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EXCERPT OF DISSERTATION

Comprehensive Studies on Magnetic Clouds in Interplanetary Space and their Associated Events*

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Abstract The relationships between the coronal mass ejections (CMEs), interplanetary disturbances and geomagnetic storms are studied, involving the solar source distribution of geoeffective halo CMEs, the periodicity of CMEs, X-ray flares and geomagnetic disturbances, the threshold of interplanetary parameters in causing geomagnetic storms, etc. As a kind of interplanetary complex structure, multiple magnetic cloud (Multi-MC) is proposed for the first time, which probably has strong geoeffectiveness. Based on the observations, some primary characteristics of Multi-MC are summarized. Moreover, the phenomenon of a shock advancing into a preceding magnetic cloud has been investigated as well as its potential geoeffectiveness. A simple theoretical model is developed to estimate the intensity of geomagnetic storm when a shock is entering a preceding cloud.

Key words coronal mass ejection, magnetic cloud, geomagnetic storm, shock, interplanetary medium

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As a consequence of coronal mass ejections (CMEs) and an important cause of moderate and intense non-recurrent geomagnetic storms, interplanetary magnetic clouds (MCs) play a pivotal role in space weather research[1]. To further study the interplanetary magnetic clouds and their associated events is meaningful and valuable for understanding the solar-terrestrial physical processes and for improving the prediction level of geomagnetic storms. On the basis of the observations of the Sun and the interplanetary medium, the following three aspects are studied observationally and theoretically.

1 Relationship between the CMEs, interplanetary disturbances and geomagnetic storms

According to the observations by the Large Angle Spectroscopic Coronagraph (LASCO) and the Extreme

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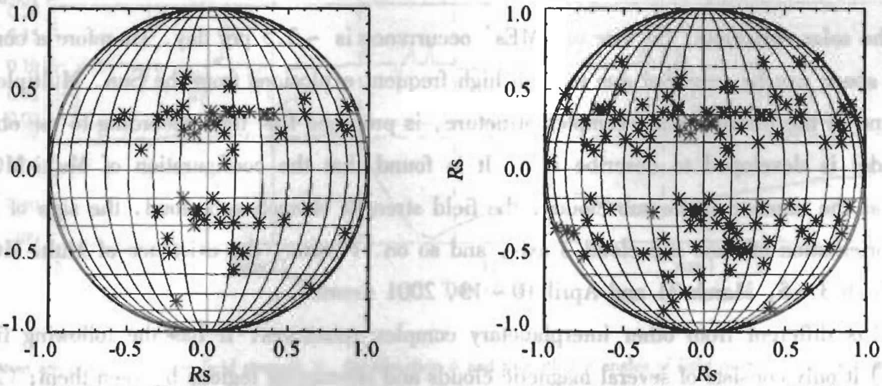
Ultraviolet Imaging Telescope (EIT) on board of the Solar and Heliospheric Observatory (SOHO), a total of 132 front-side halo CMEs from March 1997 to December 2000 are identified[2]. Among these CMEs, 45% (59/132) of them are geoeffective, which produced 36 moderate geomagnetic storms and 15 intense storms. The observations about X-ray flares by the Geosynchronous Operational Environment Satellites (GOES) show that the ratio of the Earth-directed halo CMEs associated with X-ray flares (class ≥ C) to all the Earth-directed halo CMEs is higher than that of all the front-side halo CMEs. The ratio became larger year by year from 1997 to 2000, and especially in 2000 (approaching the current solar maximum), the ratio almost reached 100%.

As for the 15 events associated with $K_p \geqslant 7$ intense geomagnetic storms, the relationship between the transit time from the Sun to the Earth of the corresponding CMEs and the initial projected speed of them approximately meets with an empirical formula:

$$T_{au} = 27.98 + \frac{2.11 \times 10^4}{V}$$

which has a good correlation coefficient of 0.87. Moreover, by analyzing 12 interplanetary southward magnetic field (B_s) events, it is found that only two events are relative to the corotating interaction regions (CIRs) and 11 events are relative to CMEs[3]. Ten of these eleven events associated with the CMEs created the intense geomagnetic storms with $Dst_{\min} \leqslant -100$ nT. The results confirm that the CMEs are the main producer of large geomagnetic storms during the solar maximum.

