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Cluster-C1 observations on the geometrical structure of linear magnetic holes in the solar wind at 1 AU

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Abstract. Interplanetary linear magnetic holes (LMHs) are structures in which the magnetic field magnitude decreases with little change in the field direction. They are a 10–30% subset of all interplanetary magnetic holes (MHs). Using magnetic field and plasma measurements obtained by Cluster-C1, we surveyed the LMHs in the solar wind at 1 AU. In total 567 interplanetary LMHs are identified from the magnetic field data when Cluster-C1 was in the solar wind from 2001 to 2004. We studied the relationship between the durations and the magnetic field orientations, as well as that of the scales and the field orientations of LMHs in the solar wind. It is found that the geometrical structure of the LMHs in the solar wind at 1 AU is consistent with rotational ellipsoid and the ratio of scales along and across the magnetic field is about 1.93:1. In other words, the structure is elongated along the magnetic field at 1 AU. The occurrence rate of LMHs in the solar wind at 1 AU is about 3.7 per day. It is shown that not only the occurrence rate but also the geometrical shape of interplanetary LMHs has no significant change from 0.72 AU to 1 AU in comparison with previous studies. It is thus inferred that most of interplanetary LMHs observed at 1 AU are formed and fully developed before 0.72 AU. The present results help us to study the formation mechanism of the LMHs in the solar wind.

Keywords. Interplanetary physics (Interplanetary magnetic fields; Plasma waves and turbulence; General or miscellaneous)

1 Introduction

Magnetic holes (MHs), also called magnetic decreases (MDs), are structures in interplanetary space with significant decreases in the magnetic field magnitude (e.g., Turner et al., 1977; Winterhalter et al., 1994; Tsurutani and Ho, 1999; Stevens and Kasper, 2007; Vasquez et al., 2007; Tsurutani et al., 2009). Turner et al. (1977) discovered the magnetic holes in the interplanetary magnetic field, and they defined a subset of holes which have no or little change in the magnetic field direction as the "linear" magnetic holes. It should be noted however that most magnetic holes in interplanetary space are not "linear" (Winterhalter et al., 1994; Tsurutani et al., 2009). There is also one type of interplanetary magnetic hole/decrease associated with phase-steepened Alfven waves (Tsurutani et al., 2005a, 2009), and other types of magnetic holes are current sheets or other structures (e.g., Fitzenreiter et al., 1978; Zhang et al., 2008). Magnetic holes we studied in this paper are interplanetary linear magnetic holes, a small subset of interplanetary magnetic holes.

Mirror mode structures have been detected in the magnetosheaths of the Earth, Jupiter and Saturn (Tsurutani et al., 1982, 1984; Balogh et al., 1992; Violante et al., 1995; Bavassano Cattaneo et al., 1998; Baumjohann et al., 1999; Lucek et al., 1999; Soucek et al., 2008; Balikhin et al., 2009). They are characterized by small or no changes in the magnetic field across the structures, with scale of tens of proton gyroradii. The magnetic structures have both magnetic decreases/holes and enhancements/peaks (Tsurutani et al., 1982). These structures have been generated by the mirror mode instability (e.g., Hasegawa, 1969, 1975; Southwood

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and Kivelson, 1993; Kivelson and Southwood, 1996, and references therein). Mirror instability is caused by anisotropic heating of ions at the perpendicular portion of the bow shocks and magnetic field line draping (Midgley and Davis, 1963; Zwan and Wolf, 1976). The criteria for instability have been discussed in Chandrasekhar et al. (1958), Vedenov and Sagdeev (1958), and Hasegawa (1969, 1975).

Because interplanetary magnetic holes are observed in mirror mode stable plasma conditions (Winterhalter et al., 1994), other mechanisms such as Compression of Alfven wave phase steepening (Tsurutani et al., 2002a,b, 2005a,b, 2009), the soliton approach (e.g., Baumgärtel, 1999; Sperveslage et al., 2000; Stasiewicz, 2004), large-amplitude Alfvenic wave packets evolution (Buti et al., 2001), directional discontinuity interactions with a shock (Tsubouchi and Matsumoto, 2005), and Alfven wave-wave interaction (e.g., Vasquez, 2007; Tsubouchi, 2007) were also developed and tested by data. All these theories and hypotheses described above were made for all magnetic holes, not just linear ones. At this time, it is unclear whether interplanetary linear magnetic holes may be generated by the mirror instability or not. Researchers that have studied all magnetic holes together assume that they are not. Tsurutani et al. (2009) concluded magnetic holes found inside CIRs are most probably not created by the mirror instability.

