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Magnetic structures inside boundary layers of magnetic clouds

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[1] We analyze 23 magnetic cloud boundary layers (BLs) in Feb. 1995–Oct. 1998 and find that: (1) the distribution functions of fluctuations in the southward field component inside the boundary layer, ΔB_{zL}, is very different from ΔB_{zS} in the background solar wind and ΔB_{zM} inside the cloud, with the enhancement in the fluctuation amplitude and the variation of the magnitude and direction of the average field. (2) in the maximum variance plane (MVP) composed of the maximum and medium variance directions, the walk of the tips of the magnetic field vectors in the BL could be classified into two types based on: (a) field vectors vibrate along a circle arc, which is possibly related with Alfven fluctuations inside the BL; (b) field vectors walk randomly in the MVP, which could be correlated with the turbulence inside the BL. (3) In the ϕ-θ plane, fields inside the BL exhibits a 'U' or inverse 'U' shape with a spacing of about 180 degree in the azimuthal angle, which indicate the existence of a field reverse region and are often associated with the Alfvenic fluctuations. The results above suggest that the cloud's BL owns the magnetic structure different from that in the solar wind and cloud body, which is a manifestation for the interaction of the magnetic cloud (MC) with the solar wind (SW). *INDEX TERMS:* 2111 Interplanetary Physics: Ejecta, driver gases, and magnetic clouds; 2134 Interplanetary Physics: Interplanetary magnetic fields; 7835 Space Plasma Physics: Magnetic reconnection; *KEYWORDS:* Magnetic clouds, interplanetary magnetic field, magnetic reconnection. **Citation:** Wei, F., R. Liu, X. Feng, D. Zhong, and F. Yang, Magnetic structures inside boundary layers of magnetic clouds, *Geophys. Res. Lett.*, *30*(24), 2283, doi:10.1029/2003GL018116, 2003.

1. Introduction

[2] Magnetic clouds have been intensively investigated [e.g. *Tsurutani et al.*, 1992; *Bothmer and Schwenn*, 1994; *Osherovich and Burlaga*, 1997; *Farrugia et al.*, 1997] since they are identified in the solar wind by *Burlaga et al.* [1981]. However, the boundary of the magnetic cloud has no objective definition yet. Many signatures have been used to identify the cloud boundary, such as temperature decrease, density decrease, directional discontinuity, magnetic hole, bidirectional streaming of suprathermal electrons, deviation from the Maxwell distribution of the electrons, and abrupt decrease in the intensity of low energy protons and plasma β [e.g., *Burlaga et al.*, 1980; *Marsden et al.*, 1987; *Gosling et al.*, 1987; *Osherovich et al.*, 1993; *Farrugia et al.*, 1994; *Fainberg et al.*, 1995; *Tsurutani et al.*, 1988; *Tsurutani and Gonzalez*, 1997; *Burlaga*, 1995; *Lepping et al.*, 1997]. However, as *Burlaga* [1995] and *Zwickl et al.* [1983] indicated, there is no consistency among those various approaches. The boundary of the MC is a problem related to the interaction of the MC with the SW, which has been highlighted in recent years. *Farrugia et al.* [2001] reported a reconnection layer associated with a magnetic cloud boundary on December 24, 1996 from the WIND observations. *Lepping et al.* [1997] analyzed an example of the MC overtaken by a corotating stream and indicated some difficulty in determining the tail boundary of the cloud on Oct 18, 1995. *Janoo et al.* [1998] found that the field directional discontinuities D_1, namely the front boundary of the cloud on Oct 18, 1995, is included in the reconnection layer. *Crooker et al.* [1998] suggested that the documented clouds, identified by magnetic signatures, are only parts of large transient structures.

[3] Recently, the BL concept have been suggested by *Wei et al.* [2003]. It could provide some clues in solving the puzzle that the three-part structure of the CME (the bright outer loop, the dark cavity and the filament) has not been identified in spacecraft observations near 1 AU, while MCs are usually regarded as an interplanetary manifestation of CMEs [*Tsurutani et al.*, 1988]. *Tsurutani et al.* [1998] suggested that the outer loop ahead of a cloud on Jan. 10, 1997 caused the auroral hotspot, theta aurora, and the horseshoe aurora. *Galvin et al.* [1987] also showed that the iron charge states observed in sheath appear to indicate a transition between the ambient solar wind and the driver plasma. According to *Wei et al.* [2003], the BL may play an important role in the initiation of cloud-magnetosphere coupling. To investigate the magnetic structures inside the BL is our first step to try to understand this role.