The source distribution of above 59 Earth-directed halo CMEs on the solar disk is east-west (E-W) asymmetrical (Fig. 1). The number of the Earth-directed halo CMEs occurring on the west is larger than that on the east by 57%. These geoeffective halo CMEs can be expected at W70 approximately but can not be found out of E40. By further investigating 69 Earth-encountered front-side halo CMEs (EFHCMEs) during 1996 ~ 2002, such E-W asymmetry in their source distribution is also found[4]. The E-W asymmetry is well relative to the transit speed of EFHCMEs from the Sun to the Earth. As for the EFHCMEs propagating faster than the background solar wind, their source distribution shifts to the west hemisphere, and the west CMEs are in the majority. On the contrary, as for the EFHCMEs propagating slower than the background solar wind, their source distribution shifts to the east hemisphere, and the east CMEs are in the majority. This phenomena can be explained in terms of the influence of the Parker spiral interplanetary magnetic fields on the CME's propagation. A kinetic model has been proposed to estimate the deflection degree of a CME when it arrives at 1 AU and the possible longitude range of an Earth-encountered CME with given transit speed.



(a) 59 geoeffective halo CMEs (b) 132 frontside halo CMEs

Fig.1 Distribution of solar source locations

Mid-term quasi-periodicities in CMEs during the most recent solar maximum cycle 23 are reported for the first time using the four-year data (February 5, 1999 to February 10, 2003) of LASCO/SOHO[5]. In parallel, mid-term quasi-periodicities in solar X-ray flares (class $\geqslant$ M 5.0) from the GOES and in daily averages of Ap index for geomagnetic disturbances from the World Data Center (WDC) at the International Association for Geomagnetism and Aeronomy (IAGA) are also examined for the same four-year time span. By Fourier and Morlet wavelet power spectral analyses, the CME, X-ray flare and Ap data all appear to contain significant power peaks at some periods. The X-ray solar flares show the familiar Rieger-type quasi-periods at 157 ± 11, 122 ± 5, 98 ± 3 days and shorter ones until 34 ± 0.5 days. The CMEs with period of 272 ± 26 days may be correlated with the flares with period of 259 ± 24 days. The CMEs with periods of 272 ± 26 days and 196 ± 13 days may be responsible for the geomagnetic disturbances with periods of 273 ± 26 days and 187 ± 12 days. Especially the peak at the second period of 187 ± 12 days in Ap data is very significant, which indicates CMEs are the main source of geomagnetic storms in the solar maximum. The geomagnetic disturbances with periods of 91 ± 5 days and 61 ± 2 days may be due to the flares with periods of 98 ± 3 days and 64 ± 2 days, which implies that parts of geomagnetic storms are created by large X-ray flares. In addition, the 28 ± 0.6 day periodicity in Ap data is most likely caused by recurrent high-speed solar winds from the coronal holes at the Earth's magnetosphere. Several conceptual aspects of possible equatorially trapped Rossby-type waves at and beneath the solar photosphere may be responsible for such mid-term quasi-periodicities.

