The evidence for the evolution of interplanetary small flux ropes: Boundary layers

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We have examined the Wind data in 1996 and identified 21 small interplanetary magnetic flux ropes (SIMFRs), and all the 21 SIMFRs have boundary layer structures. The durations of the boundary layers varied from several minutes to 30 minutes. These boundary layers also have properties of high proton temperature, density, and plasma beta. These boundary layers are formed by magnetic reconnections. In addition, in three events magnetic reconnections were occurring inside the boundary layers. It indicates that the flux rope structures have propagated for some period of time, and their boundaries were still evolving through interaction with the background solar wind. Namely it is very possible that the SIMFRs came from the solar corona.

interplanetary small flux ropes, boundary layer, magnetic reconnection exhaust

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The interplanetary magnetic flux ropes (IMFRs) are commonly observed by spacecraft in interplanetary space near 1 AU, their diameter distribution is in the range of 0.0039–0.6266 AU [1–3]. Among these IMFRs, magnetic clouds (MCs) have large-scale structures whose diameters are more than 0.20 AU [4–6]. MCs are an important subset of interplanetary coronal mass ejections (ICMEs), which are interplanetary manifestations of transient events with large amounts of material ejected from the solar atmosphere. A MC was originally defined empirically in terms of in situ spacecraft measurements of magnetic fields and particles in the interplanetary medium at ~1 AU, viz., it has the following necessary properties: (1) the magnetic field direction rotates smoothly through a large angle during an interval of the order of 1 day; (2) the magnetic field strength is higher than average; and (3) low proton temperature compared to the ambient proton temperature [7]. MCs have received considerable attention and have been intensively investigated by many

people in the last decade with a focus on the magnetic and plasma structures, its solar origins, and relevant geomagnetic activities [8–15]. In addition to large-scale MCs, only a few studies have been conducted on small interplanetary magnetic flux ropes (SIMFRs), and their origin still remains disputed [2,3,16–18]. Moldwin et al. first reported several SIMFRs, and suggested that these SIMFRs may be a result of the magnetic reconnection at the heliospheric current sheet at ~1 AU [1,2]. Their main evidence is the lack of intermediate-sized events (durations of several hours). If SIMFRs and MCs are of the same physical origin, the size distribution should be continuous. Then Wei et al. suggested that SIMFRs had a larger scale initially and came from the corona, and their magnetic fields were peeled off by the magnetic reconnections near their boundaries when moving from the Sun to the Earth and at last they reached a small scale [19]. Recently, Feng et al. found that IMFRs have a continuous size distribution. Their analysis of IMFRs with different scales showed that the physical properties of the IMFRs changed slowly with their increasing scales [3]. Therefore, Feng et al.

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suggested that SIMFRs also originate in the solar corona and are interplanetary manifestations of small solar transients.

The identification of boundaries of IMFRs has been an important problem in the investigations related to IMFRs, however, the boundaries of magnetic flux ropes are not always evident. Many properties of MCs have been found and are used to confirm the MC boundaries, such as the low plasma beta [20], the presence of increased helium abundance relative to protons [21], bi-directional ion and electron beams [22,23], an increase in the magnetic field strength, the smooth rotation of magnetic field direction, the low proton and electron temperature [24]. However, different criteria may yield different boundaries, and some approaches are to no avail in identifying the boundary of a certain event. Thus these ambiguities make the identification of MC boundaries a difficult problem. Wei et al. found that the magnetic cloud boundary is not a simple discontinuity based on the statistical analysis of many magnetic clouds [19]. They found that the magnetic cloud boundary is a boundary layer that is formed through the interactions between the magnetic cloud and the interplanetary medium (namely magnetic reconnection). Most MCs have boundary layers displaying a drop in magnetic field magnitude and a significant change in field direction. These boundary layers also have properties of high proton temperature, density, and plasma beta. Wei et al. argued that these boundary layers can form through the magnetic reconnection process as a result of the interactions between the MCs and the ambient medium, and the dimensions of IMFRs can decrease due to the magnetic reconnections near their boundaries as they propagate away from the Sun. Then, Wei et al. suggested that small IMFRs may have a larger scale initially, but when the magnetic reconnection process occurs near the boundaries, their magnetic fields are peeled off when moving from the Sun to the Earth and at last they reached a small scale [19]. If their suggestion is correct, these small IMFRs should also have the boundary layer structure. In addition, if SIMFRs came from the corona, the SIMFRs should also have the boundary layer structure. Our purpose is to investigate whether SIMFRs have the boundary layer structures or not. The boundary layers were formed through the interactions between the IMFRs and the interplanetary medium when the IMFRs propagate in interplanetary space. Therefore, if almost all the SIMFRs have the boundary layer structures, it means that the flux rope structures have propagated for some period of time, and it is very possible that the SIMFRs came from the solar corona.

