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Key Points:

- The solar wind entry rate into the lobes is the same order in different seasons
- The "north-south asymmetry" of SW entry is caused by both magnetic dipole tilt and IMF Bx
- The IMF By (with Bx) affects event occurrence, as expected from Parker Spiral

Solar wind plasma entry observed by cluster in the high-latitude magnetospheric lobes

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Abstract

Using the Cluster data during the period from January to April between 2001 and 2006, we find an observation of solar wind entry due to magnetic reconnection occurred in the terrestrial high-latitude magnetospheric lobes, tailward of the cusps under northward interplanetary magnetic field (IMF). Occurrence rate of solar wind entry events in this study is of the same order as that for the Cluster orbital interval from August to October between the years of 2002 and 2004 as reported by Shi et al. (2013). In this paper, we further study the role of the IMF B_x and B_y components in the control of solar wind plasma entry based on the investigations of different magnetic dipole tilt variations between our database and Shi et al. (2013). This study shows that the asymmetry distribution of solar wind entry events in the northern and southern lobes could be caused by the variation of magnetic dipole tilt, which could influence the locations of the reconnection site on the high-latitude lobe magnetopause. On the other hand, IMF B_x can also affect the solar wind plasma entry rate, which is also consistent with previous results. Therefore, we conclude that the "north-south asymmetry" of solar wind entry events in the lobes could be the combined result of magnetic dipole tilt and IMF B_x. In addition, the IMF B_y component can influence the entry events in conjunction with the variation of IMF B_x component, which is in line with the Parker Spiral of the IMF.

1. Introduction

It is well known that although the Earth's magnetic field can prevent plasmas from the solar wind directly interacting with the Earth 's atmosphere, a small portion of the solar wind plasmas can still penetrate into the magnetosphere. The entry of solar wind plasmas into the magnetosphere has become one of the most important issues in space physics and space weather. With the development of the space detection techniques, more and more investigators have focused on the physical mechanism of the solar wind entry into the magnetosphere [e.g., *Freeman*, 2001; *Song and Vasyliunas*, 2010]. *Paschmann et al.* [1979] observed that typically, during southward interplanetary magnetic field (IMF), high-speed plasma existed at the magnetopause, suggesting that solar wind plasmas could enter into the dayside magnetosphere through a dominant, low-latitude magnetic reconnection process. Recently, using a 3-D global-scale hybrid simulation model, *Tan et al.* [2012] found that the cusp ion injections were also associated with the dayside magnetopause reconnection during southward IMF conditions. Furthermore, all the above results were consistent with the theoretical predictions of *Dungey* [1961]. However, many studies have shown that during northward IMF, solar wind plasma could also penetrate into the magnetosphere, which can form a relatively thick and dense plasma sheet and the low-latitude boundary layer [e.g., *Le et al.*, 1996; *Otto and Nykyri*, 2002; *Øieroset et al.*, 2008], although the mechanism of plasma transport during northward IMF is still controversial.

A lot of work has focused on the mechanism of solar wind entry into the magnetosphere under northward IMF conditions. Some processes are associated with the low-latitude entry. For example, *Pu and Kivelson* [1983a, 1983b] pointed out that the surface waves can be excited by the different critical velocities on the two sides of the interface, suggesting that the Kelvin-Helmholtz instability should dominate the energy flux injection into the terrestrial magnetosphere. *Miura* [1984] also proposed that solar wind plasma can be transported across the magnetopause through the Kelvin-Helmholtz (K-H) instability along the flanks of magnetosphere. Cluster multipoint observations were analyzed by *Hasegawa et al.* [2004, 2006] to show that low-density magnetospheric plasmas and tailward speed of a fraction of the magnetosheath flow occur in one rolled-up K-H vortex, which indicates that K-H instability plays an important role in the generation of the low-latitude boundary layer during northward IMF. In addition, *Olson and Pfitzer* [1985] suggested that the solar wind entry into the magnetosphere can also be driven by gradient drift. However, for the high-latitude entry process, many observations support the high-latitude reconnection mechanism [*Dungey*, 1963]. For example, *Song and Russell* [1992] have detected a magnetosheath flux tube reconnecting tailward of the cusp region at high-latitude magnetosphere. *Kessel et al.* [1996] found sunward proton flows which are the direct evidence of high-latitude reconnection during northward IMF. There were also high-latitude reconnection observations from ISEE [*Gosling and Thomsen*, 1996], Polar/Toroidal Imaging Mass-Angle Spectrograph [*Fuselier et al.*, 2000a, 2000b], and Interball Tail [*Avanov et al.*, 2001]. MHD simulation results of *Li et al.* [2005, 2008] further supported that the high-latitude magnetic reconnection might play an important role in the solar wind plasma transport at high-latitude magnetopause. Impulsive penetration has also been suggested as an alternative mechanism of plasma entry, since signatures of transient penetration of magnetosheath plasma have been observed in the dayside magnetosphere [e.g., *Woch and Lundin*, 1991, 1992], although rarely.

