Journal of Atmospheric and Solar-Terrestrial Physics 95–96 (2013) 1–14

Contents lists available at SciVerse ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

The geo-effectiveness of interplanetary small-scale magnetic flux ropes

X.-Y. Zhang [a,*], M.B. Moldwin [a], M. Cartwright [b]

[a] Department of Atmospheric, Oceanic, and Space Sciences, University of Michigan, Ann Arbor, MI, USA
[b] Space Science Laboratory, University of California, Berkeley, CA, USA

ARTICLE INFO

Article history:
Received 30 July 2012
Received in revised form
10 December 2012
Accepted 12 December 2012
Available online 31 December 2012

Keywords:
Flux rope
Geo-effectiveness
Substorm
Solar wind-magnetosphere coupling

ABSTRACT

The geo-effectiveness of Interplanetary small-scale magnetic flux ropes (ISMFRs) are studied using multiple satellites (ACE, WIND, Geotail, Cluster, THEMIS, and geosynchronous spacecraft) and ground magnetometers. We identified 16 ISMFR events during 2007–2008 that had in situ observations of the near-Earth upstream solar wind in addition to observations from ACE and Wind at 1 AU, and observations from multiple spacecraft in the inner magnetosphere. All the upstream solar wind (and in many cases magnetosheath) satellite observations showed very similar flux rope signatures indicating that the flux rope propagates from 1 AU through the bow shock. Thirteen of the 16 events were associated with substorm activity while nine of them appeared to trigger isolated substorm onsets. Combined with earlier published databases of ISMFRs from 1995 to 2005, we also examined the geo-effectiveness using 1-min AE/AL indices. We found more than half of these events (73/141) were associated with substorms, while the rest were associated with quiet geomagnetic activity periods. Of the 73 substorm-related ISMFRs, 32 events had IMF B_z polarity signatures from south to north (SN), 31 from north to south (NS), and 10 were identified as B_y bipolar signature events. A superposed epoch analysis indicates that the timing of the substorm activity related to the ISMFRs is different between SN- and NS-events. Most of the ISMFRs associated with quiet geomagnetic activity were either B_y bipolar signature events or accompanied with complex B_z and B_y signatures. This study demonstrates that ISMFR with IMF B_z polarity signatures drive substorms, but not geomagnetic storms.

1. Introduction

Magnetic flux ropes are commonly observed in the heliosphere, and are created on the Sun, in the Earth's magnetotail, and at other planets (Linton and Moldwin, 2009). Flux ropes are twisted helical structures with a tube-like shape (Priest, 1990). The azimuthal magnetic field strength is strongest in the outer region of the flux rope while the axial field becomes more significant inward. Observationally, flux ropes appear as an increase of the magnitude of the total field with a bipolar turning in one or more of the magnetic field vectors (e.g., Klein and Burlaga, 1982; Moldwin and Hughes, 1991; Mulligan and Russell, 1998; Lepping et al., 2006; Lepping and Wu, 2007). The size of magnetic flux ropes varies widely, depending on where they are formed and observed. Previous studies have observed flux ropes with durations ranging from several minutes to over 50 h, and corresponding dimensions of 1 R_E to a significant fraction of an AU (Lepping et al., 2006).

In the solar wind, these structures are classified into large- and small-scale flux ropes. Large-scale flux ropes are often called magnetic clouds (MCs), which have been studied extensively in the heliosphere (e.g., Bothmer and Rust, 1997; Bothmer and Schwenn, 1998; Lepping et al., 1990; Lynch et al., 2008). Small-scale flux ropes observed in the solar wind (and often called interplanetary small-scale magnetic flux ropes or ISMFR) are defined by their short-durations, which strongly peaks at an hour or less with most lasting less than 4 h (Cartwright and Moldwin, 2008; Feng et al., 2008). ISMFR and MC not only differ in their time and spatial scales but also in their configuration and evolution, which implies that they may have distinct source mechanisms (Moldwin et al., 2000; Cartwright and Moldwin, 2008). Observationally, MC and ISMFR are distinguished by their durations. The average time duration of MC is $\sim$21 h, and the core field is often twice the background IMF field strength. The combined duration distribution of all solar wind magnetic flux ropes show clearly a bi-modal distribution allowing the identification between MC and ISMFR.

