence that there are no large twists or bends in the structure.

Having established the existence of the anomalous yet ordered configuration described above, let us now investigate its geometry. We can safely assume that the observed variations are primarily spatial, resulting from convection of the structure past the spacecraft. One conceivable geometry is that of a gigantic plane current sheet (tangential discontinuity), but this would imply that $\hat{n}$ is perpendicular to the ambient field direction $\mathbf{B}_o$, whereas $\hat{n}$ is observed to be nearly along $\mathbf{B}_o$. More natural and attractive configurations which are consistent with the observations are 1) a quasi-cylindrical magnetic bubble (Figure 3) or 2) a tightly-wound helical flux-tube. The minimum variance analysis results in Figure 2 indicates the possible presence of a small component of $\mathbf{B}$ along the minimum variance direction, i.e., along the axis of the cylinder. If this is statistically significant, it implies that the magnetic field has the form of a cylindrical helix rather than the form of a closed circular loops. In particular, the ratio $<|B_n|>/<F> = 0.26$ implies an angle between $\mathbf{B}$ and the axis of the cylinder of $\beta = 75^o$, but this is an lower limit on β because $<|B_n|>$ includes the effect of random errors.

The NS flow angle varies in relation to the θ angle of $\mathbf{B}$ (see Figure 1), being negative in the forward half of the cloud and positive in the rear. This pattern suggests a rotation of the plasma in the cloud about its axis. In fact, the speed profile resembles that of a Rankine combined cylindrical vortex. However, we caution against interpreting this as a general feature of planar magnetic clouds.

The magnetic structure described above is different from those discussed by Akasofu (1979) and Rosenberg and Coleman (1980). Akasofu was specifically referring to events associated with a sector boundary, and he attributed the long lasting southward or northward fields to a warping of the current sheet. There is no sector boundary in the February 1969 event. The unusual filament in the ϕ component in Figure 2 is associated with the cloud itself, and in the field is nearly normal to the spiral direction, rather than parallel to it as it would be if it were due to sector boundary crossings. Furthermore, the filament was not seen on the preceding or following solar rotations, again indicating that it was a transient structure rather than a quasi-stationary feature such as a sector. The events discussed by Rosenberg were associated with corotating interaction regions which are accompanied by a distinctive stream interface (e. g., see Burlaga, 1974; and Smith and Wolfe, 1979), which may recur from one solar rotation to the next. The February 1969, event is not of this type, for an interface was not seen and the stream did not recur. Furthermore, the density and temperature profiles in Figure 1 are almost the opposite of those associated with streams predicted by corotating interaction regions.

The magnetic cloud was preceded by a shock, indicated by the line marked A in Figure 1. The speed, density and field strength increase across the shock in Figure 1, but the temperature change is unclear from the figure due to the averaging. The high resolution magnetic field data clearly show a shock at 2024 UT on February 10. The field strength increased by 60% in 17 sec. The change in field direction across the shock was negligibly small, indicating that it was perpendicular shock. The shock normal was thus perpendicular to the local field direction which was at $\theta \approx 18^{\circ}$, $\phi \approx 312^{\circ}$. The arrival of the shock at 2024 UT on February 10 was accompanied by a worldwide geomagnetic sudden commencement at 2024 ± 1 UT. A large geomagnetic storm was observed on February 11, with $C9 = 7$, $A_p = 69$, and $\Sigma K_p = 43$ (Solar Geophysical Data, 1969a). The storm began just after the shock passed, and it persisted through February 11; during this interval the magnetic field strength and bulk speed were high and the magnetic field was pointing southward ($\theta < 0$). The storm ended near the time when the axis of the magnetic cloud passed the earth, i.e., when $\underset{\sim}{B}$ changed from a southward to a northward direction.

