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Geoeffectiveness of magnetic cloud, shock/sheath, interaction region, high-speed stream and their combined occurrence

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ABSTRACT

A subset of CMEs, called interplanetary magnetic clouds (MCs), are observed to have systematic rotation [northward to southward (NS) or southward to northward (SN)] in their field structures. These MCs identified in the heliospheric plasma and field data at 1 AU may have different features associated with them. These structures (NS/SN) may be isolated MC moving with the ambient solar wind. MCs (NS/SN) may also be associated with shock/sheath region, formed due to compression of the ambient plasma/field ahead of them. A fraction from each of these four types of MCs have additional features, being 'pushed' by fast solar wind streams from coronal holes, forming interaction region (IR) between MCs and high-speed solar wind streams (HSS). Using these different sets of MCs, we have done a detailed study of the geoeffectiveness of NS and SN turning MCs and their associated features (shock/sheath, IR and HSS). To study the process that produces the geomagnetic disturbances and influences its amplitude/duration, we have utilized the interplanetary plasma and field parameters, namely, plasma velocity, density, temperature, pressure, field strength and its north–south component, during the passage of these structures with different associated properties. Differences in the geoeffectiveness of MCs with different structural and dynamical properties have been identified. The possible role of high-speed stream in influencing the recovery time (and hence duration) of geomagnetic disturbance has also been investigated. A best-fit equation representing the relation between level of the geomagnetic activity (due to MCs) and interplanetary plasma/field parameter has been obtained.

1. Introduction

Discovery of coronal mass ejections (CMEs) is perhaps one of the most spectacular advances of space age in which large amount of solar material are propelled outward into interplanetary space from closed field regions. Their interplanetary counterparts (ICMEs) are the key to major interplanetary and geomagnetic disturbances (e.g see Badruddin, 1998; Bothmer and Zhukov, 2007; Gopalswamy, 2004, 2006; Koskinen and Huttunen, 2006; Tsurutani and Gonzalez, 1997; Webb, 1995 and reference therein) and various properties of ICMEs have been studied in the past (Cane and Richardson, 2003; Gopalswamy et al., 2001; Richardson and Cane, 2004, 2005; Riley et al., 2006). Subsets of the ICMEs, called magnetic clouds (MCs), are identified by (i) large-scale smooth field rotation, (2) enhanced magnetic field magnitude and (3) decreased plasma temperatures (Burlaga et al., 1981; Burlaga, 1991; Klein and Burlaga, 1982). Near 1 AU, MCs have dimension around 0.2–0.3 AU (Lepping et al., 1990; Zhang and Burlaga, 1988) and roughly $\frac{1}{3}$ of ICMEs, at least, exhibit the large smooth field rotation; it is usually southward during passage of at least one part of MC and northward during the passage of other part. If the leading part of MC is southward and trailing part is northward we refer it SN cloud. It is also possible that leading part of MC is northward and the trailing part is southward, such MC is termed as NS cloud (Zhang et al., 2004). Source properties, structures and effects of MCs have been discussed in several papers (e.g. see Bothmer and Schwenn, 1997; Burlaga, 1991; Hidalgo, 2003; Lepping and Berdichevsky, 2000; Gonzalez and Tsurutani, 1987; Lepping et al., 2006; Lepping and Wu, 2007; Li and Luhmann, 2004; Webb et al., 2000).

Geoeffectiveness of the interplanetary structures like shock/sheath/ICME (e.g. Bothmer and Schwenn, 1995; Cane et al., 2000; Crooker, 2000; Echer et al., 2005; Gonzalez and Tsurutani, 1987; Gopalswamy et al., 2007; Gosling et al., 1991; Kamide et al., 1998; Kane and Echer, 2007; Khabarova and Yermolaev, 2008; Lindsay et al., 1995; Srivastava and Venkatakrishnan, 2002; Tsurutani et al., 1999; Xie et al., 2006; Zhang et al., 2007), MCs (Badruddin, 1998; Burlaga et al., 1981; Echer and Gonzalez, 2004; Echer et al., 2005; Farrugia et al., 1993; Fenrich and Luhmann, 1998; Gopalswamy et al., 2008; Lepping et al., 1991; Rangarajan, 1989; Tsurutani et al., 1992, 2004; Wu and Lepping, 2002; Wu et al., 2006; Zhang and Burlaga, 1988; Zhang et al., 2004), interaction