Following the above-mentioned studies, using Cluster [*Escoubet et al.*, 1999] multispacecraft data from 2002 to 2004 (between August to October each year) during northward IMF, *Shi et al.* [2013] presented an observation of solar wind entry regions in the Earth's high-latitude magnetospheric lobes tailward of the cusps. Compared with the ions generated through magnetotail reconnection reported by *Fear et al.* [2014], these entry ions had much lower energy. The *Shi et al.* [2013] study further supports the idea that the solar wind plasmas penetrating into magnetospheric lobes may be caused by the operation of high-latitude magnetic reconnection during northward IMF, although we cannot completely rule out the other possible mechanisms (such as tail reconnection presented by *Fear et al.* [2014]). Through statistical analysis, *Shi et al.* [2013] found that the ratio of oxygen ions to protons was decreased within the entry events compared with that in the normally up-flowing ions from the ionosphere [e.g., *Maggiolo et al.*, 2011; *Cowley*, 1980], indicating that these ions entered from the magnetosheath where solar wind ions dominate. Additionally, they also suggested that the IMF B_x component influenced the solar wind entry rate by changing the occurring conditions of high-latitude magnetic reconnection (Figure 4 of *Shi et al.* [2013]). The solar wind entry was further showed to be highly related with the formation of transpolar arcs in the polar region [*Mailyan et al.*, 2015].

In this paper, based on the results from *Shi et al.* [2013], we use Cluster data of another season (January to April) between years of 2001 and 2006. Furthermore, we examine the influence of IMF B_x and B_y on the entry process.

2. Data and Event Selection Criteria

In this study, we have used the data from Cluster spacecraft (SC1), when the spacecraft traveled from the magnetosheath, through the midlatitude cusp and high-latitude lobes into the inner magnetosphere. Specifically, we have used the magnetic field data from Fluxgate Magnetometer (FGM) [*Balogh et al.*, 2001], the ion density data from Cluster Ion Spectrometry (CIS) experiment [*Reme et al.*, 2001] onboard Cluster, and the solar wind parameters and the interplanetary magnetic field data from OMNI [*Lavraud et al.*, 2005].

It should be noted that the orbits of Cluster are inertial, so that they change with season. Between January and April the apogees were in the dayside (Figure 1a), but during August to October they were in the magnetotail (Figure 1b). The work done by *Shi et al.* [2013] was based on the data from August to October phase (Figure 1b), and during this period the dipole axis is often tilted toward the Sun (i.e., positive dipole tilt) in the northern hemisphere. In our work, we further use the data from January to April (Figure 1a), during which time the dipole axis is usually tilted away from the Sun (i.e., negative dipole tilt) in the northern hemisphere.

We selected observation periods where the spacecraft were traversing the lobe region and then selected the events according to the following criteria:

1. Lobe: $B_{z\_GSM} < -50$ nT, $X_{\_GSM} < 10\ R_E$ ($R_E = 6370$ km), $N_{HIA} < 2(\mathrm{cm}^{-3})$.
2. Entry event: $700\ \mathrm{eV} < \text{ion energy} < 2000\ \mathrm{eV}$.

We deleted the events occurred during the IMF turning north to south to keep our events with stable IMF conditions. Besides these, in order to highlight the solar wind penetration into the magnetosphere through the lobe region, there should have been at least two energy channels below and above 1 keV with a PEF

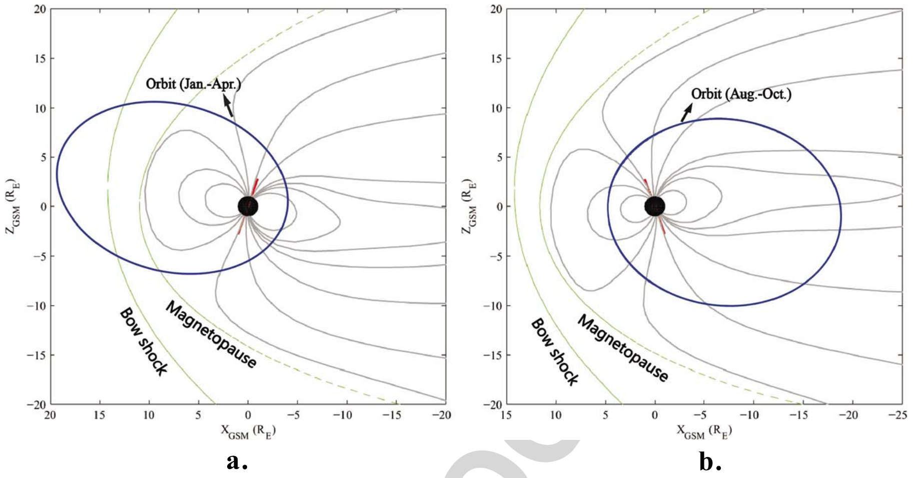

Figure 1. The blue ovals indicate the Cluster orbits in different time periods. (a) The orbit from January to April and (b) the orbit from August to October are shown. The red bar indicates the dipole axis.