There was also an unusual depression in galactic cosmic ray intensity associate with this event (see Cosmic-Ray Intensity, 1975 and Solar Geophysical Data, 1969a). It began when the shock arrived, i.e., when F and V increased, and the cosmic ray flux reached a minimum near the time when V was maximum. It is difficult to follow the time history of the event in detail, because the cosmic ray profiles vary significantly with the longitude and latitude of the observing stations (e.g., owing to the diurnal variation). The event ended when the rear of the magnetic cloud moved away from the earth. The cosmic ray profiles seem to be related more closely to V and F than to θ, i.e., the magnetic field geometry was not the only factor, or even the most important factor, in producing the cosmic ray intensity decreases.

A Magnetic Cloud Without a Stream or Shock

Here we shall discuss a configuration in which the magnetic field variations resemble those in the magnetic cloud discussed above, but the plasma data profiles and the accompanying geomagnetic and cosmic-ray effects are very different. The event was observed by spacecraft near earth on June 23, 1971. Figure 4 shows that the magnetic field direction rotated smoothly from $\theta = -49^\circ$ at hour 9 on June 23 (marked by line A in Figure 4) to $\theta = 85^\circ$ at hour 24 on that day (line B). The ϕ angle showed a filamentary form in this interval, similar to that in Figure 1. A Sonnerup minimum variance analysis showed that a component of $\underset{\sim}{B}$ rotated close to a plane ($\lambda_2/\lambda_3 = 7.5$) whose normal was $\phi_n = 173^\circ$, $\theta_n = 3^\circ$ (see Figure 4). In this case, the RMS of the component of $\underset{\sim}{B}$ normal to the plane is 0.9 nT, which is small compared to the average F = 10.3 nT, implying that the angle between $\hat{n}$ and $\underset{\sim}{B}$ is $\geq 85^\circ$. Thus the torsion of the magnetic field lines is essentially zero, and the cloud plane is the osculating plane.

There was no stream associated with this magnetic cloud; the speed was $\sim$ 345 ± 10 km/s from the middle of June 22 to the end of June 24. The density was significantly higher than average ahead of the cloud but only slightly lower than average inside the cloud. The temperature was generally close to the average solar wind value.

There was no appreciable cosmic ray decrease associated with this event (Solar Geophysical Data, 1969b) in contrast to the changes associated with the February 1969, event discussed above. Likewise, no unusual geomagnetic storm was associated with this event, ΣK_p being 14^+ and $A_p = 7$ on June 23. Nevertheless, K_p was highest (3^-) in the interval when θ was most negative (the front of the cloud) and K_p was unusually low in the interval when θ was positive (the rear of the cloud). A sudden impulse was observed at 2304 UT on June 22 at the time that the density enhance began ahead of the cloud. Sudden impulses were also observed at 0852 UT on June 23 (when the density dropped and the magnetic field moved southward) and at 1644 UT on June 23 (when $\underset{\sim}{B}$ moved northward). No flare of importance > 1 was observed in the several days preceding this event.

SUMMARY

This paper demonstrates the existence of a class of magnetic structures with a scale of the order of 0.25 AU, containing unusual field orientations. One of the events described was associated with a shock, a stream and a Forbush decrease, while the other was not. Although only two events were considered and both were observed in the vicinity of the earth, the basic phenomenon described here (the magnetic cloud) is not uncommon and it may be observed in regions remote from 1 AU.

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FIGURE CAPTIONS

FIGURE 1 Magnetic field and flow parameters associated with a magnetic cloud. The cloud is between B and D, where the latitude angle of $\underset{\sim}{B}$ varies systematically from large negative values to large positive values. This cloud is cold and moves faster than the surrounding flows.

FIGURE 2 The variation of $\underset{\sim}{B}$ in the magnetic cloud shown in Figure 1, plotted in the principal axis coordinate system where Z is along the direction of minimum variance. The component of $\underset{\sim}{B}$ along the Z axis, is small, and the transverse component rotates smoothly through $\sim 180^\circ$ in the plane normal to the Z axis.

FIGURE 3 A sketch illustrating a possible configuration of $\underset{\sim}{B}_t$ in the magnetic cloud shown in Figure 1. The vector $\hat{n}$ is the direction of minimum variance. The component of $\underset{\sim}{B}$ along $\hat{n}$ is small or zero. If it is zero, the magnetic field lines in the cloud may be closed, as suggested in the sketch. If the component of $\underset{\sim}{B}$ along $\hat{n}$ is not negligible, then it must be added to $\underset{\sim}{B}_t$ and the magnetic field in the cloud has the form of a tightly wound helix. Note that the magnetic field in the cloud is nearly orthogonal to the ambient, "spiral" field.