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region (IR) (Alves et al., 2006; Badruddin, 1998; Borovsky and Denton, 2006; Constantin, 1989; Crooker and McAllister, 1997; Filisetti et al., 1988; Kane, 2007; Lindsay et al., 1995; Mavromichalaki et al., 1988; Richardson et al., 2000, 2006; Rossberg, 1989; Tsurutani et al., 2006; Zhang et al., 2008) have been done in the past and many interesting results have been obtained. However, because of the complexities involved in the interaction of the solar wind and the earth's magnetosphere and also due to the possibility that phenomenology of interaction is different for solar wind dominated by closed field regions of transient ejecta (e.g. MCs) compared to solar wind dominated by IRs and high-speed streams from open field regions of coronal holes, a comprehensive and detailed study the geoeffectiveness and relative importance of the various interplanetary structures/features, for example, shock/sheath/MC/IR/high-speed stream is still needed.

A shock front, and a sheath region of intense and compressed magnetic field, may form in the interplanetary space ahead of a fast moving MC. Thus passage of such structures provide unique opportunity to study the effects of (a) abrupt changes in solar wind plasma and field parameters (at shock front), (b) intense and turbulent magnetic fields (during the passage of sheath), and (c) intense and quiet magnetic fields (during the passage of MCs). MCs followed by IRs and high-speed streams enable us to study the effects of plasma compression and magnetic field fluctuations (in IRs) and high-speed solar wind streams (from open field regions of coronal holes), in addition to that of intense and smooth, rotating and closed-field of flux (of MCs). MCs moving with the ambient solar wind, without any additional associated structure, are exclusively suitable for study of the effects of magnetic field strength, its orientation/direction and topology on the geomagnetic activity. Thus, interplanetary MCs, with a number of distinct associated features, provide a special and unique opportunity to study the role, and relative importance of various structures with distinct plasma and field properties, on the development, strength and duration of the resulting geomagnetic storms. However, two of the features (IR and HSS) may not be present in many cases, both with SN-MCs with and without shock. These structure with SN-MCs together with structures having corresponding features with NS-MCs, provide a very useful data for the study of the geoeffectiveness of variant structures. Fig. 1 is a representative sketch of shock-associated SN-MC followed by IR and HSS, and Fig. 2 is a sketch that represents an SN-MC (without shock) followed by IR and HSS. Later two feature (IR and HSS) may not be there if SN-MCs with/without shock are not followed by HSS. Structures with correspondingly similar features may be visualized for NS-MCs also.

MCs and their associated features play variable role in modulating galactic cosmic rays (e.g. see Badruddin, 1998; Badruddin et al., 1986, 1991; Bavassano et al., 1989; Cane, 1993; Iucci et al., 1989; Lepping et al., 1991; Lockwood et al., 1991; Quenby et al., 2008; Singh and Badruddin, 2007; Venkatesan and Badruddin, 1990; Zhang and Burlaga, 1988) as well as geomagnetic activity (Badruddin, 1998; Echer et al., 2005; Lepping et al., 1991; Tsurutani and Gonzalez, 1997; Wu and Lepping, 2002; Wu et al., 2006; Xie et al., 2006; Zhang and Burlaga, 1988; Zhang et al., 2004). It is important to understand the effect/role of various features (shock/sheath/MC/IR/HSS) of interplanetary structures on cosmic ray intensity as well as geomagnetic activity not only from the point of view of understanding the physics of cosmic-ray and geomagnetic variability, but also for better understanding and prediction of space weather phenomena. Although a connection between geomagnetic storms and cosmic ray decreases was suggested long ago (Forbush, 1937), the efforts for space weather prediction have created renewed interest in the study of cosmic ray variability before and during geomagnetic disturbances (e.g. see Badruddin, 2006; Bieber and Evenson, 1998; Kudela et al., 2000; Kudela and Brenkus, 2004; Kudela and Storini, 2005; Sabbah, 2000; Wang, 2007). Recently, Singh and Badruddin (2007) did a detailed analysis to study the effects of MCs, IR and high-speed streams on the transient modulation of galactic cosmic rays. However, in addition to the 'cosmic-ray-effectiveness' of MCs and associated features, a comprehensive study of their geo-effectiveness is also needed. Such studies are also relevant from the point of the view of space weather effects, geomagnetic storms may produce dangerous effects both in space-based and ground technological systems (Bothmer and Zhukov, 2007; Kane, 2007). It has been proposed (Denton et al., 2006) that the duration of the storm is crucial in certain space weather effects while its magnitude is more important in some other effects. Further, there are also indications that ICME-associated solar wind is more effective than the CIR-associated in producing certain space weather effects, while CIR-associated solar wind is relatively more effective in certain other space weather effects (Borovsky and Denton, 2006). Since the present study is concerned with the