Shi et al. (2009a) studied mirror mode structures in the Earth's High-altitude Cusp using multi-point observations of Cluster. Velocities and directions of the structures were calculated quantitatively using the methods described in Shi et al. (2005, 2006) (also briefly introduced in Shi et al., 2009b), and it is confirmed that the mirror mode structures observed are spatial structures travelling across the satellite one after another. Since it is difficult to stimulate mirror mode instability due to the small beta value and the weak anisotropy in the Earth's high-altitude cusp, it is suggested that nonlinear mirror mode structures in the magnetosheath could be transported into the Earth's High-altitude Cusp due to the fact that mirror mode structures are found to be transported downtail (Tsurutani et al., 1984).

In recent years, many studies on magnetic holes have been carried out with a lot of new findings (Zhang et al., 2008, 2009; Shi et al., 2009a). Zhang et al. (2008, 2009) investigated the linear magnetic holes in the solar wind at 0.72 AU using Venus Express data, believing that the linear magnetic holes may be mirror mode structures in the solar wind. Their results show that the occurrence rate of linear magnetic holes in the solar wind at 0.72 AU is about 4.2 LMHs per day, and the shapes of magnetic holes are rotational ellipsoids. Russell et al. (2008) find that the occurrence rates of linear magnetic holes roughly have no decrease in the solar wind from 0.34 AU to 8.9 AU. As we know, the geometrical structure of the linear magnetic holes in the solar wind at 1 AU has not been studied before.

It is the purpose of this work to study the characteristics of linear magnetic holes in the solar wind near the earth. Using magnetic field data provided by Cluster-C1 from 2001 to 2004, we study the linear magnetic holes in the solar wind, investigate their geometric shape and occurrence rate, and compare our results with those obtained by Zhang et al. (2008) at 0.72 AU.

2 Identification of interplanetary linear magnetic holes

In order to resolve all the small scale linear magnetic holes in the solar wind, we use the Cluster-C1 magnetic field data (Flux Gate Magnetometer, FGM, Balogh et al., 2001) with a resolution of 5 samples per second from 2001 to 2004. Cluster spacecraft only spend a relatively small portion of time traveling in the solar wind during an orbiting period. We estimate whether the satellites are in the solar wind by Cluster-C1 magnetic field data (Balogh et al., 2001) and HIA (Hot Ion Analyzer) data of the CIS (Cluster Ion Spectrometry) instrument (Reme et al., 2001). It is easy to find out the time period when the spacecraft are in the solar wind with higher velocity, lower ion density, temperature, and magnetic field magnitude compared to those in the magnetosheath.

We use the criteria of $B_{\min}\big/B < 0.75$ and $\omega < 15°$ to identify the interplanetary linear magnetic holes, which are the same as those used by Zhang et al. (2008), where $B_{\min}$ and B are the minimum and average field magnitudes within a sliding window of 300 s in length separately, and ω is the direction change angle between the initial and the last vector nearest to the two boundaries of a magnetic hole.

We use the procedure similar to that used by Winterhalter et al. (1994) to find out interplanetary linear magnetic holes automatically, which is also similar to that used by Zhang et al. (2008). The magnetic field data are continuously scanned within a 300 s interval, the minimum value of magnetic field is found out to serve as $B_{\min}$, the average of field magnitude B is calculated and the interplanetary linear magnetic holes which meet our criteria are identified. And the program also determines the width of each hole, that is, the interval from the beginning of the holes to the end, as well as the field rotation angle ω across the hole. The program outputs $B_{\min}\big/B$, ω, $B_{\min}$, B, standard deviation δ, and the time duration of the magnetic hole being crossed by the spacecraft. After the automatically calculation, we use magnetic field plots to examine the interplanetary linear magnetic holes and only the events with relatively steady ambient magnetic field background are selected as what has been done by Zhang et al. (2008). Zhang et al. (2008, 2009) defined a train of magnetic holes when at least two magnetic holes are found in a 300 s window. If only one magnetic hole is found, it is called a single magnetic hole. In our work we use the same classification as they have taken.