FIGURE 4 A magnetic cloud which is not associated with a stream. The magnetic field in the cloud rotates close to a plane, as shown in the panels on the right.

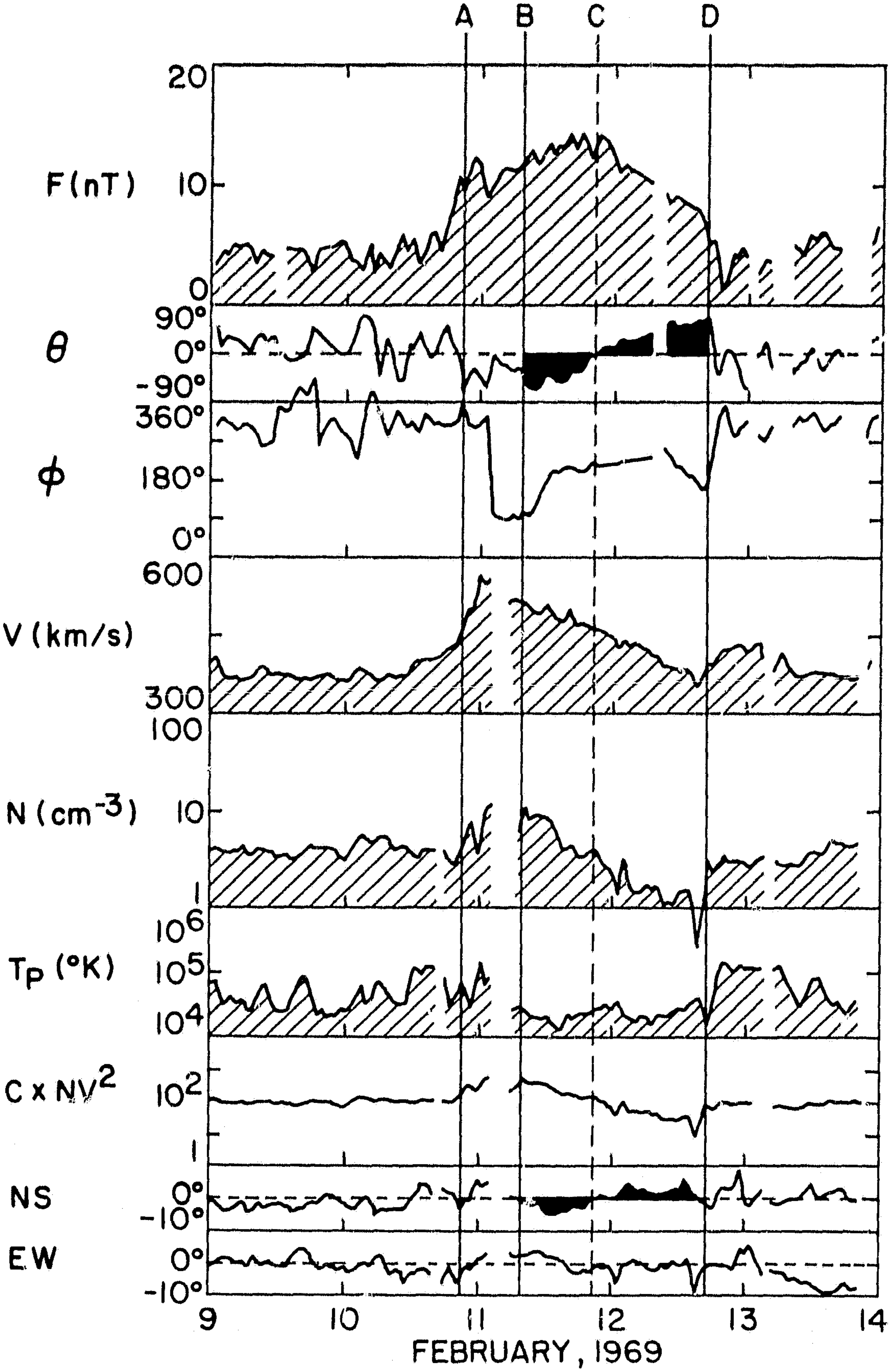
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Figure 1

