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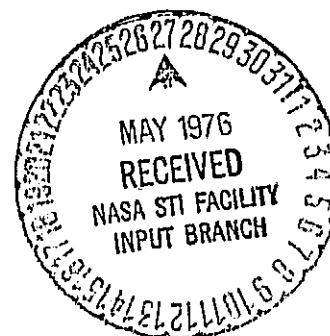
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ABSTRACT

An analysis of high resolution magnetic field measurements from the GSFC magnetometer on Explorer 43 showed that low magnetic field intensities ($< 1\,\gamma$) in the solar wind at 1 AU occur as distinct depressions or "holes," in otherwise nearly average conditions. These magnetic holes are new kinetic-scale phenomena, having a characteristic dimension on the order of 20,000 km. They occur at a rate of 1.5/day in the 18-day interval (March 18 to April 6, 1971) that was considered. Most magnetic holes are characterized by both a depression in $|\vec{B}|$ and a change in the magnetic field direction, and some of these are possibly the result of magnetic merging. However, in other cases the direction does not change; such holes are not due to merging, but might be a diamagnetic effect due to localized plasma inhomogeneities.

INTRODUCTION

Regions of very low intensity magnetic fields can be seen in high resolution measurements of the interplanetary magnetic field near 1 AU. We define low intensity by $|\vec{B}| < 1\,\gamma$ which is to be compared with the average intensity of 5 γ and the most probable value of 6 γ. Most low field intensities were found to occur in isolated regions in the form of discrete "holes" imbedded in a background of otherwise uniform fields of nearly average intensity. The existence and the characteristics of these magnetic holes are the subjects of this paper.

Our analysis is based on ≈ 18 days of interplanetary data from Explorer 43 (IMP-I) in the period March 18 to April 9, 1971, the interval during which the GSFC plasma analyzer was operating. Low field regions ($|\vec{B}| < 1\,\gamma$) were initially identified in plots of 15 s magnetic field averages. The "holes" thus found have a very small radial extent, but the high sampling rate of the magnetometer (12.5/s) resolved the structure of every event. The plasma sampling rate was much lower (a spectrum was measured in approximately one minute and successive spectra were obtained at four-minute intervals) and the structure of holes could not be resolved, but the plasma instrument did provide measurements of the pre- and post-hole states. The magnetic field and plasma experiments are described in reports by Fairfield (1973) and Ogilvie and Burlaga (1974), respectively.

RESULTS

We identified 28 magnetic "holes" using the criterion $|\vec{B}| < 1\,\gamma$ and the data set discussed above. Typical examples are shown in Figure 1,

which contains plots of magnetic field intensity for 10-min intervals.
Nearly all holes are essentially isolated depressions in magnetic field
intensity which is otherwise nearly average. They are distinct entities,
not just random fluctuations in low intensity, disturbed field regions.
Thus, the lowest magnetic field intensities in the solar wind near 1 AU,
like the highest field intensities, apparently are the result of special
physical processes distinct from those which produce the most probable
fields.

Given 28 holes in 18 days of data, one obtains an occurrence rate
of 1.5/day. This is intermediate between the rate for shocks ($\approx$ .05/day),
(Chao and Lepping, 1974) and that for directional discontinuities
($\approx$ 25/day) (Burlaga, 1972). The period used in this study is a represent-
ative solar wind state, in the sense that there were several well-defined
streams (Burlaga and Ogilvie, 1973), 2 shocks (Ogilvie and Burlaga, 1974),
and the types of "Alfven waves" that are often observed (Belcher and
Davis, 1971, Burlaga and Turner, 1976). Thus, the rate of 1.5 holes
per day, or $\approx$ 40 per solar rotation, is probably typical. Figure 2 shows
the relations between the holes and the features just mentioned, and one
can see that they are distributed fairly uniformly with respect to the
streams, with perhaps some preference for the regions of decreasing speed.
This gives us further reason to expect that the occurrence rate of $\approx$ 1.5/day
is representative and not very strongly biased by conditions in our
limited sample of data.