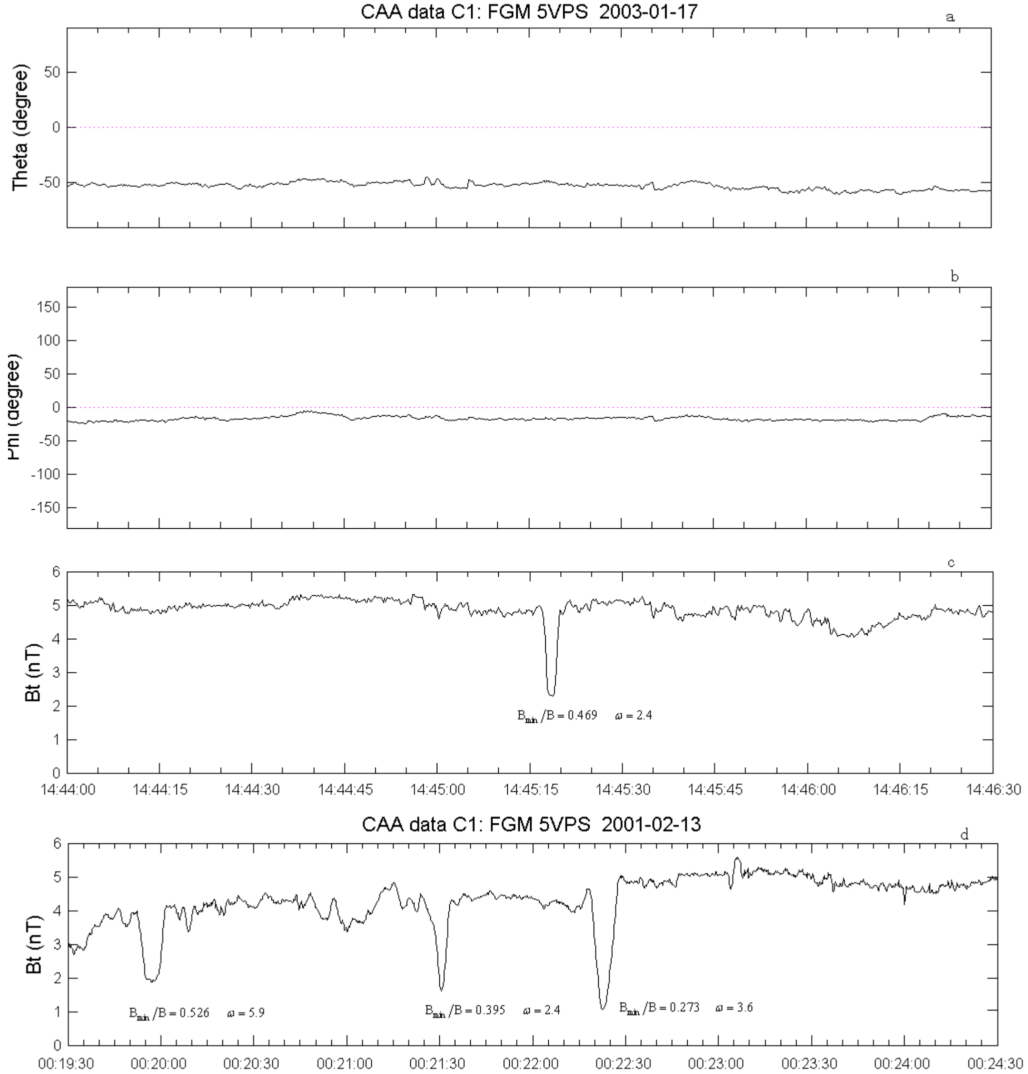

Fig. 1. (a)–(c) A typical example of a single magnetic hole in the solar wind observed by Cluster C1, (a) the polar angle, (b) the azimuthal angle (c) the field magnitude. **(d)** The field magnitude of a magnetic hole train with 3 magnetic holes in 300 s.