(particle energy flux) $> 8 \times 10^4$ keV/(s cm^2 sr keV) (the energy range for these four channels is 700 eV–2000 eV), and there should have been eight channels in total with a PEF $> 8 \times 10^4$ keV/(s cm^2 sr keV). So the possible ionosphere up-flowing ions can be removed through this automatic selection. Using the above criteria, we selected the magnetosheath-like ions with energy about 1 keV.

3. Results

3.1. Cluster Observations of Entry Regions on 05 February 2006

In order to ensure the reliability of each event, we have plotted the parameters including the ion energy flux, particle density, magnetic field, and interplanetary magnetic field of all events and checked them one by one. Figure 2 shows an entry event example on 05 February 2006. As we can see, the ion energy flux and the particle density observed within the event are much higher than those in the background lobe region and the IMF is northward. We have recorded the set of events in a similar way.

3.2. Statistical Analysis

Using the Cluster data from January to April during 2001 to 2006, we have found a total of 100 events, 46 of which occurred in the northern hemisphere, and 54 occurred in the southern hemisphere (there were no IMF data for four events). This result is supported by the previous study that with negative dipole tilt, the southern hemisphere reconnection site would allow more of the magnetosheath plasma distribution to be seen than that in the northern hemisphere [*Petrinec et al.*, 2011]. Figure 3a shows the Cluster satellites' orbit through the lobe region in X_{GSM}-Z_{GSM} plane. Figure 3b shows the locations of events in X_{GSM}-Z_{GSM} plane. We find that during this period, the solar wind plasma entry events can also be found in the Earth's high-latitude magnetospheric lobes tailward of the cusps. Furthermore, in order to study the dipole tilt effect, we compared the occurrence rates of the entry events between ours and *Shi et al.* [2013] with different dipole tilt in two seasons. We have calculated the number of the events normalized by the total time of lobe crossing. As a result, during January to April the occurrence rate of entry events is about 1.5×10^{-3}/min, of the same order as that from August to October, which is 8.9×10^{-4}/min.

The influence of the IMF B_x component on entry event occurrence rate is analyzed in Figure 4, where we examine the entry events in the northern and southern hemispheres separately. We have found 76 events occurred under northward IMF conditions, 20 events occurred under the southward IMF conditions (there were no IMF data for four events). Each arrow in Figure 4 represents the mean IMF magnitude and direction for each entry event, calculated by OMNI IMF data. It is obvious that in the northern hemisphere more events occurred under negative IMF B_x as shown in Figure 4a, and in the southern hemisphere events occurred almost equally under positive or negative IMF B_x, as shown in Figure 4b. That is because from January to April the geomagnetic dipole axis is usually pointing away from the Sun (negative dipole tilt) in the northern hemisphere, which causes the IMF to be much closer and antiparallel to the lobe field lines in the southern