By using interplanetary magnetic field data and plasma data from the ACE and Wind spacecraft during 1998 ~ 2001, the relationship between interplanetary parameters and geomagnetic storm's intensity is studied[6]. An updated criteria of interplanetary parameters causing geomagnetic storms is found. For moderate storms with $Dst_{\min} \leqslant -50$ nT, the threshold values are $\overline{B_s} \geqslant 3$ nT, $-\overline{VB_z} \geqslant 1$ mV/m and $\Delta t \geqslant 1$ hour; for intense storms with $Dst_{\min} \leqslant -100$ nT, the threshold values are $\overline{B_s} \geqslant 6$ nT, $-\overline{VB_z} \geqslant 3$ mV/m and $\Delta t \geqslant 2$ hours. The importance of $-\overline{VB_z}$ is much greater than that of Δt in creating storms, and a long duration is not very helpful for further enhancing a storm's intensity. An empirical formula:

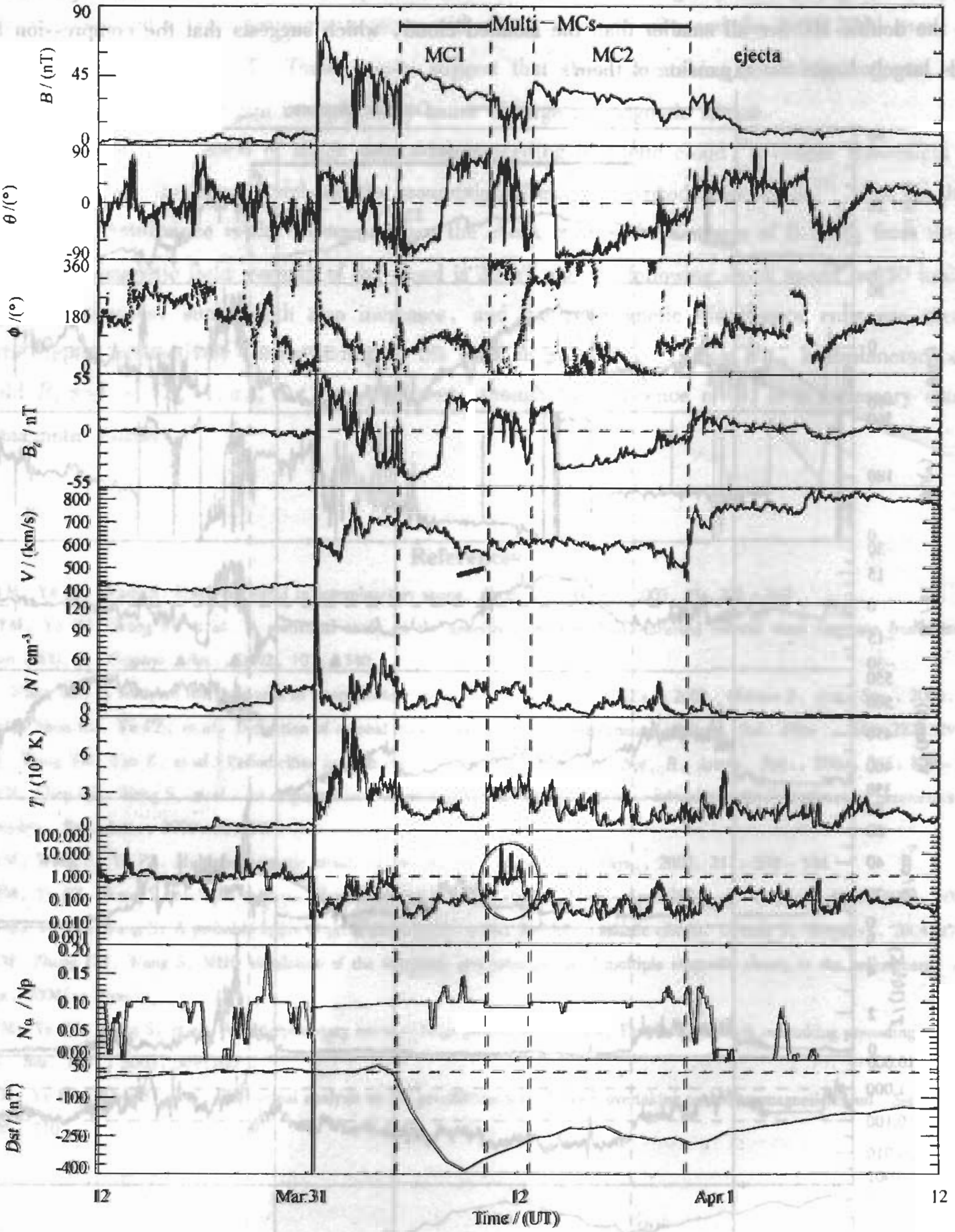
$$Dst_{\min} = -19.01 - 8.43(-\overline{VB_z})^{1.09}(\Delta t)^{0.30}$$