Figure 1a–c shows a typical single interplanetary linear magnetic hole event. Figure 1c shows that the magnetic field magnitude of the linear magnetic hole drop significantly from about 4.9 nT to 2.3 nT in about 2.4 s, and with little field directional change after crossing the structure as illustrated by Fig. 1a and b. Figure 1d shows a magnetic hole train, in which there are three linear magnetic holes.

3 Statistical results

We find 67 interplanetary linear magnetic holes (LMHs) in 2001, 78 LMHs in 2002, 229 LMHs in 2003 and 193 LMHs in 2004, respectively, and totally 567 interplanetary linear magnetic holes from year 2001 to 2004. To make comparisons with Zhang et al. (2008)'s results at 0.72 AU, we take the train as one single event which represented by the largest hole in the group as they have done when calculating the geometrical shape and the occurrence rate of linear magnetic holes.

3.1 Geometry of the magnetic holes

3.1.1 Relationship between the duration of magnetic holes and the field orientation

We use 567 interplanetary linear magnetic holes to study the geometry of the linear magnetic holes. Figure 2 shows the durations as a function of the orientation of the magnetic field ($\left|B_x/B\right|$), where B_x is the x component of the magnetic field in GSE coordinate system where x component points towards the sun and B is the total magnetic field at the beginning of the magnetic holes. The average values for each 0.1 $\left|B_x/B\right|$ bin are shown by the asterisks in

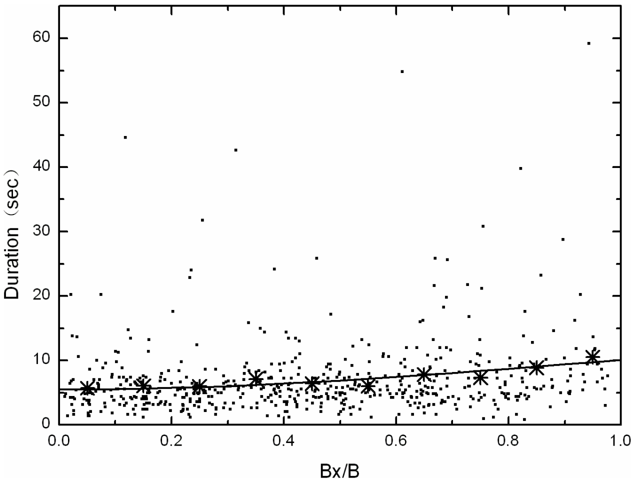

Fig. 2. Magnetic hole duration versus the orientation of the magnetic field deduced from Cluster-C1 data. The orientation of the magnetic field is represented by the value of $\left|B_x/B\right|$, where B_x is the x component of the magnetic field at the beginning of the magnetic holes. Small crosses represent the 567 LMHs selected for this study. asterisks are the medians for each 0.1 $\left|B_x/B\right|$ bin. The curve fitting are presented based on the asterisks.

Fig. 2. From the curve of Fig. 2, which is described by $\mathrm{Dt}^2 = 71.92\left|B_x/B\right|^2 + 29.84(s^2)$ with the correlation coefficient 0.908 from linear regression of $\left|B_x/B\right|^2$ on Dt^2, where Dt is the duration of the linear magnetic holes we find that there are two characteristic time. One is 10.1 s when $\left|B_x/B\right|$=1, and the other is 5.5 s when $\left|B_x/B\right|$=0. The ratio of the two is about 1.84:1 and this makes it possible for us to study the shape of magnetic holes as follows.

3.1.2 Relation between the scale of linear magnetic holes and the field orientation

Tsurutani et al. (2005) have used multi-satellite techniques to show that interplanetary magnetic holes are nonpropagating. We suppose that the interplanetary linear magnetic hole structure is non-propagating in the plasma frame. Since the main velocity of the solar wind in GSE is V_x, we consider that the satellite travels across the magnetic holes along the direction of the x component of solar wind. We have $\left|B_x/B\right| = \cos\theta(0° \le \theta < 180°)$, where θ is the angle between the path of the satellite across the linear magnetic hole structures and the background magnetic field direction. Therefore, the satellite is travelling across the interplanetary linear magnetic holes perpendicular to the magnetic field direction when $\left|B_x/B\right|$=0 and along it when $\left|B_x/B\right|$=1. The duration of linear magnetic holes in our study is less than 60 s. The average time for the satellite travel across the structures along and perpendicular to the magnetic field is about 10.1 s and 5.5 s, respectively.