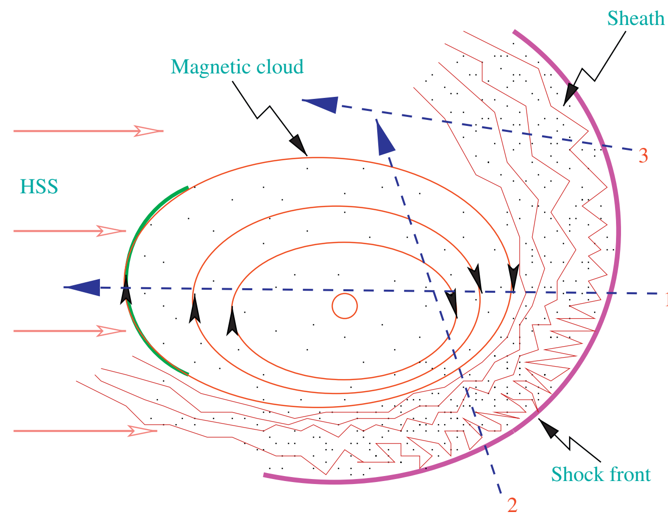

Fig. 1. Shock-associated magnetic cloud and possible structures formed in the interplanetary space. An instrument onboard spacecraft will observe a shock, sheath, SN-MC, IR and HSS if the structure moving right passes through path 1. It will observe only three features shock, sheath and MC if it passes through path 2. Only shock and sheath will be observed in case the structure crosses through path 3. This structure may not have IR and HSS if not followed by HSS.

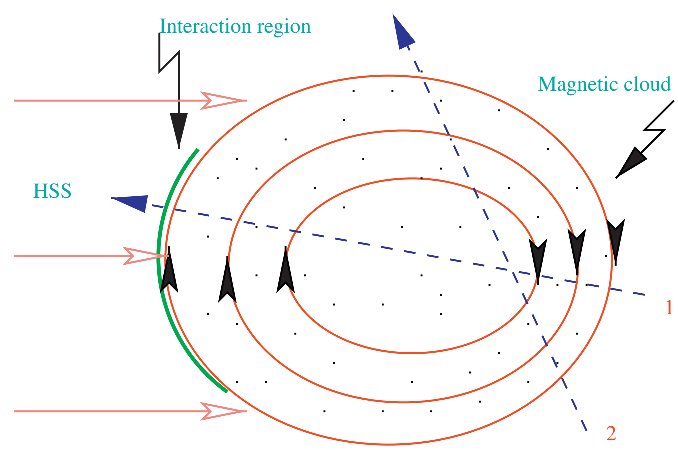

Fig. 2. Magnetic cloud not associated with shock and possible structures formed in the interplanetary space. Instrument onboard a spacecraft will observe an SN-MC, IR and HSS if a right moving structure crosses it through path 1. However, only an MC structure will be seen if it passes through path 2. This structure may not have IR and HSS if not followed by HSS.