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Magnetic Holes in the Solar Wind

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An analysis of high-resolution magnetic field measurements from the GSFC (Goddard Space Flight Center) 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 of the order of 20,000 km. They occurred at a rate of 1.5/d in the 18-day interval (March 18 to April 6, 1971) that was considered. Most magnetic holes are characterized by both a depression in $|\mathbf{B}|$ 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 $|\mathbf{B}| < 1\ \gamma$, which is to be compared with the average intensity of 6 γ and the most probable value of 5 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 Goddard Space Flight Center (GSFC) plasma analyzer was operating. Low-field regions ($|\mathbf{B}| < 1\ \gamma$) 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 1 min, and successive spectra were obtained at 4-min intervals), and the structure of holes could not be resolved, but the plasma instrument did provide measurements of the prehole and posthole states. The magnetic field and plasma experiments are described in reports by *Fairfield* [1974] and *Ogilvie and Burlaga* [1974], respectively.

Results

We identified 28 magnetic holes using the criterion $|\mathbf{B}| < 1\ \gamma$ 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/d. This is intermediate between the rate for shocks (≈ 0.05/d) [*Chao and Lepping*, 1974] and that for directional discontinuities (≈ 25/d) [*Burlaga*, 1972]. The period used in this study is a representative solar wind state in the sense that there were several well-defined streams [*Burlaga and Ogilvie*, 1973], two shocks [*Ogilvie and Burlaga*, 1974], and the types of 'Alfvén waves' that are often observed [*Belcher and Davis*, 1971; *Burlaga and Turner*, 1976]. Thus the rate of 1.5 holes per day, or ≈ 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, showing perhaps some preference for the regions of decreasing speed. This gives us further reason to expect that the occurrence rate of ≈ 1.5/d is representative and not very strongly biased by conditions in our limited sample of data.

The 'widths' of the holes ranged from ≈ 2 to ≈ 130 s, with the median being 50 s. Since they are convected radially past the spacecraft at a speed of the order of 400 km/s, their thickness along the radial direction is of the order of 2×10^4 km, and since the proton Larmor radius R_L near (but not in) the holes is typically ≈ 100 km, the radial thickness of the holes is of 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. Below 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/s and are displayed in a coordinate system in which $\hat{y}$ is the average field direction for 2 s 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

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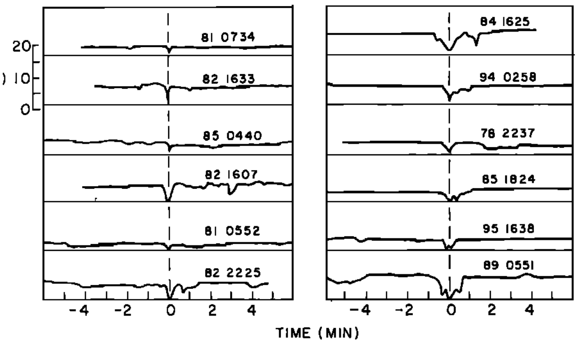

Fig. 1. Representative examples of magnetic holes. In each panel, 15-s averages of the magnetic field intensity are plotted versus time. The events are labeled by decimal day and universal time. Despite the variety of shapes and widths, there is a common characteristic, i.e., a distinct depression to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

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 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 the magnetic field is annihilated. The magnetic field intensity depressions in the *D* sheets discussed heretofore are much broader than the depression 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 sub-Alfvénic 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 sub-Alfvénic streaming toward the current sheet ($V_0/V_A = 0.04$), where V_0 is the flow speed normal to the current sheet and V_A is the Alfvén 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 1).

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, an observation indicating that the directional discontinuity is tangential. The width is only 8 s, 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 sub-Alfvénic flow toward the current sheet. The important feature is that the observed minimum field is significantly smaller than that predicted by the merging model using the measured angular separation ω between the fields preceding and following the hole, $\mathbf{B}_1$ and $\mathbf{B}_2$, respectively (see Table 1). 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 was 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.

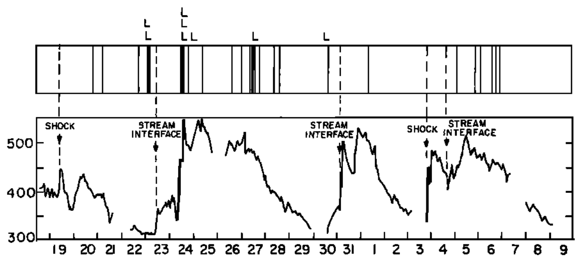

Fig. 2. Relation between magnetic holes and mesoscale interplanetary conditions.