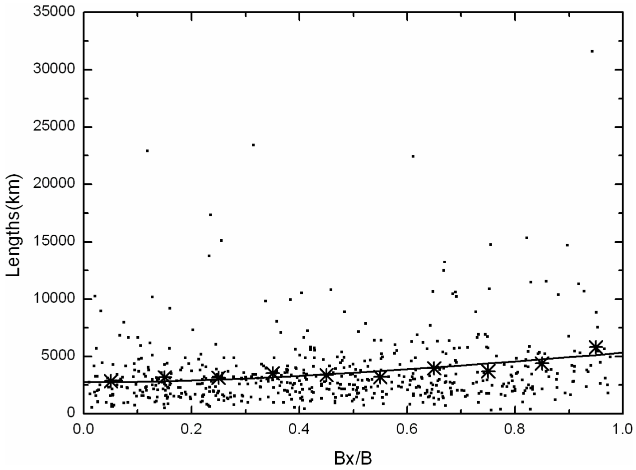

Fig. 3. The relation between scales of the magnetic holes and the orientation of magnetic field deduced from Cluster C1 data. The abscissa represents the value of $\left|B_x/B\right|$, the ordinate is the scale of each magnetic holes Length. Small crosses are the 567 events selected for this study. Asterisks are the medians for each 0.1 $\left|B_x/B\right|$ bin. The curve fitting are presented based on the asterisks.

If the shape of the structures could be fitted with an ellipsoid, the length as a function of the orientation of the magnetic field should be a hyperbolic equation. We fit the shape of every structure with an ellipsoid, similar to previous work by Zhang et al. (2008), and calculate its traversing length by the solar wind velocity measured by Cluster. The results are displayed in Fig. 3. The ordinate represents the scale of linear magnetic holes which is the product of the measured solar wind velocity and the duration of the interplanetary linear magnetic holes, while the abscissa is $\left|B_x/B\right|$. The average values for each 0.1 $\left|B_x/B\right|$ bin are shown by the asterisks in Fig. 3. We could find that the scale across the interplanetary linear magnetic holes L as a function of $\left|B_x/B\right|$ is best fitted with hyperbola equation described as $L^2 = 2.1\times10^7\left|B_x/B\right|^2 + 7.6\times10^6(\mathrm{km}^2)$, and the correlation coefficient is 0.874 from linear regression of $\left|B_x/B\right|^2$ on L^2. Then the geometric structure of the linear magnetic holes in the solar wind at 1 AU can be consistent with an ellipsoid. From this calculation one find that the length of interplanetary linear magnetic holes along the magnetic field is 5329 km and that across the magnetic field is 2757 km, and the ratio of scales along and across the magnetic field is about 1.93:1. The eccentricity of the ellipsoid corresponding to the interplanetary linear magnetic hole structure is 0.86.

Zhang et al. (2008) investigated the structure of linear magnetic holes (which they deemed as mirror modes) in the solar wind at 0.72 AU using Venus Express magnetic field measurements. In order to calculate the scales of linear magnetic holes, they suppose the solar wind sweep by the

Table 1. LMHs in the solar wind found by Cluster C1 from 2001 to 2004.

year	2001	2002	2003	2004	total
LMH number*	57(s)+10(t)=67	59(s)+19(t)=78	196(s)+33(t)=229	149(s)+44(t)=193	461(s) +106(t)=567
C1 in solar wind (days)	15.80	17.61	65.06	56.22	154.69
Occurrence rate (LMHs/d)	4.2	4.4	3.5	3.4	3.7

* "s" denotes single LMH and "t" denotes LMH train.

spacecraft with a typical velocity of 400 km/s and find that the shape of the mirror mode structure is best represented by a rotational ellipsoid and the ratio of the length of linear magnetic hole structure along and across the magnetic field 2.55:1. In order to compare our study with the result of Zhang et al. (2008), we take the velocity of solar wind as 400 km/s to calculate the scale of the structure. Using the same method as stated above, we get the results that the fitted curve is described as: $L^2 = 1.2 \times 10^7 \left|B_x \big/ B\right|^2 + 4.8 \times 10^6 (\mathrm{km}^2)$ (here we do not show the plot as that in Fig. 3, the length of magnetic holes along the magnetic field is 4035 km and that across the magnetic field is 2185 km, and the ratio of the length of the interplanetary linear magnetic hole structure along and across the magnetic field is 1.85:1. The results are also similar to those of Zhang et al. (2008). Comparing with the result using the measured solar wind velocity, the scale of the linear magnetic holes is smaller, but the ratio shows little change.