1 Data analysis

In this study 3-sec-averaged plasma and magnetic field data measured by Wind are used, and the magnetic field data obtained from Magnetic Field Investigation (MFI) magnetometer and the proton data obtained from the 3-Dimension Plasma (3DP) analyzer [25,26]. We have examined the Wind

data in 1996 and identified 21 SIMFRs which are listed in Table 1. Here, we identify a SIMFR through the following steps: (1) the candidate of SIMFRs is selected by identifying the rotation of magnetic field direction and enhanced magnetic field strength (compared to the ambient medium) with naked eyes; (2) then we examine the correlation coefficient of the velocity and magnetic field components to exclude the possible Alfvén wave structures, if their field and velocity components have a correlation coefficient greater than 0.6, it is considered to be Alfvén wave structures [27–30]; (3) last we use the geometric parameter of the flux rope to identify the possible events, namely we define it as the magnetic field variation which can be fitted to the cylindrical constant-alpha force-free field. When the difference between the model geometry and the observation data is larger than a criterion value ($\sqrt{\chi^2} = 0.3$), the case is not considered as a flux rope. The deviation can be expressed by the minimum chi-square χ^2 (see eq. (2) of Feng et al. [17]). A detailed description of the fitting method can be found in Feng et al. [17]. In addition, we also referred to the SIMFR lists published in the literature [16,17].

2 Results

According to the boundary layer criteria used by Wei et al. [19], the high-resolution (3 s) magnetic field and plasma data from Wind were examined; it was found that all the 21 SIMFRs have boundary layer structures. Table 1 lists the identi-

Table 1 The boundary layers of Small interplanetary flux ropes in 1996

No. ^{a)}	F ₁ ^{b)}	F ₂ ^{c)}	R ₁ ^{d)}	R ₂ ^{e)}
1	1996-01-28 22:13	22:22	22:58	23:09
2	1996-02-03 02:38	02:38	03:51	04:07
3	1996-02-06 19:46	20:01	01:36N	01:38N
4	1996-02-08 04:04	04:30	05:39	05:45
5	1996-02-10 17:39	18:41	22:08	22:30
6	1996-02-24 04:38	04:38	05:52	06:07
7	1996-03-02 01:43	01:58	10:07	10:07
8	1996-03-03 13:38	13:38	14:55	15:16
9	1996-03-07 23:58	00:12N	05:19N	05:37N
10	1996-03-08 19:47	19:47	02:56N	03:24N
11	1996-03-09 08:50	09:19	13:58	14:23
12	1996-03-13 09:17	09:27	10:21	10:21
13	1996-04-15 14:31	14:31	15:23	15:33
14	1996-05-02 05:30	05:44	06:47	06:47
15	1996-05-14 21:52	21:59	23:09	23:24
16	1996-05-17 00:42	00:58	04:20	04:50
17	1996-06-20 16:40	16:47	18:30	18:57
18	1996-08-06 00:04	00:26	03:35	03:46
19	1996-08-29 01:10	01:20	02:13	02:13
20	1996-09-01 23:35	23:37	03:07N	03:15N
21	1996-09-13 17:47	17:51	19:04	19:09

a) The code number of the interplanetary magnetic flux rope; b) the beginning of the front boundary layer (UT); c) the end of the front boundary layer (UT), and N indicates the time on a following day; d) the beginning of the rear boundary layer (UT); e) the end of the rear boundary layer (UT).

Figure 1 Interplanetary magnetic field and speed data measured by the Wind spacecraft during the 1996 September 13 SIMFR passage. The vertical lines F_1 and F_2 indicate the start and end times of the front boundary layer, and the vertical lines R_1 and R_2 indicate the start and end times of the rear boundary layer.

fied boundary layers related to SIMFRs. The second and third columns show the start and end times of the front boundary layer, and the fourth and fifth columns list the start and end times of the rear boundary layer. The durations of the front boundary layers varied from 2 to 29 min with a mean value of 12.5 minutes; the durations of the rear boundary layers varied from 2 to 30 min with a mean value of 17.1 min. All the boundary layers have the reconnection features, such as the relatively high proton temperature, high proton density, and high plasma beta, a significant change of the observed field orientation. As Wei et al. pointed out, these features are formed by magnetic reconnection. As an example, Figure 1 shows the magnetic field and plasma data of the magnetic reconnection of the 1996 Sep. 13 SIMFR. The magnitude of the total magnetic field (B_t); the x , y , z components of the magnetic field (B_x , B_y , B_z); the proton speed (V); the proton temperature (T_p); the plasma beta; and the proton density (N) are shown from the top to the bottom of the panels. The coordinate system is the geocentric solar ecliptic (*GSE*) Cartesian system. From Figure 1 it is easy to see that the SIMFR displays a smooth rotation of the magnetic field direction. One can also find that the bipolar field appears in the (B_z) component. These are all classic flux rope signatures. The front and