While ISMFRs have been extensively studied in recent years, their formation mechanisms are still widely debated. Given their magnetic field structure is similar to ICMEs, they have been

* Corresponding author. Tel.: +1 7342767789.
E-mail address: zhangxy@umich.edu (X.-Y. Zhang).

1364-6826/$ - see front matter © 2013 Elsevier Ltd. All rights reserved.
http://dx.doi.org/10.1016/j.jastp.2012.12.006

suggested to be the interplanetary manifestations of small-scale solar eruptions (e.g., Tu et al., 1997; Mandrini et al., 2005; Feng et al., 2007; Wu et al., 2008). What may be more complex than these solar eruptions is the observations of small flux ropes in the vicinity of coronal sector boundaries reported by Kilpua et al. (2009) suggesting that they form near sector boundaries. Studies of Earth's magnetosphere have also shown multiple X-line reconnection is responsible for small-scale flux rope chains in the plasma sheet (e.g., Moldwin and Hughes, 1993; Slavin et al., 2003; Zong et al., 2004; Eastwood et al., 2005; Liu et al., 2009). The observations led to the suggestion that ISMFRs are the products of local magnetic reconnection in the solar wind across the heliospheric current sheet (HCS) (e.g., Moldwin et al., 2000; Cartwright and Moldwin, 2008; Ruan et al., 2009). It is possible ISMFRs are formed both in the corona and interplanetary space, but it is unknown which formation mechanism is more active.

A long history of research has demonstrated the importance of the IMF in coupling the solar wind with the geomagnetic field leading to storms and substorms (Watermann et al., 2009). For instance, Eriksson et al. (2003), Manoj et al. (2008), and Newell and Liou (2011) have demonstrated that the turning in IMF B_z changes the ionospheric electric field and current systems. Matsui et al. (2005) concluded that there is also correlation between the behavior of the Earth's magnetic field and IMF B_y variations. Lennartsson (1995), Brauigam et al. (1991) and Lyons (1996) suggested that the polarity of IMF determines the effectiveness of particle energization and precipitation in Earth's magnetosphere and ionosphere.

A substorm is one of the principle response modes of the Earth's magnetosphere to solar wind driving (Akasofu, 1964; McPherron, 1979). Substorm onsets can be induced by internal sources Horwitz (1985); Henderson et al. (1996) during periods of quiet solar wind conditions, or external sources such as solar wind shocks and certain configurations of IMF (e.g., Heppner, 1955; Lyons, 1995; Zhou and Tsurutani, 2001). Some studies suggest that even for the internally excited substorms, the varied solar wind and IMF conditions affect or lead to the expansion phase (Meng and Liou, 2004). The change of IMF direction, especially the northward turning of the IMF (e.g., Burch, 1972; Samson and Yeung, 1986; Lyons, 1996) and a directional change in the *y*-component of IMF (e.g., Troshichev et al., 1986; Bae et al., 2001), have been considered as the main reasons for triggered substorm onset. Recently, Du et al. (2011) suggested that the solar wind energy injected and stored in the magnetotail/magnetosphere/ionosphere is the main factor of substorms occurrence. However, the determination of the mechanism of substorm triggering is still an area of active research. Pi 2 waves are one of the indicators of substorm onset (e.g., Olson, 1999; Cao et al., 2008; Keiling et al., 2008). Other ULF oscillations are also important signatures of changes to the global and/or regional configuration of Earth's magnetosphere. In addition, they play a role in the modulation of energetic particles on the dayside, the interaction with oxygen ions from the ionosphere, and the transformation of the convection electric field (e.g., Zong et al., 2007; Liu et al., 2009; Yang et al., 2011).