From the results above, we can conclude that the geometry shape of the interplanetary linear magnetic hole structure at 1 AU has little variety compared with the result at 0.72 AU, and that the geometry shape of the structure can be also fitted with an ellipsoid.

3.2 The occurrence rate of linear magnetic holes in the 1 AU solar wind

We estimate the occurrence rate of linear magnetic holes in the solar wind at 1 AU referring to the method used by Zhang et al. (2008), in which multi magnetic holes (train) within 300 s are counted as one single event. The results are listed in Table 1. According to our statistics, the satellite have spend 15.80 days in the solar wind during the year 2001, and totally 67 linear magnetic holes are identified. Then the occurrence rate of interplanetary linear magnetic holes in year 2001 is 4.2 LMHs/d. We have obtained totally 78 linear magnetic holes in 17.61 solar wind days in 2002, and the occurrence rate of interplanetary linear magnetic holes is 4.4 LMHs/d. In 2003, the number of the linear magnetic holes are 229, the time that satellite spend in solar is about 65.06 days, and the occurrence rate of interplanetary linear magnetic holes is 3.5 LMHs/d. In 2004 the time that satellite spends in solar wind is about 56.22 days and 193 events are obtained, and then the occurrence rate of interplanetary linear magnetic holes is about 3.4 LMHs/d. We have obtained 567 events in total and the occurrence rate of interplanetary linear magnetic holes is about 3.7 LMHs/d from 2001 to 2004.

Compared with the occurrence rate of interplanetary linear magnetic holes of 4.2 LMHs/d at 0.72 AU calculated by Zhang et al. (2008), one find that the difference is only about 11.9%, that is, the occurrence rate of magnetic holes for 0.72 AU and 1 AU is almost the same.

4 Summary and discussion

We surveyed the interplanetary LMHs from 2001 to 2004 using Cluster-C1 data and analyzed the geometry shape and the occurrence rate of the LMH structures at 1 AU.

The occurrence rate of LMHs observed by Cluster-C1 in the solar wind at 1 AU is 3.7 LMHs/d. Turner et al. (1977) have found 28 MH structures at 1 AU using Explorer 43 data, and the occurrence rate of MHs is about 1.5 MHs/d with the criterion $|B| < 1$ nT. Among 28 MHs they found that 9 changed greatly and 8 with little or no change in the magnetic field direction. Thus the Turner et al. (1977) LMH rate would be ∼0.5 LMHs/d. Since their number of samples was small and the criterion they took was different from ours, the great difference between the occurrence rate they obtained and ours is understandable. Our result is almost the same as that of Zhang et al. (2008) (4.2 LMHs/d) which was obtained at a distance of 0.72 AU from the Sun. It is implied that there are no more interplanetary LMHs generated between 0.72 AU and 1 AU. Russell et al. (2008) studied the occurrence rate of LMHs using different spacecraft in various heliocentric distances (∼0.34 AU, ∼0.72 AU, ∼1.35, ∼5.4 AU, and ∼8.9 AU) from the sun after checking one month of data for each of those distances using the criteria of $B_{\min} \big/ B < 0.5$, which is different form ours ($B_{\min} \big/ B < 0.75$). They found the occurrence rate decreases linearly with increasing distance. Considering the effect that the decline of the occurrence rate is simply caused by the decrease in the angular size in the direction of the structure along the field, they concluded that the number of LMHs from 0.34 AU to 8.9 AU should not be changed (Russell et al., 2008). So our result of the approximately unchanging number of LMHs from 0.72 AU to 1 AU is generally consistent with what Russell et al. (2008) obtained, investigating a larger spatial extension.