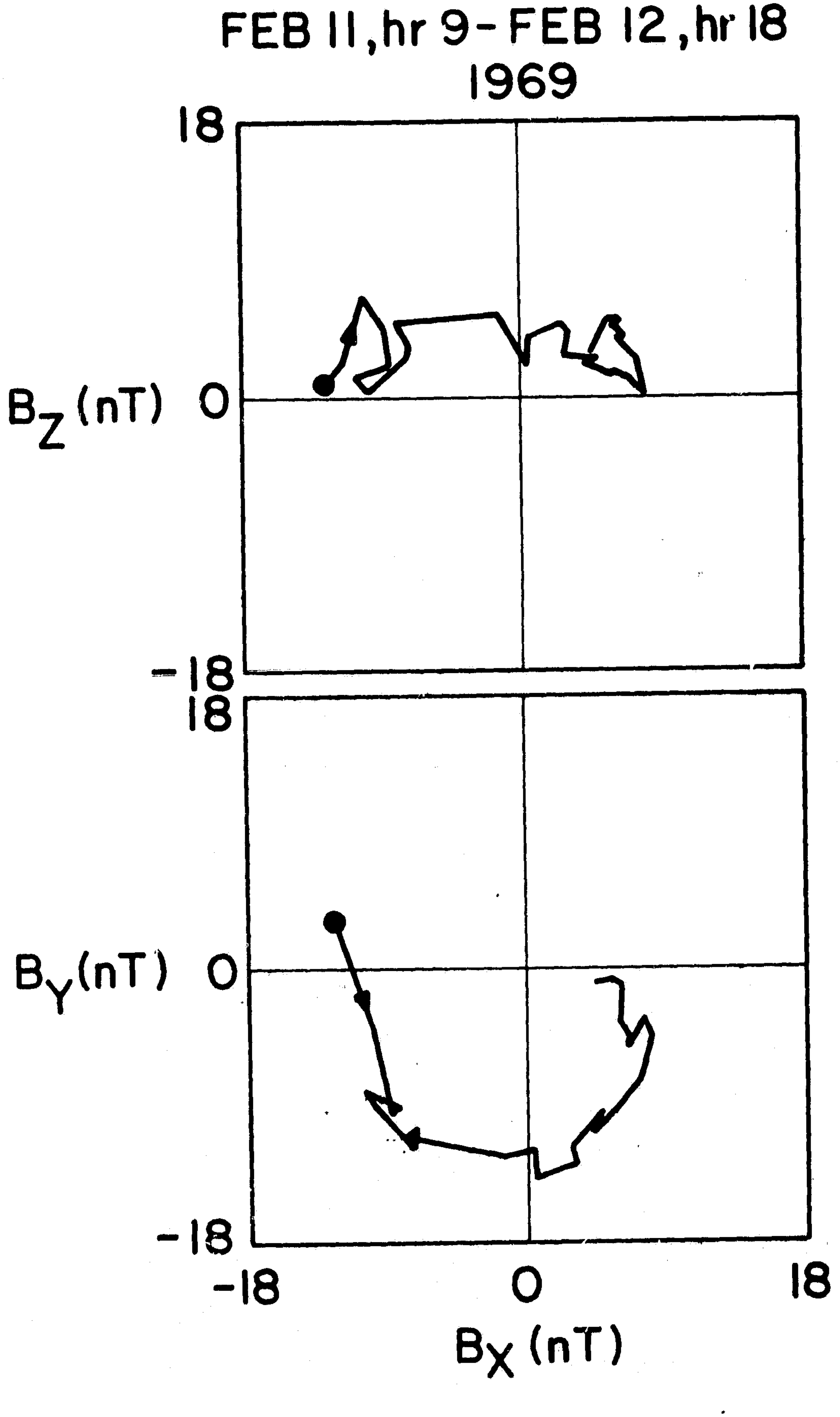

Figure 2

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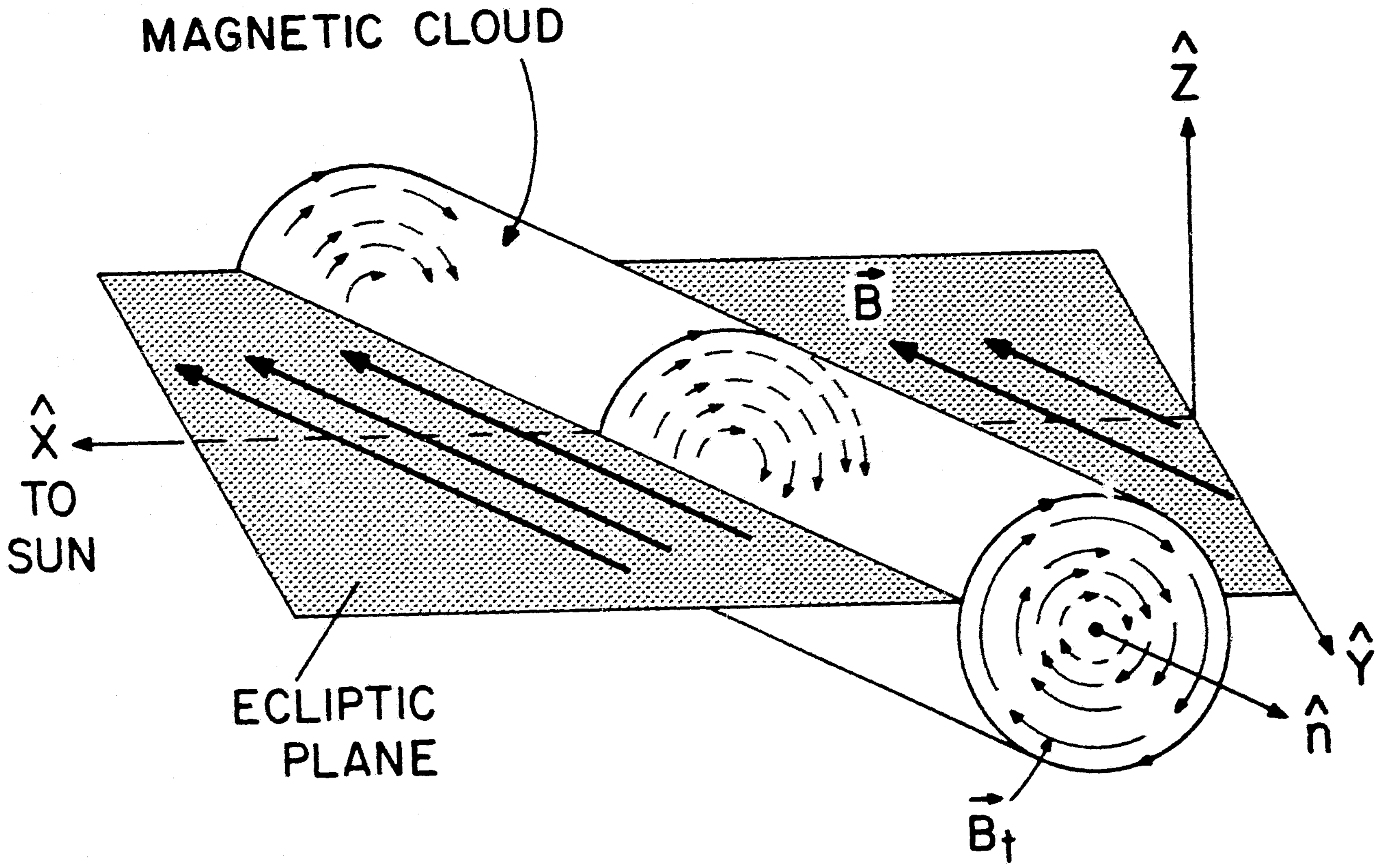
MAGNETIC CLOUD