with the correlation coefficient of 0.95 is found. From the formula, one can conclude that compressed southward magnetic fields have a more intense geoeffectiveness. Assuming the magnetic flux per length $\phi = -\overline{VB_z}\Delta t =$ constant, if Δt is shortened to a half, and $-\overline{VB_z}$ enhances 1 time accordingly, the value of $(Dst_{\min} + 19.01)$ is therefore 1.73 times its original value.

2 Interplanetary multiple magnetic clouds (Multi-MCs)

During the solar maximum, the rate of CMEs' occurrence is ~3.5 per day. Therefore a complex structure in interplanetary space can be expected due to such high frequent explosions from the Sun. Multiple magnetic cloud, one special kind of the interplanetary complex structure, is proposed first time according to the observations, and a theoretical model is developed to describe it[7]. It is found that the configuration of Multi-MC relies on many factors, such as the number of the sub-clouds, the field strength of each sub-cloud, the sign of each sub-cloud's helicity, the orientation of each sub-cloud's axis, and so on. Further, the existence of Multi-MC is confirmed by analyses of March 3 ~ 5, March 31 and April 10 ~ 13, 2001 events[8].

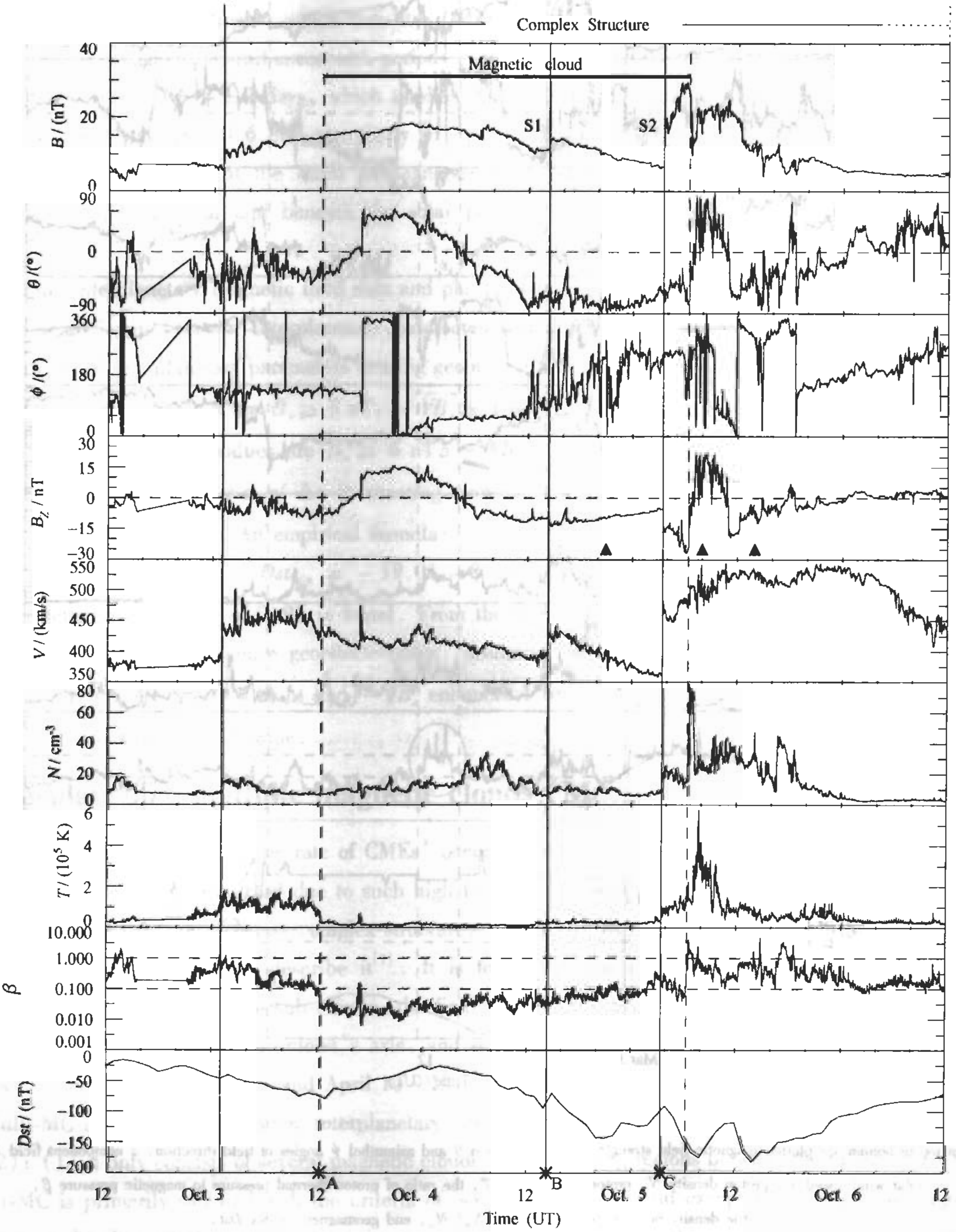
Multi-MC is different from other interplanetary complex structures. It has the following five characteristics (Fig. 2): (1) it only consists of several magnetic clouds and interacting regions between them; (2) each sub-cloud in Multi-MC is primarily satisfied with the criteria of isolated magnetic cloud except that the proton temperature is not as low as that in typical magnetic cloud due to the compression between the sub-clouds; (3) the speed of solar wind at the rear part of the front sub-cloud does not continuously decrease, rather increases because of the overtaking of the following sub-cloud; (4) inside