Moreover, we calculated the occurrence rate of interplanetary LMHs for different years separately: 4.2 LMHs/d in 2001, 4.4 LMHs/d in 2002, 3.5 LMHs/d in 2003, and 3.4 LMHs/d in 2004. These statistical results are slightly higher in 2001 and 2002, and a bit lower in 2003 and 2004, which might give some clues about the influence of the solar minimum and maximum on the occurrence rate. But clearly, more statistical work is needed in the future.

By using the measured velocity of the solar wind to calculate the dimension of the LMH structure, we find that the geometrical structure of the LMHs in the solar wind at 1 AU can be fitted with a rotational ellipsoid, and the lengths along and across the magnetic field are about 5300 km and 2700 km separately with their ratio about 1.93:1, which is almost the same as the results of Zhang et al. (2008) based on the assumption that the velocity of solar wind is constantly 400 km/s. Therefore not only the occurrence rate, but also the geometry shape of the interplanetary linear magnetic holes has little change statistically between 0.72 AU and 1 AU, which suggests that most of the interplanetary LMHs observed at 1 AU have formed before 0.72 AU and then fully developed to stable structures.

Using data from the Ulysses spacecraft at 5 AU from the Sun, Tsurutani et al. (2009) showed that MHs found within CIRs and located near the forward or reverse shocks were created locally near 5 AU. The interplanetary MHs those were near the CIR interface were phenomenon that were probably created inside 1 AU (in agreement with the present results) and then convected as plasma fossils out to Ulysses distances.

The important result of the Tsurutani et al. (2009) is that there are far greater number of MHs found within CIRs. In this study and the previous Zhang et al. (2008) and Russell et al. (2008) studies, the type of solar wind structure was not taken into account. In a future work, we will separate interplanetary MHs detected within ICME, CIR, high speed streams and slow speed streams. This is beyond the scope of the present work.

Winterhalter et al. (2000) investigated the occurrence of LMHs in the solar wind from –80° to 80° helio-latitude and found different rates between in high speed streams and the near equatorial plane solar wind. They found that about 5 holes per day using the criterion of $B_{\min}/B < 0.5$ and $\omega < 5°$. We will study these distinctions in the future.

Concerning to the mechanism of the formation of the linear magnetic holes, one view of mirror mode instability predicted that the length of the magnetic holes along magnetic fields should be much larger than that across the magnetic fields (Price et al., 1986; Southwood and Kivelson, 1993), but the statistics of ours and Zhang et al. (2008)'s show that their ratio is only 1.93:1 (or 2.55:1) which may not reach the degree of "much larger". This reminds us that the explanation of mirror mode instability to the formation of interplanetary LMHs might not be so perfect, although recent work (Horbury and Lucek, 2009) found that mirror structures may tend to be isotropic in the nonlinear growing phase in the magnetosheath. Whether other explanations introduced in many other literatures (e.g., Baumgärtel, 1999; Sperveslage et al., 2000; Buti et al., 2001; Stasiewicz, 2004; Tsubouchi, 2009; Tsurutani et al., 1994, 2009, and references therein) are more suitable or not is not clear. Zhang et al. (2009) have studied different kinds of LMHs and revealed some evolutionary features of LMHs (mirror mode structures) in the solar wind at 0.72 AU, which might give some clues on the formation mechanism of LMHs. In addition, interaction between the LMHs in the solar wind and the magnetosphere, and the possible influence of LMHs on the space weather are still unknown. Obviously, more work is needed in the future.

The main results of this work can be summarized as follows. By using the measured velocity of the solar wind to calculate the scale of the LMH structure, we get the lengths along and across the magnetic field are about 5300 km and 2700 km respectively with the ratio about 1.93:1 and find that the geometrical structure of the linear magnetic holes in the solar wind at 1 AU can be consistent with a rotational ellipsoid. The occurrence rate of interplanetary LMHs the year 2001 to 2004 is about 3.7 LMHs/d. It is found that both of the shape and the occurrence rate of interplanetary LMHs show no significant change from 0.72 AU to 1 AU in comparison with Zhang et al. (2008)'s study at 0.72 AU, which therefore suggests that most of interplanetary LMHs observed at 1 AU are formed and fully developed before 0.72 AU.

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