2. Analyses and Results

[4] On the basis of the work [*Wei et al.*, 2003], we have analyzed 23 BLs using the magnetic field data

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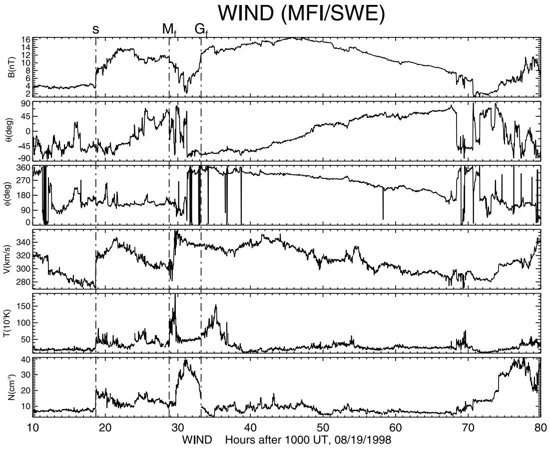

Figure 1. A magnetic cloud and its boundary layer (0450–0913 UT) bordered by two vertical lines (M_f, G_f), observed by WIND spacecraft on Aug. 20, 1998. Here, total magnetic field magnitude B, latitudinal angle θ and azimuthal angle ϕ, velocity v, temperature T, and number density N are given.

(3 seconds resolution) observed by WIND spacecraft during the period of 1995–1998. As an example, a magnetic cloud event on Aug. 20, 1998 and its BLs (04:50–09:13UT) are given in Figure 1. We can see several basic structures as follows: An interplanetary sheath region begins at 1845UT on Aug. 19, 1998, with a shock discontinuity ahead of the sheath (marked by a vertical line with the letter S); A boundary layer, labelled by the two vertical lines with the letter M_f and G_f, begins at 0450UT on Aug. 20 1998; after the layer the MC begins at 0913UT on Aug. 20 1998; and a tail BL possibly begins at 2200UT on Aug. 21, 1998, which is identified with certain ambiguity due to the overtaking effect from a higher speed flow. Their basic features have been described by *Wei et al.* [2003]. The main difference of the BL from the sheath and the cloud lies in the magnetic field behaviors. Its magnetic structures will be analyzed further below.

2.1. B_z Fluctuations in the BL

[5] As *Wei et al.* [2003] suggested, the BL is formed through the interactions of the MC with the SW. Thus it is not surprising that the behavior of magnetic fields and plasmas will undergo certain changes across the BL. For example, Figures 2a and 2b show from top to bottom respectively the distribution functions F_1, F_2 and F_3 of the fluctuation of the field southward component in the SW, inside the BL and in the MC on Sep. 21, 1997 and Feb. 8, 1995. We can see that the distribution function undergoes significant changes across the BL. The fluctuation amplitude in Figure 2a have enhanced from ±2.5 nT in the SW to ±7.0 nT in the BL. The magnitude and direction of the average field $\langle B_z \rangle$ have also changed, rotating from the southward -4.04 nT in the SW to the northward 0.29 nT inside the BL, and $\langle B_z \rangle = 1.55nT$ in MC is mainly determined by the nature of the cloud itself. These changes can also be seen in Figure 2b. Similar changes in the B_z may be found almost in all BLs of the MCs. It implies that intensive interactions have occurred inside the BL, but there is no significant influence on the B_z in MC.

