作者姓名：汪毓明

论文题目：行星际磁云及其相关事件的综合研究

作者简介：汪毓明，男， 1976 年 09 月出生，1999 年 09 月师从于中国科学技术大学王水教授，于 2003 年 07 月获博士学位。

中 文 摘 要

作为联接太阳和地球的一个重要的纽带，行星际磁云在空间天气学中占有重要的地位。它是日冕物质抛射在行星际空间中的一种产物，也是中等以上非重现性地磁暴的主要制造者。本文主要以分析观测资料为主，同时通过建立理论模型和进行数值模拟，对日冕物质抛射（CME）、行星际扰动和地磁暴之间的联系、行星际中多重磁云结构和激波追赶磁云等现象，进行了综合研究。

1．日冕物质抛射、行星际扰动和地磁暴之间的统计关系

根据 SOHO 飞船上的 LASCO 和 EIT 以及 GOES 卫星上的观测资料，分析了 1997 年 3 月到 2000 年底的所有正面晕状（halo）CME，发现 45%（59/132）的 CME 具有地磁效应，它们引起了 51 次中等以上地磁暴。C 级以上耀斑的伴随情况显示，具有地磁效应的晕状 CME 的耀斑伴随率普遍偏高；随着太阳活动的增强，耀斑伴随率也在逐年增加。在太阳高年（2000 年）期间，几乎 100%的晕状 CME 都伴随有 C 级以上耀斑。对于 Kp≥ 7 以上的大磁暴事件，其 CME 的日地传输时间与初始的投影速度基本满足经验关系 Tau = 27.98 + 2.11×104 / V (hours)，相关系数达到 0.87。通过分析 2000 年中 12 次行星际南向磁场（Bs）事件，发现仅有 2 次与共转流相互作用区有关，有 11 次与 CME 有关。11 次与 CME 有关的 Bs 事件中，有 10 次引起了 Dstmin≤−100nT 的大磁暴。

同时，统计分析表明，对地晕状 CME 的日面位置分布具有东西不对称性。爆发在西边的 CME 比东边的多出 57%，且西边的出现经度可以到 70º，而东边的不超过 40º。进一步分析了 73 次到达地球的正面晕状 CME，发现这种东西不对称性与 CME 在行星际空间中的运行速度有关。快于背景太阳风速度的 CME 会向东偏转，从而使对地晕状 CME 的日面源区分布向西移动；而慢于背景太阳风速度则会向西偏转，使对地晕状 CME 的分布向东移动。这种现象可能是由行星际螺旋引起的。

通过对 1999 年 2 月到 2003 年 2 月期间的 CME 和 M5.0 级以上 X 射线耀斑的爆发次数以及地磁指数 Ap 的 24 小时平均值，进行周期谱分析，发现 CME、X 射线耀斑和磁暴 Ap 指数均有较明显的中准周期规律，其中 X 射线耀斑确实具有 Rieger 类型的中准周期。它们中的部分中准周期彼此相互吻合，说明了它们之间复杂的相关性。太阳上可能存在的大尺度 Rossby 类型波动是这种中准周期现象的一种理论解释。

通过分析 1998–2001 年 ACE 和 Wind 飞船的行星际磁场和太阳风等离子体数据，研究了行星际参数与地磁暴强度之间的关系，得到了产生中等以上地磁暴的行星际条件。对于 Dstmin

≤−50nT 的中等磁暴，阈值为 Bs≥3nT、−VBz≥1mV/m 和Δt ≥1h；对于 Dstmin≤−100nT 的强磁暴，阈值为 Bs≥6nT、−VBz ≥3mV/m 和Δt ≥2h。并且发现，在引起磁暴的过程中−VBz 的重要性远大于Δt，且持续时间越长，能量的耗散效应就越明显。磁暴的峰值 Dstmin 与−VBz 和Δt 满足经验公式 Dstmin =−19.01−8.43(−VBz)1.09(Δt)0.30 (nT)，与观测值比较，相关系数达到 0.95。这公式指出了压缩后的南向磁场普遍具有更强的地磁效应。