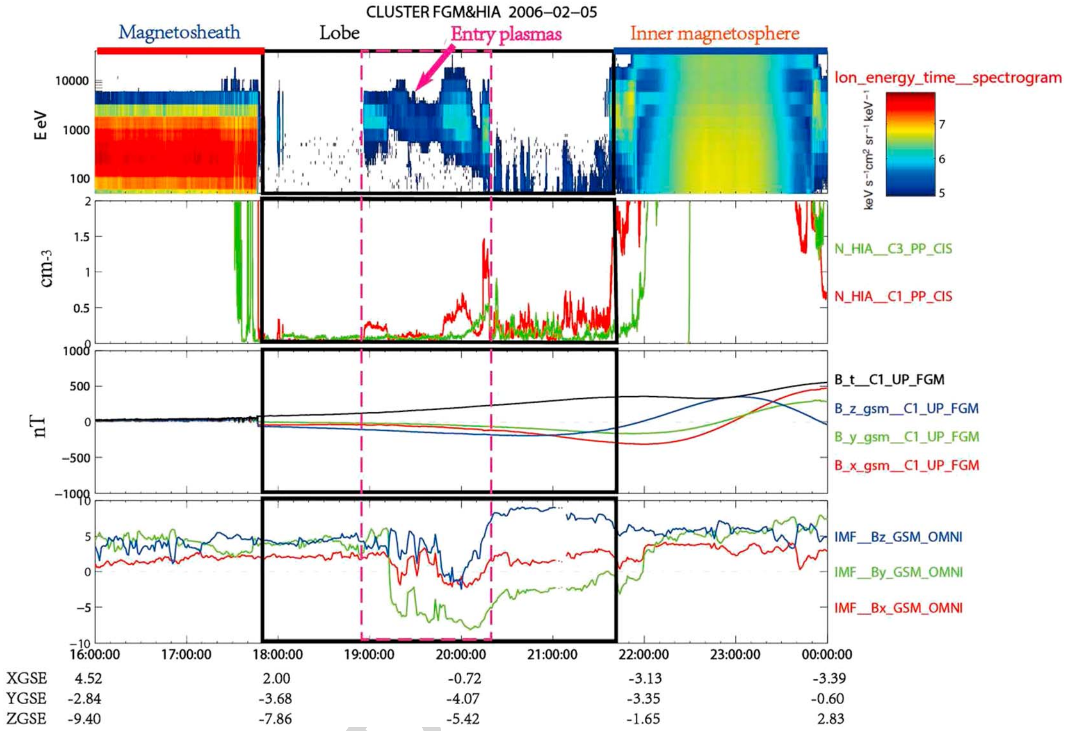

Figure 2. An example for the entry plasmas observed at the high-latitude magnetosphere on 05 February 2006. From left to right are magnetosheath, lobe, and inner magnetosphere regions. The black box indicates the lobe region we selected, while the pink box indicates the entry events. From top to bottom (first to fourth panels) are ion energy flux, particle density, magnetic field, interplanetary magnetic field, and the locations of Cluster.

hemisphere than that in the northern hemisphere. As a result, no matter whether the IMF B_x component is positive or negative, then magnetic reconnection at south hemisphere could occur easily. It shows that more events can occur in the southern hemisphere than that in the northern hemisphere, which is consistent with the result of dipole tilt effect in the paper of *Petrinec et al.* [2011]. On the contrary, the IMF B_x control appears only in the winter hemisphere, which means that in the northern hemisphere if the IMF B_x component was negative enough, the magnetic reconnection would occur. This is consistent with our observation (shown at Figure 4). It indicates that the influence of large IMF B_x component can also dramatically affect the locations

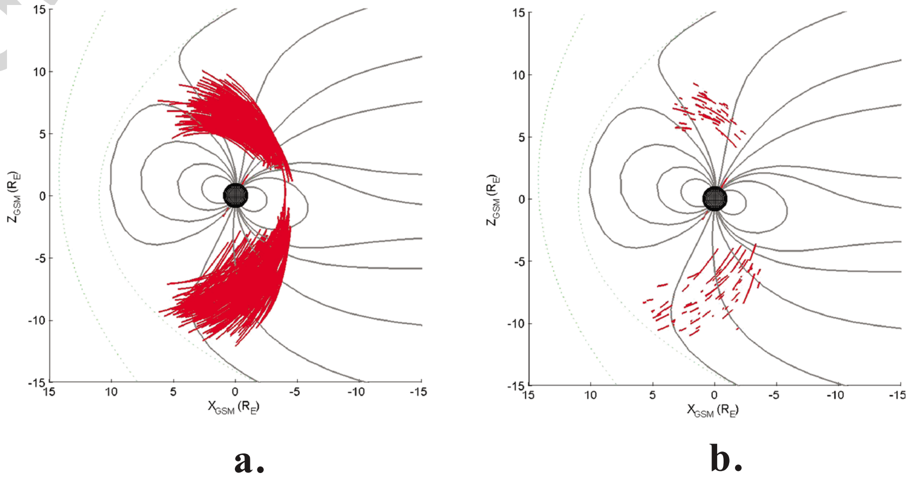

Figure 3. The red lines indicate (a) the orbits in the lobe, and (b) the locations of events from January to April as red marker in planes of X_{GSM}-Z_{GSM}.