the interacting region between the sub-clouds, the magnetic field becomes less regular and its strength decreases obviously, and (5) β value increases to a high level in the interacting region. Due to the compression between the sub-clouds, each sub-cloud is much smaller than the typical isolated magnetic cloud. In three cases, two Multi-MCs are associated with the great geomagnetic storms ($Dst \leqslant -200$ nT). The observational results imply that Multi-MC has a strong geoeffectiveness generally and is possibly another type of the interplanetary origin of large geomagnetic storms[9].



From top to bottom are plotted magnetic field strength B, the elevation θ and azimuthal ϕ angles of field direction, z component field B_z, solar wind speed V, proton density N, proton temperature T, the ratio of proton thermal pressure to magnetic pressure β, the density ratio of He^{++} to proton N_α / N_p, and geomagnetic index Dst.

Fig. 2　Observations by ACE spacecraft from 1200 UT on 30 March to 1200 UT on 1 April 2001 (in GSM)

In addition, the characteristics and propagation of double-MC are numerically studied by using fractional step scheme[10]. The simulation results are consistent with the observations approximately. The double-MC with the leading cloud's initial speed of 400 km/s and the following cloud's initial speed of 600 km/s arrives at 1 AU after ~72 hours. It has a double-peak structure in magnetic field, B_z has two fluctuations within the double-MC, the solar wind speed decreases continuously, and the temperature is low within the two sub-clouds. Between the two sub-clouds, the magnetic field strength reaches the minimum, and β increases to a relatively high value. The sub-clouds in the double-MC are all smaller than the isolated cloud, which suggests that the compression between the sub-clouds largely limits the expansion of them.