2.2. "Walks" of the BL Field Vectors

[6] We adopt the general Minimum Variance Analysis Method to analyze the "walks" of the BL field vectors in

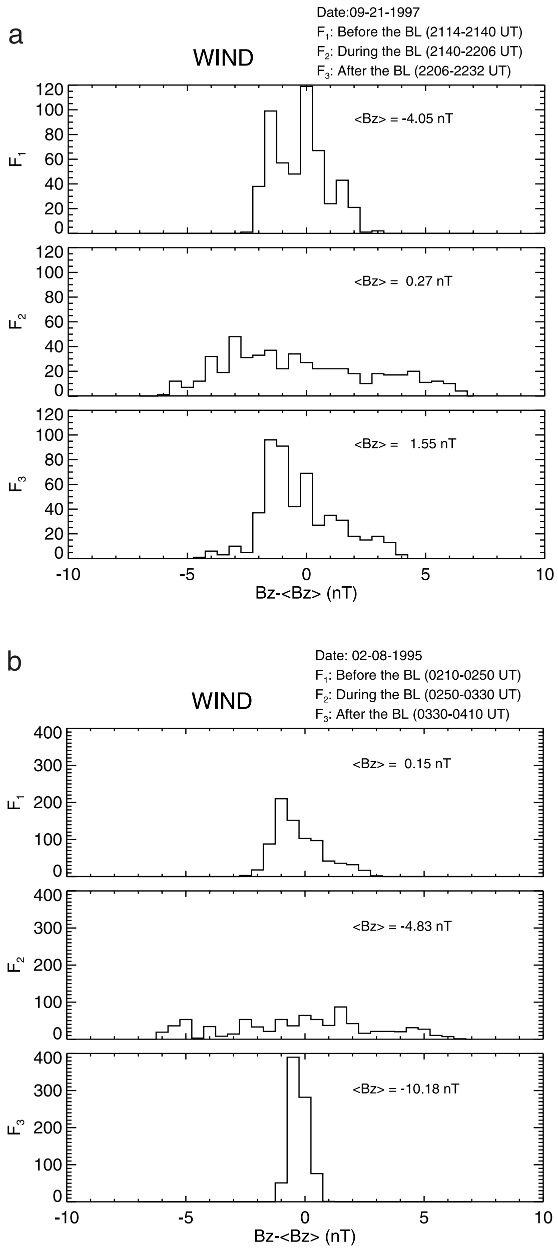

Figure 2. Comparison of distribution functions for the southward component fluctuations of interplanetary magnetic fields, ΔB_z ($B_z - \langle B_z \rangle$), in the background solar wind (the top), the boundary layer (the middle) and the magnetic cloud (the bottom). (a) The magnetic cloud event on Sept. 21, 1997. (b) The magnetic cloud event on Feb. 08, 1995. In the Figures F_1, F_2, F_3 and $\langle B_z \rangle$ represent the distribution functions analyzed intervals before, during and after the boundary layer and the averaged B_z over the interval investigated, respectively. The interval length averaged is the same for all features SW, BL and MC and is labelled in the top right corner.