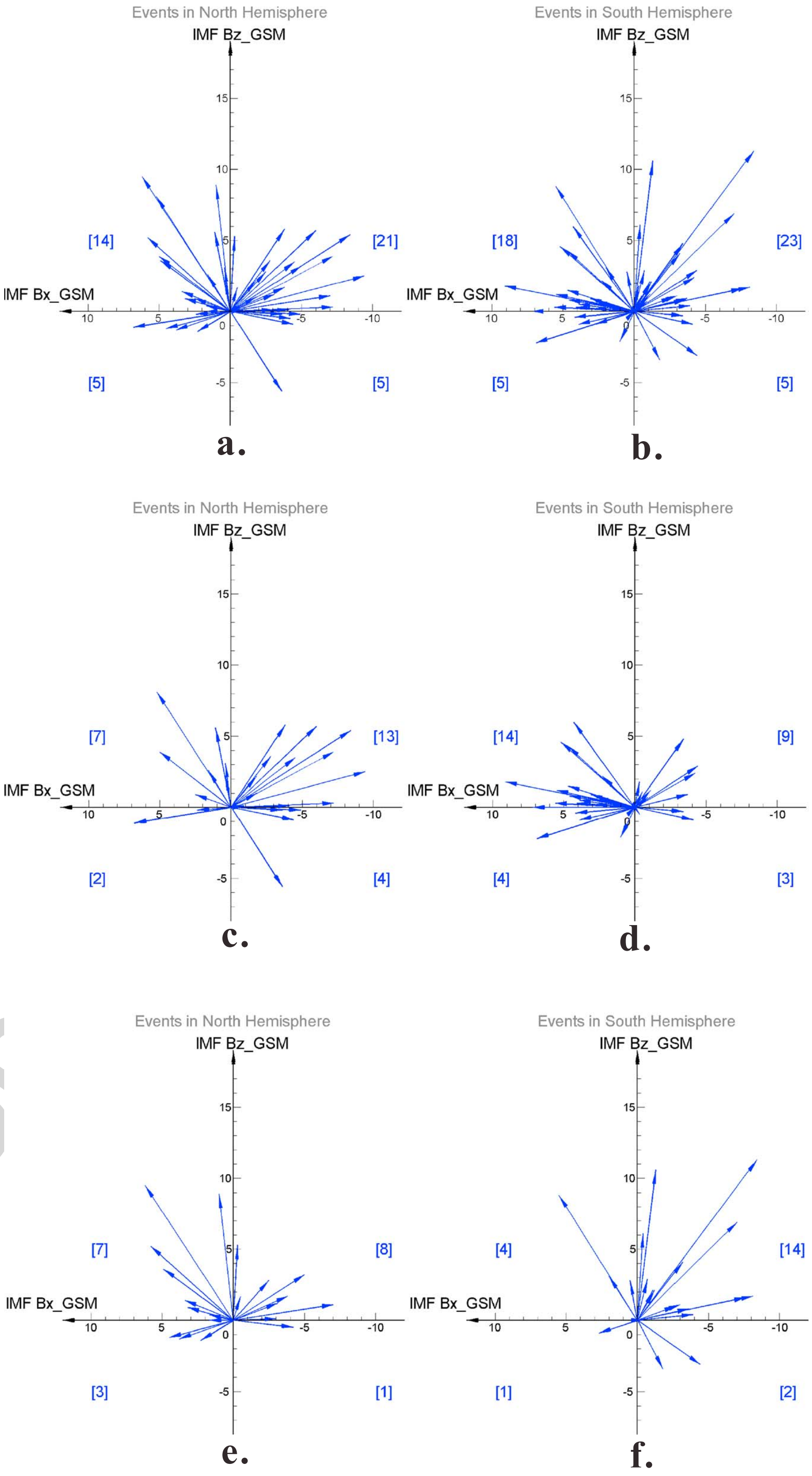

Figure 4. The statistical results of IMF B_x component influence (January to April). (a) The events in the northern hemisphere (46 events) and (b) the events in the southern hemisphere (54 events) are shown. There were no IMF data for four events. We divided our events into two groups, one of which occurred during (c and d) the large negative dipole tilt angle (from −30° to −10°), and another occurred during (e and f) the small negative dipole tilt angle (from −10° to 0°), respectively. The numbers show the quantity of events in each quadrant.

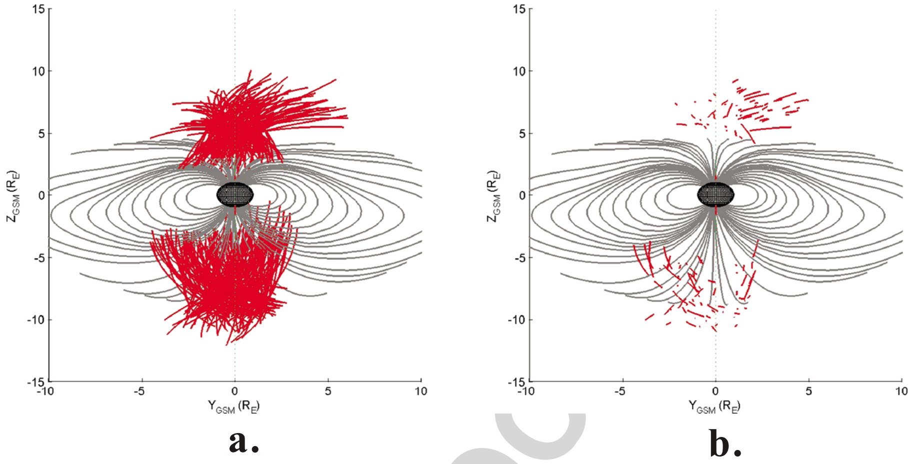

Figure 5. The red lines indicate (a) the orbits in the lobe, and (b) the locations of events from January to April as red marker in planes of Y_{GSM}-Z_{GSM}.