S1 and S2 denote the shock arrivals

Fig.3 Observations by ACE spacecraft from 1200 UT Oct. 2 to 1200 UT Oct. 6, 2000 (in GSM)

3 Phenomenon of a shock overtaking a preceding magnetic cloud

Two events of shock overtaking preceding magnetic cloud in October 2000 and November 2001 respectively are reported[11]. Commonly, the shock can not propagate within the low β magnetic cloud. However, in these two events, the shocks both advanced into the clouds and caused the large geomagnetic storms. These observations suggest that a shock can propagate and penetrate the low β cloud as long as its speed is high enough (Fig. 3). The Oct. 2000 event produced a large geomagnetic storm with $Dst_{\min} = -175$ nT, and the Nov. 2001 event created a great storm with $Dst_{\min} = -292$ nT. These results suggest that shock overtaking preceding magnetic cloud and advancing into it is also one important interplanetary cause of large geomagnetic storms.

To analyze the geoeffectiveness of shock overtaking preceding magnetic cloud, a simple theoretical model is developed by applying the flux rope model and the assumption of exactly perpendicular shock[12]. The result suggests that the geomagnetic disturbance is the strongest when the shock arrives the distance of $0.86R_0$ from the cloud's center if the central magnetic field strength of the cloud is 20 nT and the following shock speed is 550 km/s. When the shock speed increases, such depth also increases, and the geomagnetic disturbance enhances accordingly. Moreover, the depths respectively corresponding to the peak of geomagnetic index Dst, interplanetary southward magnetic field B_s and $-\overline{VB_z}$ (i.e., Δt) are different, though the existence of B_s is a necessary condition in causing geomagnetic storms.

References

[1] Wang YM, Ye PZ, Wang S. Magnetic cloud in interplanetary space. *Progress in Astron*, 2003, 21: 301 ~ 317

[2] Wang YM, Ye PZ, Wang S, *et al*. A statistical study on the geoeffectiveness of Earth-directed coronal mass ejections from March 1997 to December 2000. *J. Geophys. Res.*, 2002, 107: 1340

[3] Ye PZ, Wang YM. A study on the Bs events in interplanetary space and the associated CMEs in 2002. *Chinese J. Space Sci.*, 2003, 23: 7 ~ 17

[4] Wang YM, Shen CL, Ye PZ, *et al*. Deflection of coronal mass ejections in the interplanetary medium. *Sol. Phys.*, 2004, 222: 329 ~ 343

[5] Lou YQ, Wang YM, Fan Z, *et al*. Periodicities in solar coronal mass ejections. *Mon. Not. R. Astron. Soc.*, 2003, 345: 809 ~ 818

[6] Wang YM, Shen CL, Wang S, *et al*. An empirical formula relating the geomagnetic storm's intensity to the interplanetary parameters: $-VBz$ and Δt. *Geophys. Res. Lett.*, 2003, 30: 2039

[7] Wang YM, Wang S, Ye PZ. Multiple magnetic clouds in interplanetary space. *Sol. Phys.*, 2002, 211: 333 ~ 344

[8] Wang YM, Ye PZ, Wang S. Multiple magnetic clouds: several examples during March - April 2001. *J. Geophys. Res.*, 2003, 108: 1370

[9] Wang YM, Ye PZ, Wang S. A probable origin of great geomagnetic storm: multiple magnetic clouds. *Chinese J. Geophys.*, 2004, 47: 417 ~ 423

[10] Wang YM, Zheng HN, Wang S. MHD simulation of the formation and propagation of multiple magnetic clouds in the heliosphere. *Astron. and Astrophys*, 2004 (in Press)

[11] Wang YM, Ye PZ, Wang S, *et al*, An interplanetary cause of large geomagnetic storms: Fast forward shock overtaking preceding magnetic cloud. *Geophys. Res. Lett.*, 2003, 30: 1700

[12] Wang YM, Ye PZ, Wang S, *et al*. Theoretical analysis on the geoeffectiveness of shock overtaking preceding magnetic cloud. *Sol. Phys.*, 2003, 216: 295 ~ 310