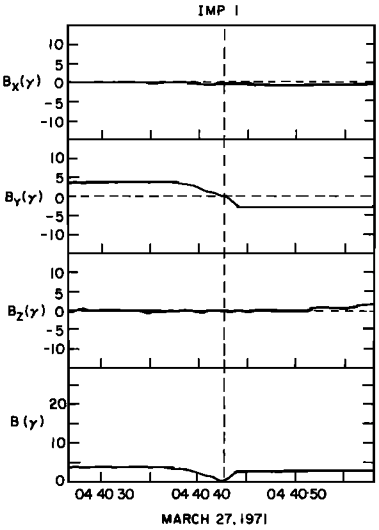

Fig. 3. A magnetic hole which might be the site of magnetic merging. The magnetic field direction rotates through 180° in a plane, and its intensity drops to nearly zero.

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 no 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 2). Their width along the radial direction is similar to that of other magnetic holes. Table 2 indicates that there was possibly a change in one or more of the plasma parameters across the

TABLE 1. Magnetic Holes That Resemble *D* Sheets

Event Date and Time, UT	ω, deg	$B_{\min}$(pred.)/ $B_{\min}$(obs.)*	Thickness, R_L
March 27, 0440	180	1.2	
March 28, 1637	129	1.2	20
April 6, 1638	167	2.7	14
April 1, 1025	131	7.1	4

*Here pred. stands for predicted, and obs. for observed.

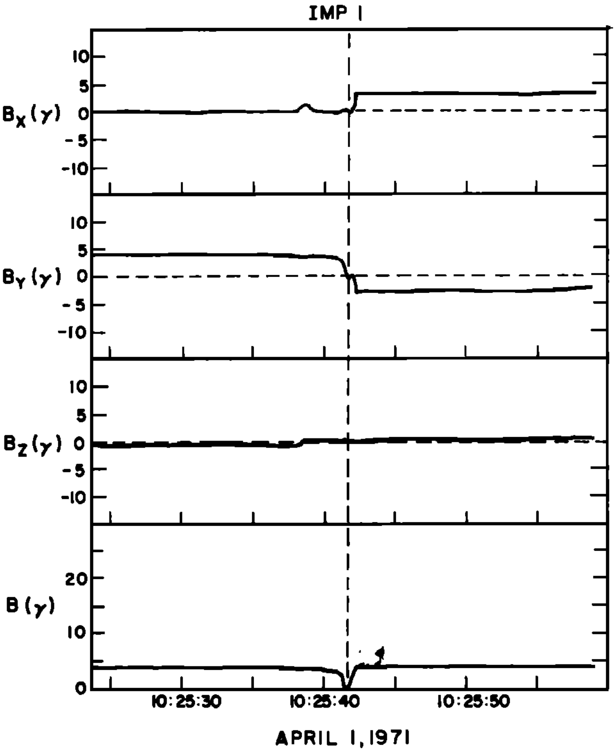

Fig. 4. A magnetic hole which resembles a magnetic merging region but in which the minimum field intensity is lower than is expected from the merging hypothesis.

TABLE 2. Linear Magnetic Holes

Event Date and Time, UT	n_1/n_2	T_1/T_2	V_1/V_2	β_1	β_2	ω, deg
March 23, 0552	0.92	0.86	1.01	3.80	2.02	6
March 24, 1607	1.15	0.90	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	1.09	0.97	0.40	0.24	13

The subscripts 1 and 2 refer to preevent and postevent measurements, respectively.

linear holes, but more examples are needed before one can draw a general conclusion. Four other linear holes were identified having the same basic characteristics, but they differed in that the field intensity did not vary smoothly in the hole. In these cases the field intensity varied irregularly outside 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 letter L in Figure 2.