of the reconnection site on the magnetopause for conditions of northward IMF, which agree with the results of *Petrinec et al.* [2003] and *Fairfield and Scudder* [1985]. Additionally, for northward IMF, it is suggested that most of the potential imposed on the polar cap is a direct representation of the solar wind-magnetosphere coupling through the high-latitude magnetic reconnection [*Maezawa*, 1976; *Burke et al.*, 1979; *Reiff*, 1982]. And, our observation of solar wind entry was mainly caused by the high-latitude magnetic reconnection. Therefore, we would expect the larger potential *F*, the more high-latitude reconnections happen, and the more entry events. *Taguchi and Hoffman* [1995] found that when the IMF was northward and the northern dipole axis pointed to the Sun, the polar cap potential *F* for the northern hemisphere is the largest, when $ø_h$* (the angle between the IMF vector projected to the *X-Z* meridian and the Earth dipole axis.) is negative and large (~ −100°). So it also means that a larger negative IMF B_x results in a larger potential *F*, and the more entry events. Their result is consistent with our observation that in the northern hemisphere, more events occurred under negative IMF B_x as shown in Figure 4a. In summary, under negative dipole tilt, more entry events can occur in the southern hemisphere, which is dominated by dipole tilt effect, while the occurrence rate of entry events in the northern hemisphere is dominated by IMF B_x effect. These results provide new evidence that the “north-south asymmetry” in the conditions for high-latitude magnetic reconnection is mainly caused by the dipole tilt effect. Furthermore, under this north-south asymmetry conditions, the IMF B_x component can also control the solar wind plasma entry rate in the winter hemisphere (i.e., under negative dipole tilt it means northern hemisphere), which is also in good agreement with the results of *Shi et al.* [2013] and further support the high-latitude magnetic reconnection mechanism. Therefore, we conclude that the north-south asymmetry of solar wind entry events in the lobes could be the combined result of magnetic dipole tilt and IMF B_x.

Furthermore, we divided the events into two groups. One group occurred during the large negative dipole tilt angle (from −30° to −10°) shown in Figures 4c and 4d, and the other group occurred during the small negative dipole tilt angle (from −10° to 0°) shown in Figures 4e and 4f. When the negative dipole tilt angle is large, more events occurred under negative IMF B_x in the northern hemisphere, but in the southern hemisphere events occurred almost equally under positive or negative IMF B_x. It is shown that the group with large negative dipole tilt angle is more consistent with the result in Figures 4a and 4b than the group with small negative dipole tilt angle, which indicates that the dipole tilt angle effect plays the primary role in the north-south asymmetry distribution of solar wind entry events. During small dipole tilt angle other effects, such as IMF B_x or B_y, may be important in the control of solar wind entry. But due to the limitation of events number in this group, results are inconclusive.

Many previous studies [*Wilder et al.*, 2013; *Øieroset et al.*, 2008] suggested that IMF B_y component can affect the position of high-latitude magnetic reconnection sites. Here we study whether the IMF B_y component could influence how the solar wind plasma penetrates into the magnetosphere. Figure 5a shows the **F5**