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TO SUN
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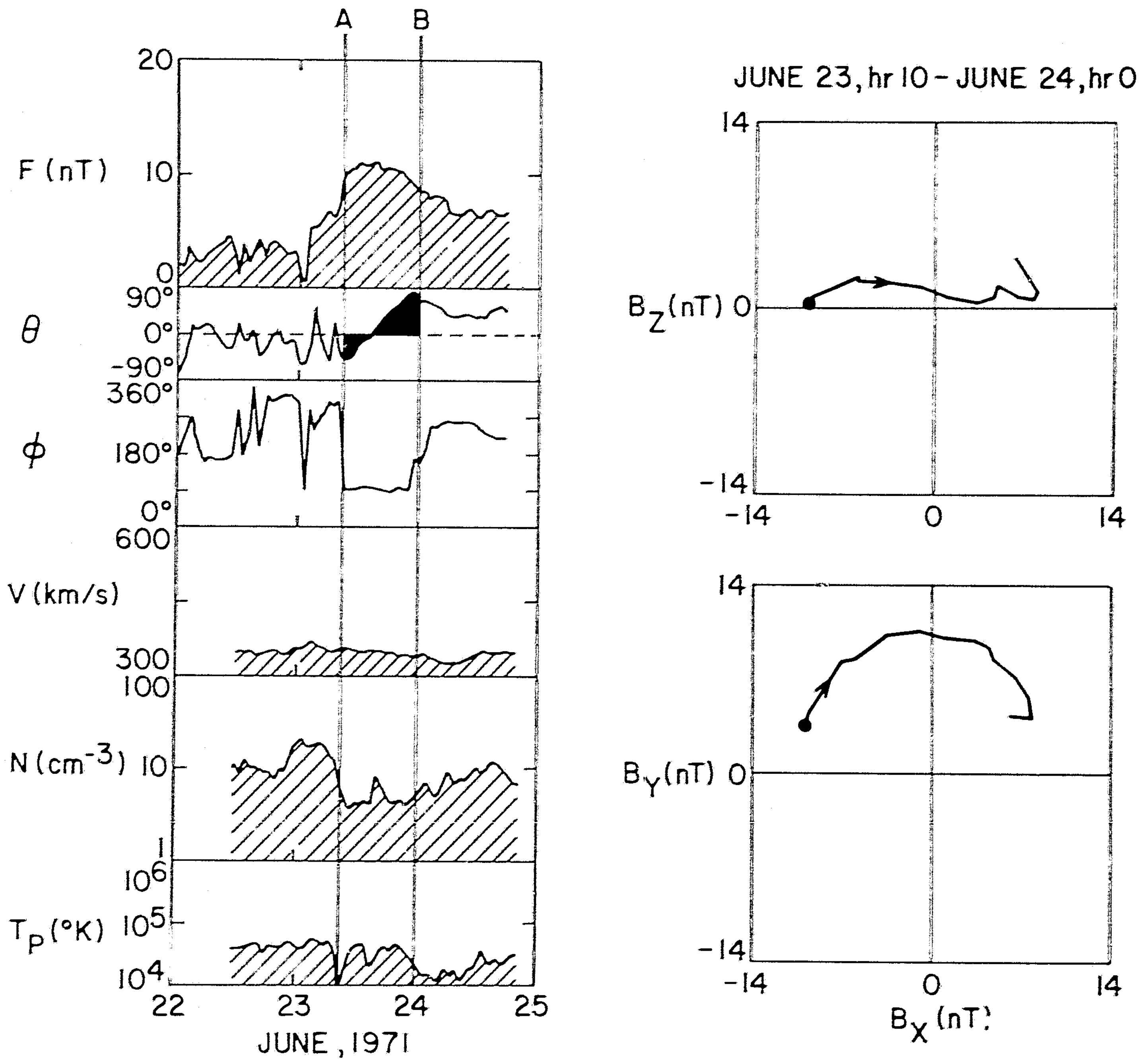
Figure 3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JUNE 23, hr 10 - JUNE 24, hr 0
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Figure 4