The "widths" of the holes ranged from $\approx$ 2 s to $\approx$ 130 s, with a median
of 50 s. Since they are convected radially past the spacecraft at a
speed on the order of 400 km/s, their thickness along the radial direction

is on the order of 2×10^4 km, and since the proton Larmor radius near (but not in) the holes, R_L, is typically ≈ 100 km, the radial thickness of the holes is on the order of $200\ R_L$. If the holes are field-aligned, the actual thickness is somewhat smaller, $\approx 150\ R_L$. Because of their small size, magnetic holes are kinetic scale phenomena in the classification scheme of Burlaga (1969).

Turning now to the change in direction of the magnetic field across the holes, we find that it may change abruptly by a large amount, it may vary irregularly, or it may not change at all. Of the 28 events, 8 had little or no directional change, 9 were similar to D-sheets and 11 fell into neither of those categories. In the following, we shall discuss several examples of such changes. The plots to be presented are based on the high resolution data obtained at 12.5 samples/sec and are displayed in a coordinate system in which $\hat{y}$ is the average field direction for 2 seconds before the event, $\hat{z}$ is the direction of minimum variance for points in the interval during which the transition takes place, and $\hat{x}$ is orthogonal to $\hat{y}$ and $\hat{z}$ and forms a right-handed coordinate system. It should be stressed that the coordinate system varies from event to event. In any case, however, tangential "discontinuities" in this system are indicated by $B_z = 0$.

An example in which the magnetic field direction changes abruptly across the holes is shown in Figure 3. The change in direction is centered about the time of minimum intensity, and B_z is essentially zero in the transition layer, indicating a tangential "discontinuity." The width of the March 27 event is 8 s, which is typical for directional discontinuities in the solar wind. The magnetic field direction changes

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by 180° in the March 27 event (Table 1), and the magnetic field intensity drops to nearly zero, 0.12 γ. In this respect, the structure resembles a D-sheet. Observations of D-sheets have been discussed by Burlaga (1968) and Burlaga and Scudder (1974) presented evidence that some D-sheets are the result of Sweet's mechanism, by which magnetic field is annihilated. The magnetic field intensity depressions in the D-sheets discussed heretofore are much broader than that in Figure 3 and occur much more infrequently than holes. For the March 27 event, the annihilation hypothesis predicts that the minimum intensity in the hole is $B_{min} = 0.15 \gamma$; this is in very good agreement with the observed value, 0.12 γ. Unfortunately, the orientation is such that we cannot test for the subalfvenic streaming toward the current sheet which is predicted by Sweet's mechanism (see Burlaga and Scudder (1974) and references therein).

Another magnetic hole that resembles a D-sheet is the March 28, 1637 UT event, described in Table 1. In this case one can determine that the thickness is 20 R_L. The observations suggest a subalfvenic streaming toward the current sheet ($V_o/V_A = 0.04$), where V_o is the flow speed normal to the current sheet and V_A is the Alfven speed outside and adjacent to the current sheet. The value of B_{min} predicted by the annihilation hypothesis is very close to the measured value (Table I).

Figure 4 shows an event that resembles a thin D-sheet, but which is not entirely consistent with the annihilation hypothesis. There is essentially no B_z component, indicating that the directional "discontinuity" is tangential. The "width" is only 8 sec, and the thickness along the normal ($\hat{z}$) direction is only 4 R_L. The velocity measurements were not sufficiently accurate to determine whether or not there was a subalfvenic

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flow toward the current sheet. The important feature is that the observed minimum field is significantly <u>smaller</u> than that predicted by the merging model using the measured angular separation, ω, between the fields preceding and following the hole, $\vec{B}_1$ and $\vec{B}_2$, respectively (see Table I). Thus, either merging can operate in a way that is not understood or there is an entirely different process involved instead of or in addition to merging. There were other events which had minimum fields significantly smaller than predicted by the merging model (e.g., April 6, 1638 UT, in Table 1). The events in this category had normals which were nearly radial. It should be noted that all of the holes discussed in this paper differ from the D-sheets discussed by Burlaga (1968) in that here the depression is confined to a region the size of that in which the direction changes, whereas it is much broader in D-sheets.