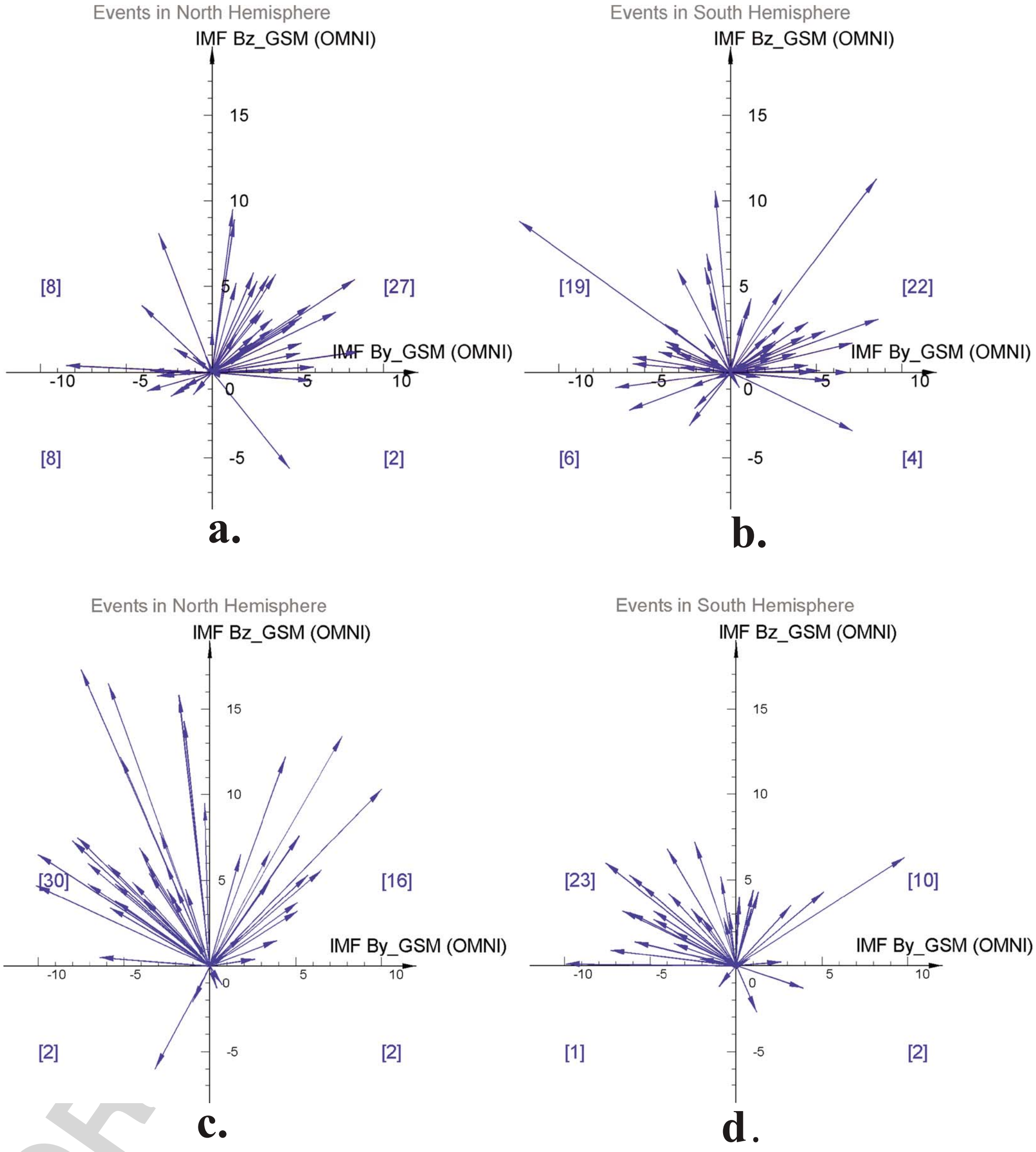

Figure 6. The statistical results of IMF B_y component influence. (a and b) The data from January to April and (c and d) the data from August to October were used. Figures 6a and 6c show the events in the northern hemisphere, and Figures 6b and 6d show the events in the southern hemisphere. The color coding in the arrows was defined as in Figure 4.

Cluster satellite orbits through the lobe region in Y_{GSM}-Z_{GSM} plane, 41,634 min of which were in the lobe region of duskside and 42,764 min were in the lobe region of dawnside, which indicate that the durations of Cluster orbits in the lobe region we selected in both duskside and dawnside are almost equal. Figure 5b shows the locations of events in Y_{GSM}-Z_{GSM} plane. The distribution of entry events is asymmetric in the $Y_{\_GSM}$ direction, which may be caused by IMF B_y component. So we have statistically analyzed the influence of the IMF B_y component in different hemispheres, as shown in Figure 6. It is obvious that from January to April in the southern hemisphere the number of the events is independent regardless of the positive/negative IMF B_y, but in the northern hemisphere most events occur when the IMF B_y component is positive (shown at Figures 6a and 6b). In order to examine further the influence of IMF B_y component, we also statistically analyzed the events during August to October (shown at Figures 6c and 6d). It is also shown that in the northern hemisphere, the solar wind entry events occur independently regardless of positive/negative IMF B_y component, but in the southern hemisphere most events occur when the IMF B_y component is negative (dawnside).

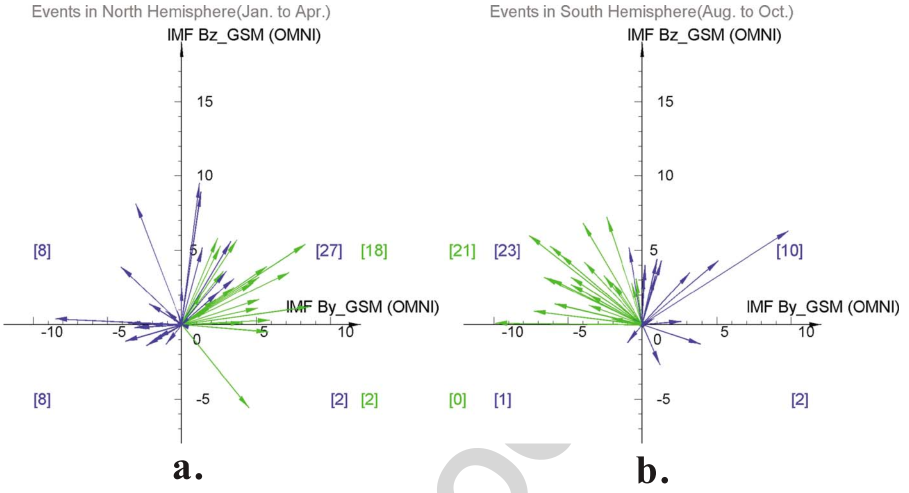

Figure 7. (a) The entry events in the northern hemisphere during January to April. (b) The entry events in the southern hemisphere during August to October. The green arrows indicate that the B_y and B_x components are opposite ($B_y > 0$ and $B_x < 0$ or $B_y < 0$ and $B_x > 0$). In the asymmetric hemispheres, most of the events occurred under the opposite IMF B_y and B_x condition.