rear boundary layers are labeled by “F1–F2” and “R1–R2”, respectively. Inside the boundary layers, the total magnetic field strength decreased sharply, reaching a minimum near the center. It can also be seen that the proton temperature, number density, plasma beta, and proton velocity increased considerably compared with the plasma in the adjacent background solar wind and the SIMFR body. They are the typical characteristics of boundary layers. As mentioned above, the relatively high proton temperature, high proton density, and high plasma beta are possibly formed by magnetic reconnection, and the outer boundary is a possible happened reconnection exhaust boundary. Among the 21 SIMFRs, three events provided sure-enough evidence of An example will be presented later magnetic reconnections were happening inside the boundary layers. Then we will give a detailed example. In addition, some SIMFRs have no front, in two locations here or rear boundary layers. We further analyzed the observational characteristics of the SIMFR events without front or rear boundary layers and found that the plasma and magnetic field characteristics are similar before and after the boundary, and the orientation of B straddled a relative small change ($< 100^\circ$).

Figure 2 shows the velocity and interplanetary field data

Figure 2 Interplanetary magnetic field and speed data measured by the Wind spacecraft during the 1996 May 14 SIMFR passage. The vertical lines F_1 and F_2 indicate the start and end times of the front boundary layer. The SIMFR has no rear boundary layer, so the R_1 and R_2 are at the same time. The gray shaded region indicates the magnetic reconnection exhaust.

on 1996 May 14. From Figure 2 it is easy to see that the SIMFR displays a smooth rotation of the magnetic field direction and enhanced magnetic field magnitude. One can also find that the bipolar field appears in the B_z component, and the core field appears in the B_x and B_y components. From Figure 2, we can find that there is a magnetic reconnection exhaust (the shaded region) inside the front boundary layer, and the leading boundary of the magnetic reconnection exhaust is just the outer boundary of the front boundary layer. In addition, Figure 3 also provides expanded views of the magnetic field and velocity curves of the magnetic reconnection exhaust. As can be seen from Figures 2 and 3, the reconnection exhaust is within 21:53:05–21:53:58 UT; the change of the observed field orientation in this exhaust is large (122°); within the exhaust the plasma beta, the proton temperature and density are all higher than outside; The magnetic field strength is weaker than that of the surrounding solar wind; the changes in V and B are correlated with one another at the front boundary of the event and are anticorrelated at the rear boundary; the ambient solar wind has a low proton beta (< 0.3). These features satisfy the criteria of the reconnection exhausts [31]. These observations indicated that the magnetic flux in the flux rope was decreasing by the magnetic reconnection. It means that the magnetic fields are peeling off from the magnetic flux rope. Therefore, the spatial scale of the flux rope would diminish gradually, and their boundaries were still evolving through interaction with the background

solar wind, as suggested by Wei et al. [19].

3 Summary and discussion

SIMFRs are widely observed and reported at 1 AU in recent years, but their origin is still debatable [2,3,16,17]. The current studies indicate the generation of SIMFRs has two possibilities. One is that these SIMFRs result from magnetic reconnection in the solar wind well away from the Sun [2,16]. The other one is that the SIMFRs are produced by solar eruptions [3,17,19], that is to say, they are the interplanetary manifestations of small CMEs, or they have a larger scale initially, but when the magnetic reconnection process occurs near the boundaries, their magnetic fields are peeled off when moving from the Sun to the Earth and at last they reach a small scale [19]. If these small IMFRs came from the corona, like MCs, the SIMFRs should also have the boundary layer structures. We have examined the magnetic field and plasma data around the boundary of the SIMFRs in 1996, and found that all the identified 21 SIMFRs have boundary layer structures. Like the duration of SIMFR is shorter than that of MC, the duration of the boundary layer of SIMFR is also shorter. The durations of the boundary layers varied from several minutes to 30 minutes. These boundary layers also have properties of high proton temperature, density, and plasma beta. In addition, three magnetic reconnection exhausts were found inside

Figure 3 Interplanetary magnetic field and speed data measured by the Wind spacecraft during the 1996 May 14 magnetic reconnection exhaust passage. The dotted vertical lines indicate the beginning and the end of the reconnection exhaust.

the boundary layers. It implies that the boundary layer was formed through the magnetic reconnection process as a result of the interactions between the magnetic cloud and the interplanetary medium. Therefore, it is possible that some SIMFRs have larger scales initially and come from the corona; their magnetic fields are peeled off when moving from the Sun to the Earth, where they reach small scales [19]. Nevertheless, it is also possible that these SIMFRs have less scales than normal MCs when they erupt in the corona. These observational facts at least indicated that the flux rope structures have propagated for some time, and their boundaries were still evolving through interaction with the background solar. Namely it is very possible that the SIMFRs came from the solar corona. In addition, there is a large body of evidence of small eruptions in the literature, such as small CME, plasma blobs, X-ray bright sigmoidal structures, X-ray plasmoids [32–38]. The correlation between the small eruptions and small-scale IMFRs may exist and our future work will include a survey of their correlation.

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