This study examines the geo-effectiveness of ISMFRs during 2007–2008 when multiple satellites were in the solar wind (ACE, WIND, Geotail, THEMIS, Cluster) and in the inner magnetosphere (THEMIS, Cluster, GOES). This interval occurred during the recent unprecedented solar minimum (Russell et al., 2010), which provides an opportunity to study the Earth's dynamics under nominally low solar driving conditions. In addition, we conduct a superposed epoch study of IMSFRs observed from 1995 to 2008 to examine the role of ISMFRs' magnetic polarity structure on substorm occurrence. Feng et al. (2010) showed ISMFRs are geoeffective and can trigger substorms. In this study, we have extended the solar wind observations to the near-Earth upstream solar wind and dayside magnetosheath region besides the ACE and Wind data. This shows the propagation of the structure from L1 through the bow shock and provides validation to the propagation time. It also enables us to identify the scale-size of the ISMFR and determine which structures observed at L1 are also observed just upstream of the magnetopause. We considered the polarity structure of the ISMFRs and how this structure influenced their geo-effectiveness (relationship with substorm phases). The non-substorm related ISMFRs are also studied and discussed in this paper. In addition, ULF wave activity at geosynchronous orbit is examined.

2. Methodology

ACE and WIND magnetic field data (in GSE coordinates) from 1 January 2007 to 31 December 2008 were surveyed for ISMFR events. The 16-s ACE data and 1-min WIND data, plotted in 6-h windows from the OMNI web site (http://cdaweb.gsfc.nasa.gov/cdaweb/istp public/) are used to examine the solar wind and IMF conditions at L1. Such time resolution and window length are used because the duration criterion in this study selects events from 0.5 h to 4 h.

Fig. 1 shows an example ISMFR selected in this study. In Fig. 1, the magnetic field magnitude and vector components in GSE coordinates of an identified ISMFR on 2 June 2007 are illustrated. The time intervals of the ISMFR observed by different satellites are not the same. From left to right, the measurements are displayed in time sequence of the detection by WIND, ACE, THEMIS-A, Cluster-1, and Geotail. Fig. 2 shows the projections on the (a) GSE *XY*-plane and (b) GSE *XZ*-plane of the satellite (in near Earth region locations) for the case in Fig. 1. The length of the trace associated with each satellite symbol represents the distance traveled by the satellite in an 5-h interval after 1800 *UT* on 2 June 2007. This event is used to illustrate the selection criteria used in this study.

The ISMFR events are selected by visually inspecting upstream solar wind data from ACE and Wind. We used the criteria similar to previous studies to examine ISMFR (Feng et al., 2007; Cartwright and Moldwin, 2008). An ISMFR in this study has the following characteristics:

(1) A strong core field, which is identified by an increase of the total magnetic field compared to the background field. The presence of a strong core field is used to distinguish the ISMFR events from the other structures like Alfvèn waves which also show bipolar signatures. The first panel in Fig. 1(a) shows IMF B_t and the maximum at around 1850 *UT*.
(2) The second criterion states that the presence of a bipolar turning is mainly in B_y and/or B_z to eliminate HCS crossings (Cartwright and Moldwin, 2010). The typical example with polarity signature of B_z is shown in Fig. 1. As defined in Moldwin and Hughes (1992), the change of B_z from positive to negative value is called a northward–southward (NS) bipolar turning, and the opposite is classified as a SN turning. If B_y is changing from positive to negative, such a polarity feature is named an eastward–westward (EW) turning, with the westward–eastward B_y bipolar turnings labeled as WE.
(3) The two end points of the flux rope are identified by local minima associated with this maximum. These end points are denoted by the different durations in each subfigure of Fig. 1.
(4) The next step is to exclude all the candidate flux ropes that last less than 0.5 h or more than 4 h to identify the small-scale events.
(5) Finally, the magnetic field data from other satellites in the region closer to Earth (less than 30 R_E in all the three