Linear magnetic holes are certainly not produced by a merging process, since a change in the direction of **B** is a necessary signature for merging. A possible explanation is that they are diamagnetic responses to localized plasma inhomogeneities. Indeed, high values of $\beta = nkT/(B^2/8\pi)$ (where n and 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 2). 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 $|\mathbf{B}|$ changes. In one layer, from $z \to -\infty$ to z_0, where $|\mathbf{B}|$ is a minimum, the magnetic field intensity decreases; in the other layer, from z_0 to $z \to +\infty$, 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 $|\mathbf{B}|$, thereby providing the current which maintains the structure in

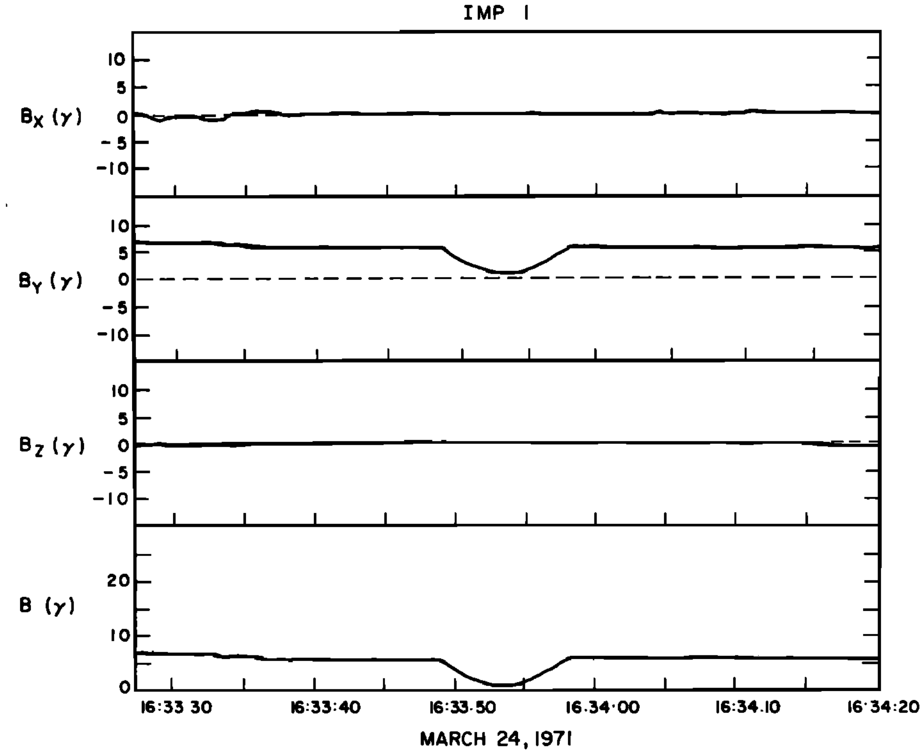

Fig. 5. A linear magnetic hole. In this case the hole is certainly not the result of merging. This and perhaps all magnetic holes might be a diamagnetic effect due to a localized plasma inhomogeneity.

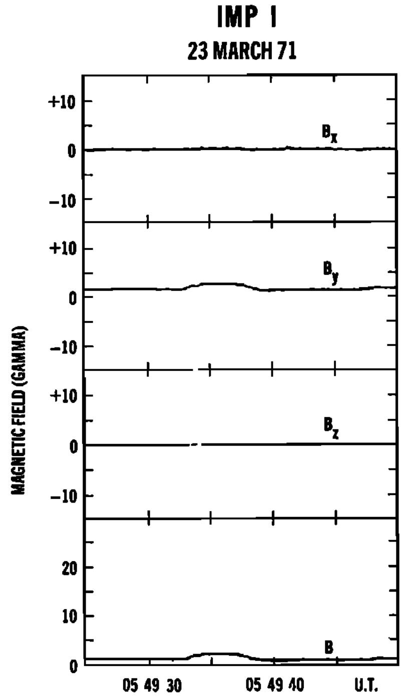

Fig. 6. Antithesis of a magnetic hole. Here the magnetic field intensity increases in a 7-s interval, while the direction remains constant. Presumably, the plasma pressure was low during the magnetic field enhancement.

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 does not explain the origin of the plasma inhomogeneities. High-resolution plasma measurements are needed to understand the true nature 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 of the order of 200 R_L. They occurred at a rate of 1.5/d during the 18-day period which was considered, a rate intermediate between that of shocks and that of directional discontinuities.

The direction of **B** changes across most magnetic holes, much as it does in the current sheets associated with directional discontinuities with no change in $|\mathbf{B}|$; 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 **B**. Some of the directional holes resemble *D* sheets, although there is an important difference in that the depression in $|\mathbf{B}|$ 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 **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 an unambiguous explanation for their origin.

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