According to the study of *Lee et al.* [2010], when the IMF B_y is nonzero (positive or negative), the antiparallel reconnection should occur at each hemisphere in different Y directions (dawn-dusk asymmetry). However, the result of *Gou et al.* [2014] showed that the distributions of entry events were not consistent with this "dawn-dusk asymmetry," which indicates that the contribution by IMF B_y to high-latitude reconnection for the solar wind entry events might be weaker than other effects. Our results show that the effect of dipole tilt might be more important than the IMF B_y effect. But in order to explain the asymmetry of IMF B_y influence, we have selected the hemispheres with asymmetric IMF B_y distribution properties as mentioned above (the events in the northern hemisphere during January to April and those in the southern hemisphere during August to October shown in Figure 7). The green arrows indicate that in those entry events the IMF B_x and **F7** B_y components are opposite (either $B_y < 0$, $B_x > 0$ or $B_y > 0$, $B_x < 0$). Obviously, almost all of the events influenced by IMF B_y component in the hemispheres with asymmetric IMF B_y distribution properties are connected with IMF B_x component. A possible explanation is provided after we have plotted the IMF B_x and B_y distributions when Cluster was in the lobe region during the time we have studied shown in Figure 8, which **F8** shows that the opposite signs of IMF B_x and B_y components for most of the time near the Earth are consistent with the Parker Spiral. We conclude that the asymmetry of IMF B_y influence for the entry events is due to the Parker Spiral.

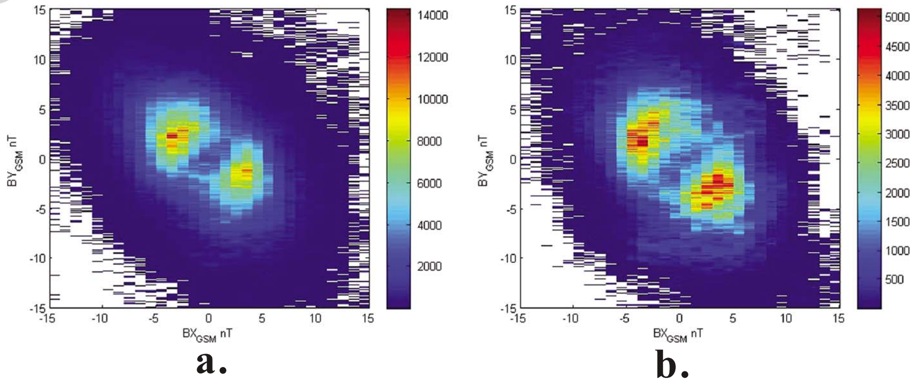

Figure 8. (a) The IMF *Bx* and *By* conditions near the Earth during crossing the lobe regions from January to April were shown. (b) That from August to October were also presented. And, the color codes indicate the counts. The IMF B_x and B_y are almost opposite, which is consistent with the Parker Spiral of IMF.

4. Summary and Conclusion

In this study, based on Cluster multispacecraft data between January and April from 2001 to 2006, when the IMF is northward and the geomagnetic dipole angle is negative, we find that the entry events can also be observed at the Earth's high-latitude magnetospheric lobes tailward of the cusp and with different dipole tilts the occurrence rate of the entry events is of the same order as that found in another period by *Shi et al.* [2013]. Through statistical analysis, we find that under negative dipole tilt condition, more entry events can occur in the southern hemisphere, which is dominated by dipole tilt effect. While the IMF B_x control appears only in the winter hemisphere, which means in the northern hemisphere if the IMF B_x component was negative enough, the magnetic reconnection would occur. These results show that the asymmetry distribution of solar wind entry events in the northern and southern lobes could be caused by the variation of magnetic dipole tilt, which could influence the locations of the reconnection site on the high-latitude lobe magnetopause. On the other hand, IMF B_x can also affect the solar wind plasma entry rate, which is also in good agreement with the results of *Shi et al.* [2013] and further support the high-latitude magnetic reconnection mechanism. Therefore, we conclude that the north-south asymmetry of solar wind entry events in the lobes could be the combined result of magnetic dipole tilt and IMF B_x. We also analyze the influence of IMF B_y component. It turns out that the IMF B_y component can influence the entry events in conjunction with the variation of IMF B_x component, which is in line with the Parker Spiral of the IMF.

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