A distinctly different type of magnetic hole (which we call a linear hole) is shown in Figure 5; here is a smooth, symmetrical depression in magnetic field intensity, but <u>no</u> change in direction. The change is seen only in the B_y component, which is the average field direction, and in the intensity. Four such linear holes were found among the 28 events (see Table II). Their width along the radial direction is similar to that of other magnetic holes. Table II indicates that there was possibly a change in one or more of the plasma parameters across the linear holes, but more examples are needed before one can draw a general conclusion. Four other linear holes were identified with the same basic characteristics, but differed in that the field intensity did not vary smoothly in the hole. In these cases, the field intensity varied irregularly outside of the holes as well, and it is likely that the nonuniformity in the holes is

due to external conditions. The occurrence of linear holes relative to streams is indicated by the 'L's in Figure 2.

Linear magnetic holes are certainly not produced by a merging process, since a change in the direction of $\vec{B}$ is a necessary signature for merging. A possible explanation is that they are diamagnetic responses to localized plasma inhomogeneities. Indeed, high values of $\beta \equiv nkT/(B^2/8\pi)$ (where n, T are the density and temperature, respectively, of the protons, and B is the magnetic field intensity) were observed adjacent to the holes (see Table II). One can model linear holes using the theory for diamagnetic boundary layers developed by Sestero (1964) and Lemaire and Burlaga (1976). In particular, one can regard a hole as two adjacent boundary layers across which $|\vec{B}|$ changes. In one layer, from $z \rightarrow -\infty$ to z_o where $|\vec{B}|$ is a minimum, the magnetic field intensity decreases; in the other layer, from z_o to $z \rightarrow +\infty$, the magnetic field intensity increases. The model implies a localized plasma inhomogeneity (dense and/or hot plasma) which "excludes" the magnetic field. An electric field is set up along the "normal" to the current sheet and particles drift in this field and in the gradient of $|\vec{B}|$, thereby providing the current which maintains the structure in a steady state. This model allows magnetic field enhancements as well as holes, if the plasma inhomogeneity is due to a decrease in density and/or temperature. An observation of such an event is shown in Figure 6. We did not attempt to study the statistics of such events. Of course, the application of this model to magnetic holes is only speculative, and it doesn't explain the origin of the plasma inhomogeneities. High resolution plasma measurements are needed to understand the true nature

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and origin of magnetic holes. Multispacecraft measurements are needed to determine their spatial structure and to follow their evolution.

SUMMARY AND DISCUSSION

In the high time resolution data from Explorer 43 (IMP-I), we found that the lowest magnetic field intensities ($< 1 \gamma$) in the solar wind at 1 AU nearly always occur as distinct depressions or "holes" in otherwise nearly average interplanetary magnetic fields. These magnetic holes are new kinetic scale phenomena, convecting past a fixed spacecraft in some tens of seconds and having dimensions on the order of tens of proton Larmor radii. They occur at a rate of 1.5/day during the 18-day period which was considered, a rate intermediate between that of shocks and that of directional discontinuities.

The direction of $\vec{B}$ changes across most magnetic holes, much as it does in the current sheets associated with directional discontinuities with no change in $|\vec{B}|$, i.e., it rotates in a plane and has a thickness of several proton gyroradii. However, there are some magnetic holes at which there is virtually no change in the direction of $\vec{B}$. Some of the directional holes resemble D-sheets, although there is an important difference in that the depression in $|\vec{B}|$ has the same dimension as the change in direction at holes whereas it is much broader than the change in direction at D-sheets. In particular, some holes are possibly the result of magnetic merging. However, the linear holes are certainly not the result of merging, which requires a change in the direction of $\vec{B}$. These linear holes (and perhaps all holes) are possibly diamagnetic effects due to the presence of localized plasma inhomogeneities, but we

can neither observe such small inhomogeneities because of the low plasma data sampling rates nor offer a unambiguous explanation for their origin.

ACKNOWLEDGMENTS

TABLE I

Magnetic Holes that Resemble D-Sheets

Event Time	ω	$\dfrac{B_{min} \text{ (predicted)}}{B_{min} \text{ (observed)}}$	Thickness (R_L)
March 27, 0440	180°	1.2	-
March 28, 1637	129°	1.2	20
April 6, 1638	1o7°	2.7	14
April 1, 1025	131°	7.1	4

TABLE II

Linear Magnetic Holes

(1 = pre event, 2 = post event)

Event	(n_1/n_2)	(T_1/T_2)	(V_1/V_2)	(B_1)	(B_2)	ω
March 23, 552	.92	.86	1.01	3.80	2.02	6°
March 24, 1607	1.15	.90	1.03	1.38	1.18	17°
March 24, 1633	1.03	1.02	1.02	1.11	1.02	5°
March 27, 1823	1.11	1.02	.97	.40	.24	13°

FIGURE CAPTIONS

Figure 1   Representative examples of magnetic holes. In each panel, 15 s averages of the magnetic field intensity are plotted versus time. The events are labeled by decimal day and universal time. Despite the variety of shapes and widths, there is a common characteristic, viz., a distinct depression to $|\vec{B}| < 1\ \gamma$ in an otherwise normal magnetic field profile.