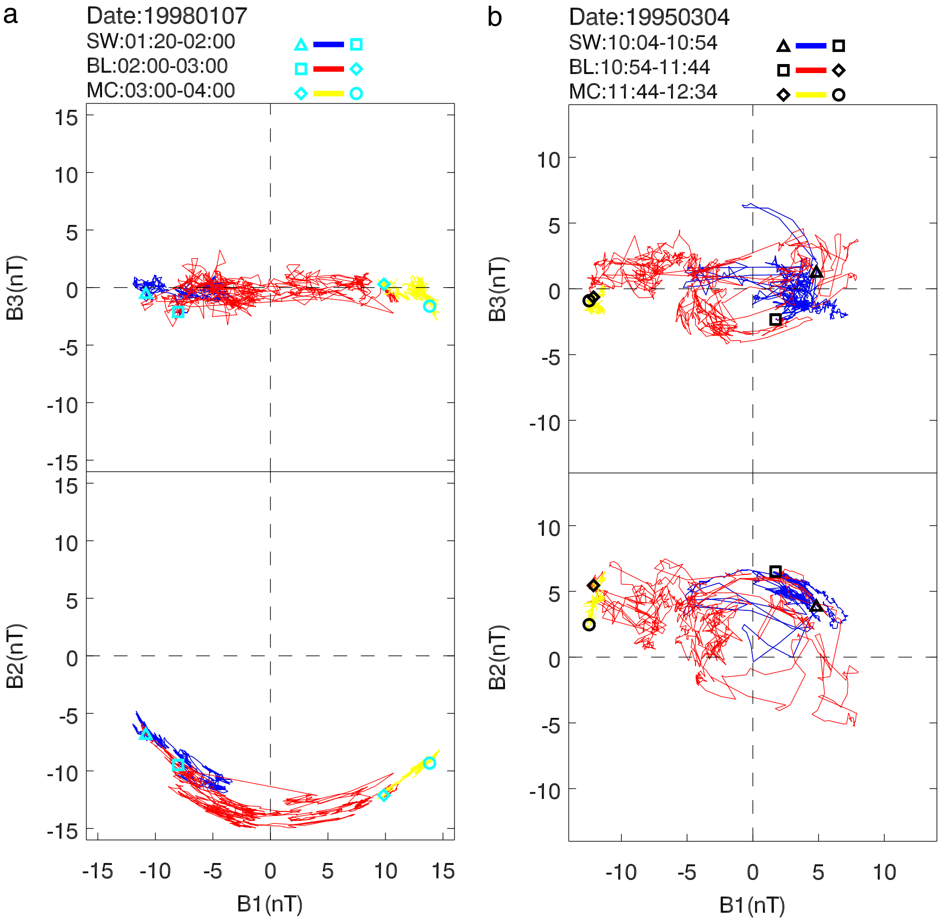

Figure 3. The variation of magnetic field observed by WIND, plotted in the principal axis coordinate system where B_1, B_2, and B_3 are in the maximum, intermediate and minimum variances, respectively. (a) The first type walk, the B_3 component is very small and the transverse components, B_1 and B_2, vibrate along an arc mainly in the quadrant, $(\pm B_1, -B_2)$ in the MVP. (b) The second type walk, the transverse components, B_1 and B_2, walk randomly in the MVP. In Figure 3, the analyzed intervals are noted in the top, the blue, red and yellow lines represent the SW, BL and the MC, respectively. The position of the initial magnetic field vector of each interval is indicated by a triangle (△), square (□) and rhombus (◇), respectively and the final position of the last magnetic field vector by a circle (○).

the Maximum Variance Plane (MVP) composed of the maximum and intermediate variance directions, $\mathbf{B}_1$ and $\mathbf{B}_2$. The behavior of the "walk" in the BLs could be classified into two types as follows. The first type: The tips of field vectors vibrate along an circular arc in the MVP, and the magnetic field in the minimum variance direction, $\mathbf{B}_3$, is close to zero. Typical examples are given in Figure 3a, which show that the magnetic vectors in the SW (blue), in the BL (red) and in the MC (yellow) often vibrate along different circular arcs. This behavior may be caused by the Alfvenic fluctuations, the similar situation has been discussed by *Tsurutani et al.* [1994]; the second one: The tips of field vectors walk relatively randomly and its radius may change in a large region in the MVP, as shown in Figure 3b. This random walk could be relative to enhanced turbulence and complex structures. The BLs of the two types of wlaks used for the analysis are given below, where the time interval in bracket stands for the beginning and ending of the BLs.

[7] The first type: 950208(0250–0326), 951018(1820–1904), 960701(1500–1800), 961225(1130–1206), 970110(0350–0443), 970515(0730–954), 971010(2024–2200), 971107(0440–0600), 980106(2220–2600), 980204(0220–0500), 980304(1400–1440), 980602(0912–1032), 980918(0256–0353), 981019(0357–0423). The second type: 950304(1057–1143), 961224(0120–0310), 970111(0250–0325), 970715(0448–0612), 970803(1000–1400), 970918(0250–0400), 970921(2146–2208), 970922(1726–2006), 980820(0440–0916).

2.3. Distributions of the ϕ, θ Angles in the BL

[8] For most cases, as showed in Figures 4a and 4b, the distributions of the ϕ, θ angles in BL fields exhibit an asymmetrical "U" or reverse "U" shape, which will depend on the BL fields whether directed to the above (North) or the below (South) of the heliospheric current sheet. The data points ϕ, θ concentrate basically on one "leg" and a spacing of about 180 degrees between the two "legs", which is consistent with the existence of the field reverse region. Obvious Alfvenic fluctuations are often observed inside this kind of BLs, for example, the magnetic clouds 19961225, 19970515, 19970803, 19980304, 19980204 and etc.. In addition, we can see the annihilation of the magnetic field in the field reverse region at the two legs, which could be