Figure 2   Relation between magnetic holes and mesoscale interplanetary conditions.

Figure 3   A magnetic hole which might be the site of magnetic merging. The magnetic field direction rotates through 180° in a plane, and its intensity drops to nearly zero.

Figure 4   A magnetic hole which resembles a magnetic merging region but in which the minimum field intensity is lower than expected from the merging hypothesis.

Figure 5   A linear magnetic hole. In this case, the hole is certainly not the result of merging. This, and perhaps all magnetic holes might be a diamagnetic effect due to a localized plasma inhomogeneity.

Figure 6   The antithesis of a magnetic hole. Here the magnetic field intensity increases in a 7 s. interval while the direction remains constant. Presumably the plasma pressure was low during the magnetic field enhancement.

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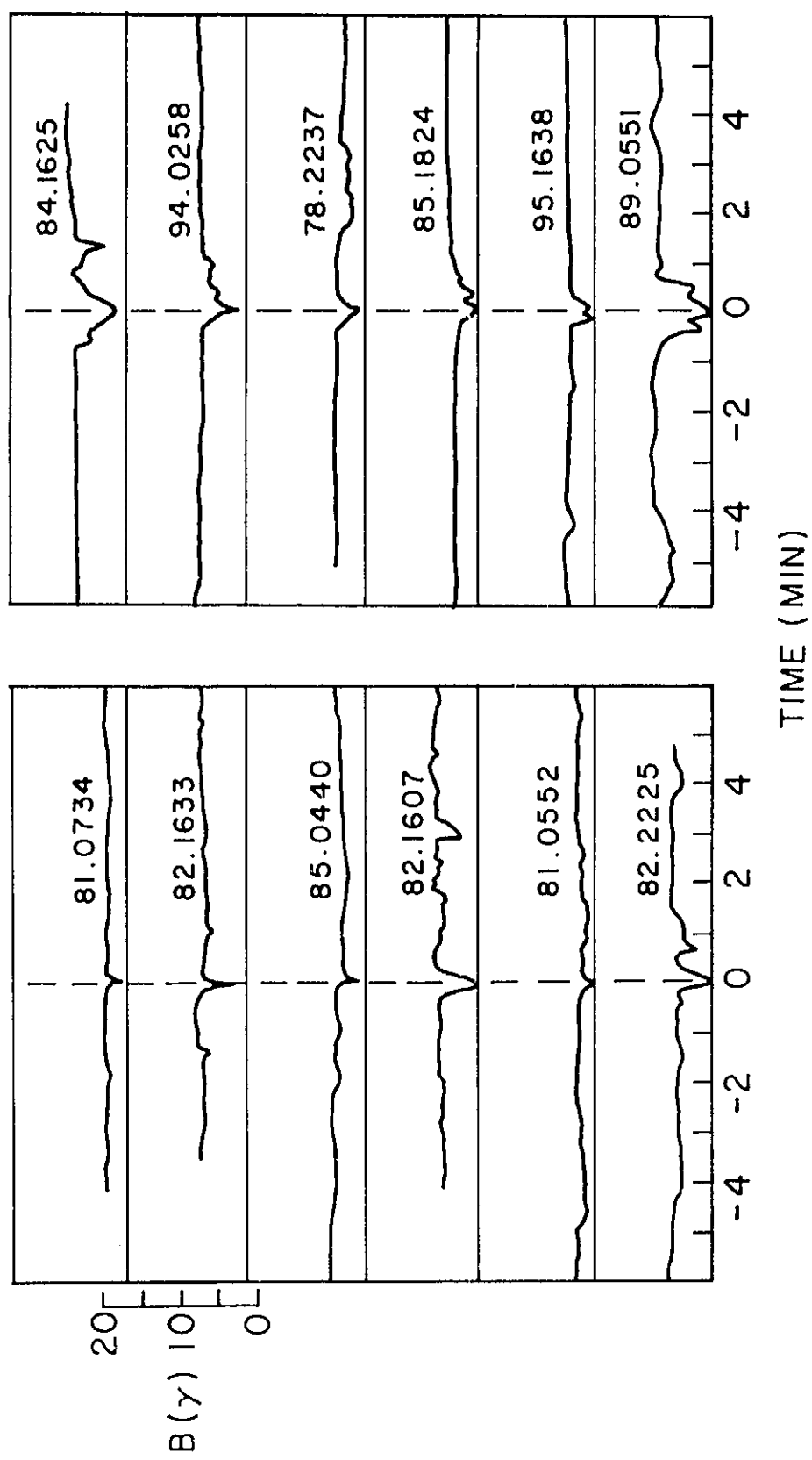
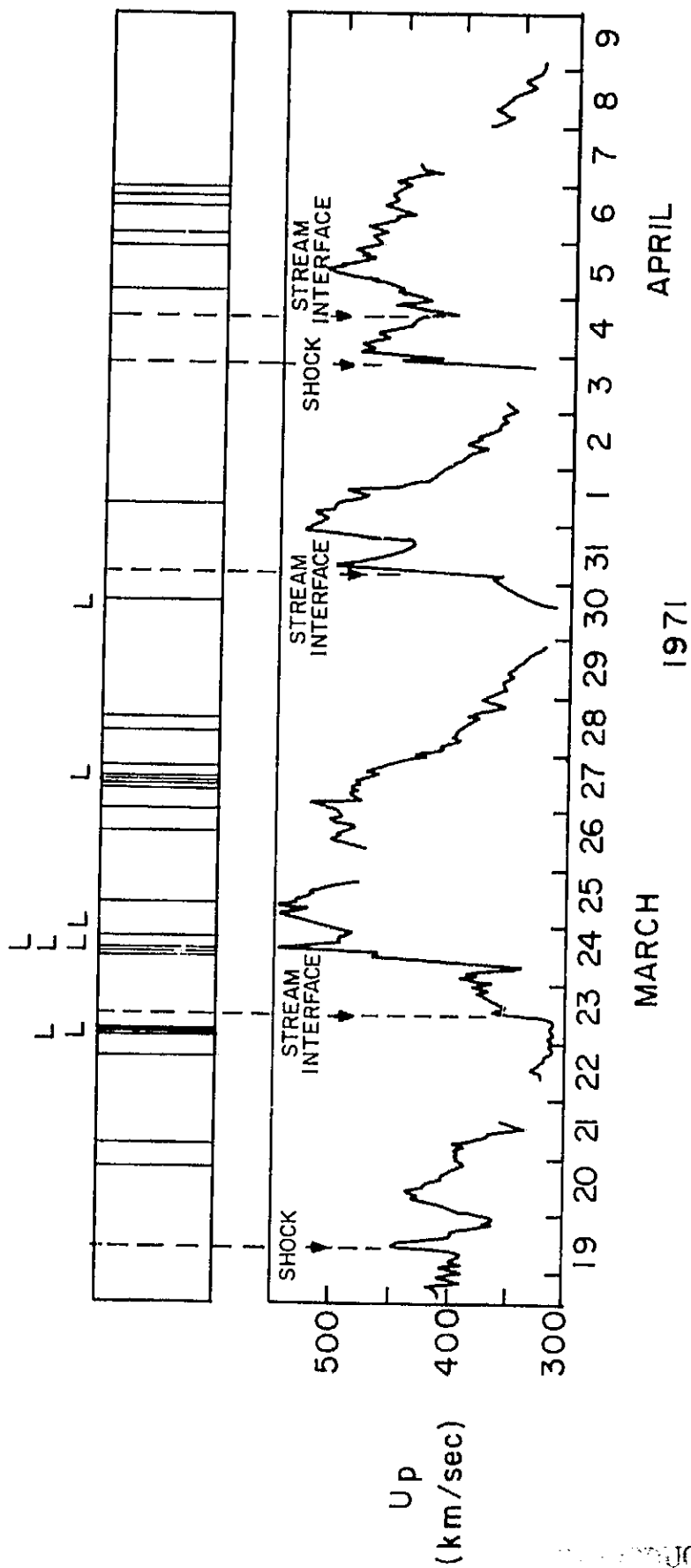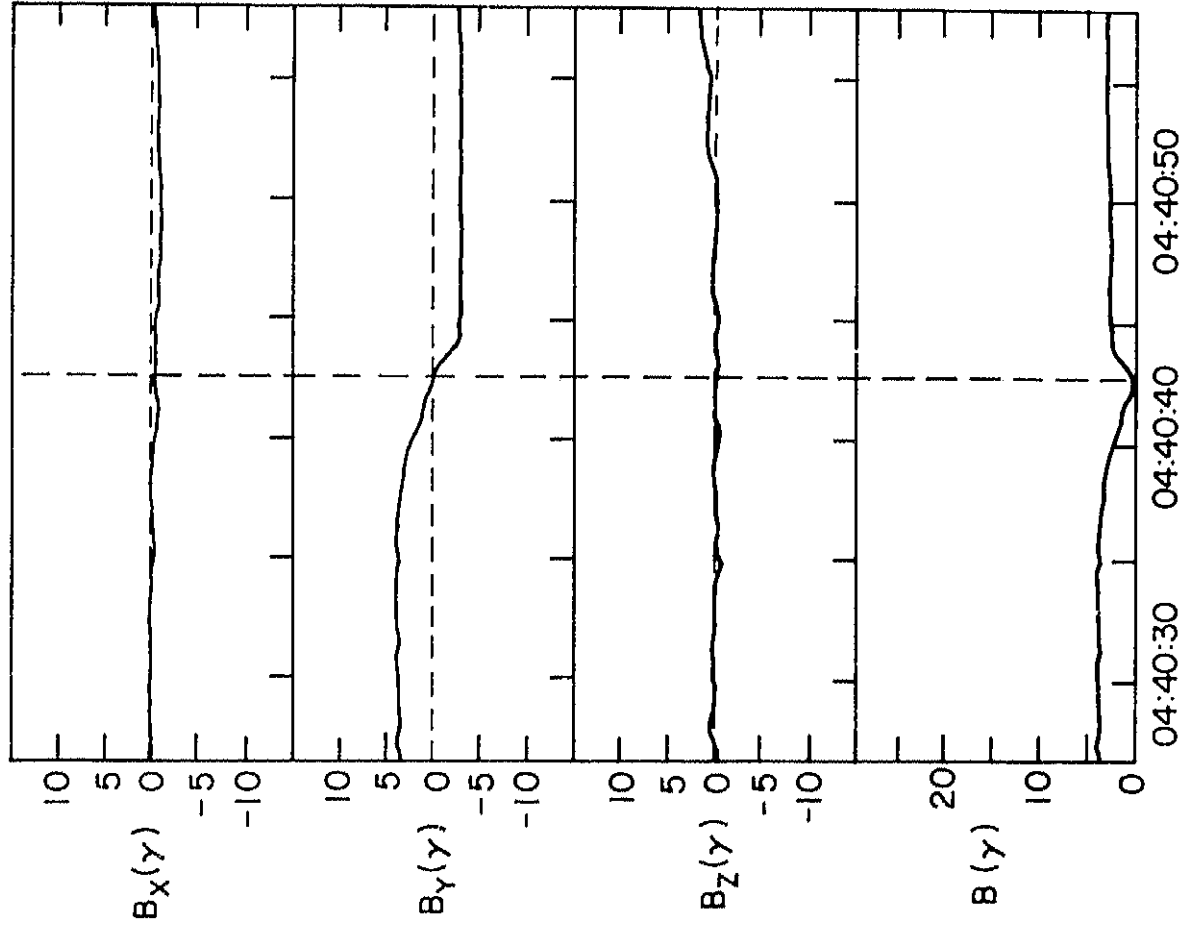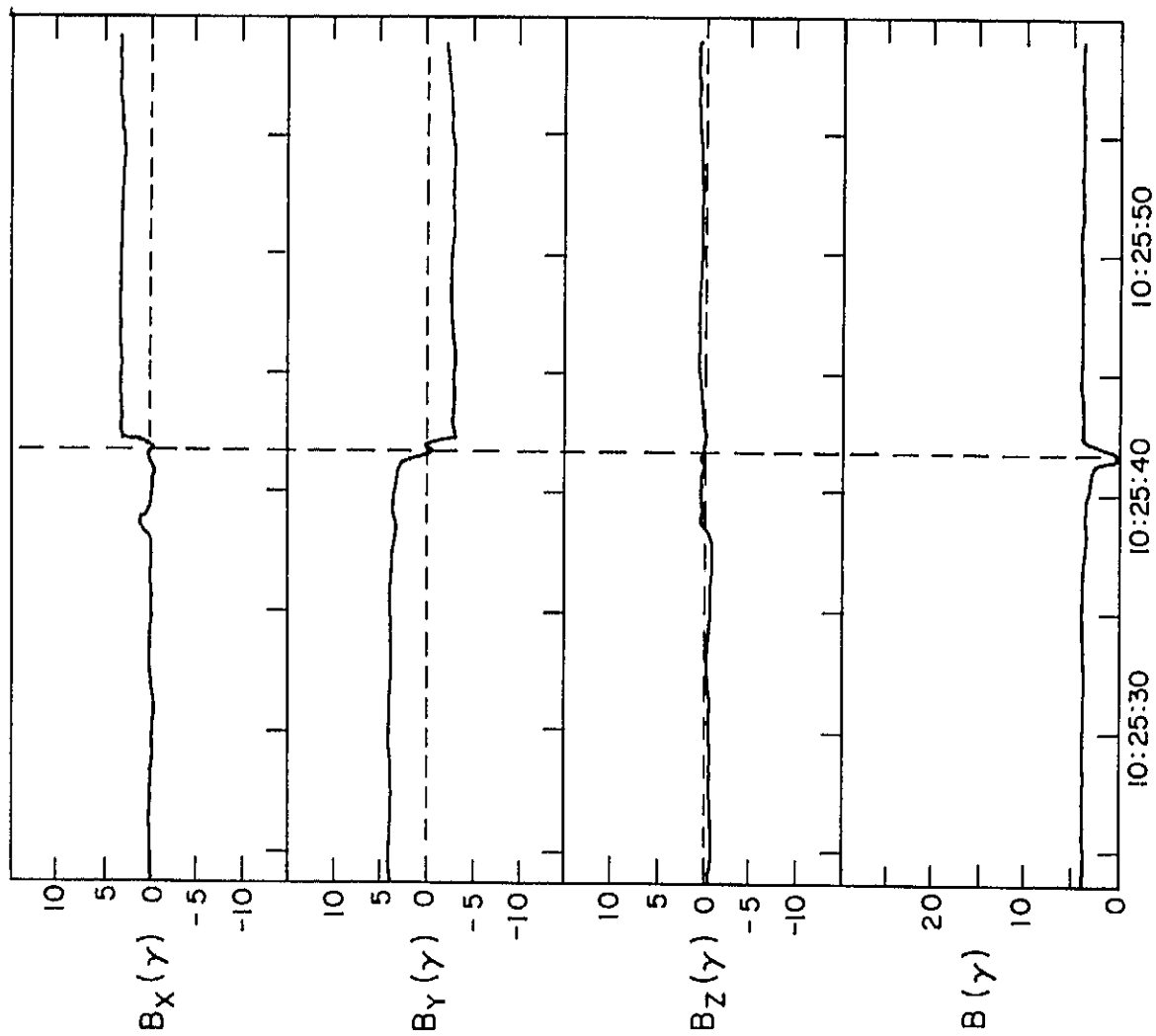Sestero, A., Structure of plasma sheaths, _Physics of Fluids_, 1, 44, 1964.

Fig. 1

Fig. 2

IMP I

MARCH 27, 1971

Fig. 3

IMP I

$B_X(\gamma)$

$B_Y(\gamma)$

$B_Z(\gamma)$

$B(\gamma)$

10:25:30   10:25:40   10:25:50

APRIL 1, 1971

FIG. 4

IMP-I

$B_X (\gamma)$ $B_Y (\gamma)$ $B_Z (\gamma)$ $B (\gamma)$

MARCH 24, 1971

16:33:30 16:33:40 16:33:50 16:34:00 16:34:10 16:34:20

IMPI
23 MARCH 71