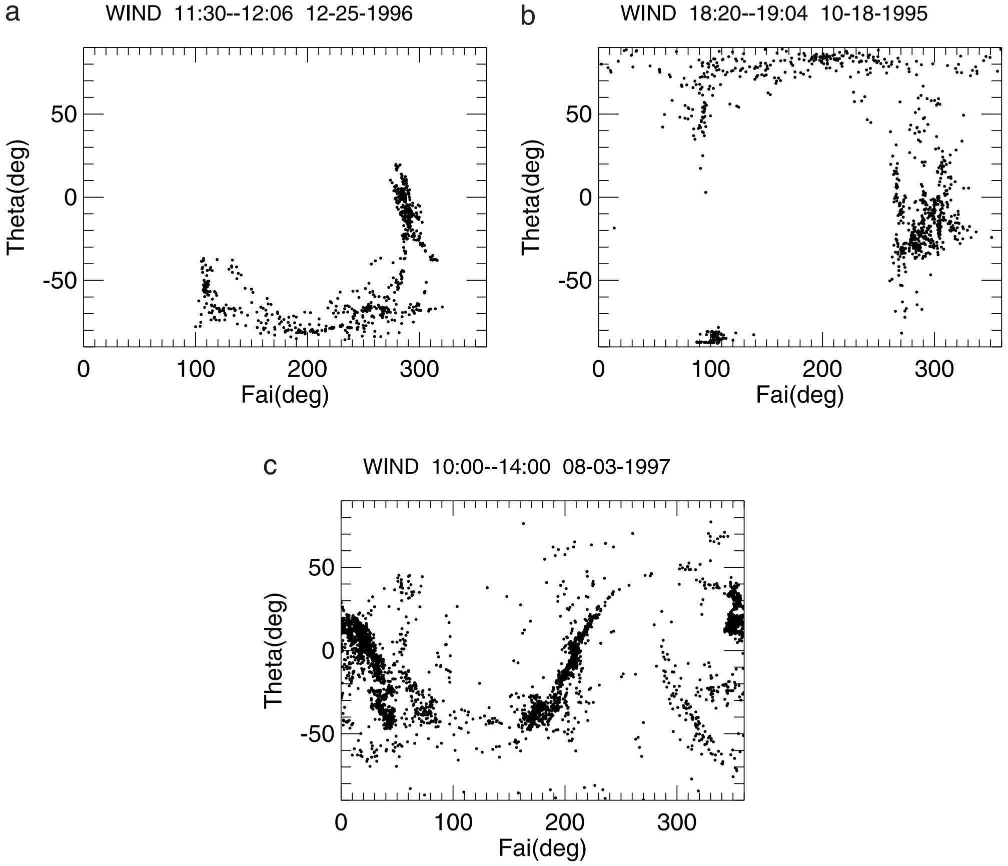

Figure 4. θ-ϕ diagram of the magnetic field in the BL. (a) Usually, ϕ, θ angles in the BL exhibit an asymmetrical "U" or (b) reverse "U" shape. (c) Sometimes, a sine-like distribution, similar to that of planar magnetic structure, may appear in the BL.

speculated as a diagnosis for the magnetic reconnection possibly occurring in the BL. The distribution of the ϕ, θ angles in the front boundary layer during 1000–1400 UT on Aug. 3, 1997 looks like a sine-like distribution showing twice field reversal (Figure 4c). It is similar to the distribution of Planar Magnetic Structures [*Nakagawa et al.*, 1989], which is totally different from the distributions of the Alfvenic fluctuation, sector boundary and flux rope.

3. Conclusion and Discussions

[9] The paper presented here is to show that the BL of the MC has its own magnetic structures which are totally different from those in the SW or inside the MC. It is an important structure closely related with the interaction process between the MC and the SW. One role of the BL would affect the properties of the interplanetary southward field. Thus, it could affect the initiation of the interactions of the cloud with the magnetosphere, since the earth's magnetosphere could be immersed in the boundary layer for about 1 $\sim$ 3 hours. The behavior of the magnetic field inside the BL may denote or preserve the information about the interaction between the MC and the SW. For example, the U or reverse U-like distributions in ϕ-θ and the walk's way of fields in the MVP could provide some diagnosis for Alfvenic fluctuation, directional discontinuity and the magnetic reconnection in the BL. The physical processes occurring in the BL will be a hard topic. In addition, the relationship between the structure of the BL with the basic structures of CMEs is a very interesting topic to be studied deeply.

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