2．行星际多重磁云结构

太阳高年期间 CME 频繁爆发，造成了复杂的行星际结构。根据行星际的观测资料，首次从理论和观测上提出和证实了多重磁云的存在。多重磁云不同于其他行星际复杂抛射结构，它具有以下 5 个观测特征：（1）仅包含磁云及磁云间的相互作用区；（2）每个子磁云都满足单个磁云的基本特征。由于子磁云间的相互压缩，质子温度可能偏高，但质子β值仍然低于 0.1；（3）在前导（即被追赶的）子磁云的尾部，太阳风速度会有所抬升；（4）相互作用区内的磁场强度相对较弱，且起伏较大，没有规则；（5）相互作用区内，质子温度和β回升到较高的值。由于多重磁云携带较规则的磁场，且存在较大的压缩现象，故一般具有强烈的地磁效应。在 2001 年 3 月到 4 月期间三个多重磁云事件中，有两个事件造成了 Dstmin≤−200nT 的特大地磁暴。

在无力场磁通量管模型的基础上，建立了多重磁云的理论模型。同时，进一步运用分数步法，数值模拟了子午面内双重磁云在行星际空间中的传播。模拟的结果与实际的观测结果大体一致。双重磁云的磁场有两个峰值，Bz 有两次起伏，太阳风速度持续下降，粒子温度和β均呈现两个低值槽，两磁云之间的磁场出现一极小值，即为相互作用区，相互作用区内，β回升到较高值。双重磁云中两个子磁云的尺度都要小于单个磁云运动时的尺度，这说明子磁云间的相互挤压限制了它们的膨胀。

3．激波追赶磁云现象

压缩后的南向磁场具有更强的地磁效应。与多重磁云相同，激波追赶磁云，压缩磁云内部的南向磁场分量，也会引起大的地磁暴。通过分析 2000 年 10 月和 2001 年 11 月两次激波追赶磁云的事件，首次报道了激波压缩磁云内部磁场引起特大地磁暴的现象，并再次证实了在低β的磁云内部，激波一样可以存在并传播。

利用磁云的磁通量管模型和垂直激波假设，建立了激波进入磁云的简单的理论模型，分析了激波进入磁云的深度与所能引起的磁暴强度之间的关系，发现对于中心磁场强度为 20nT 的磁云，当追赶的激波速度为 550km/s 时，激波进入磁云距中心 0.86R0 处的地磁扰动最强。且随着激波强度的增加，该深度也在加深，同时地磁扰动也相应地增强。而且，尽管磁场南向分量 Bs 的存在是引起较大地磁暴的前提条件，地磁效应 Dstmin、Bs 和−VBz（即对应Δt）分别达到最大峰值所对应的激波进入磁云的深度是有差别的。

关键词：　日冕物质抛射　行星际磁云　激波　地磁暴

Comprehensive studies on magnetic clouds in the interplanetary space and their associated events

Wang Yuming

ABSTRACT

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 an pivotal role in space weather research. To further study the interplanetary magnetic clouds and their associated events is meaningful and valuable to understand the solar-terrestrial physical processes and improve 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. The relationship between the CMEs, interplanetary disturbances and geomagnetic storms

According to the observations by the Large Angle Spectroscopic Coronagraph (LASCO) and the Extreme 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. Among these CMEs, 45%(59/132) of them are geoeffective (or Earth-directed) and 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 the all Earth-directed halo CMEs is higher than that of the all front-side halo CMEs. The ratio becomes larger year by year from 1997 to 2000, and especially in 2000 (approaching the solar maximum), the ratio almost reaches 100%. As for the 15 events associated with Kp ⩾ 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: Tau = 27.98 + 2.11×104 / V (hours), which has a good correlation coefficient of 0.87. Moreover, by analyze 12 interplanetary southward magnetic field (Bs) events, it is found that only two events are relative to the corotating interaction regions (CIRs) and 11 events are relative to CMEs. Ten of these eleven events associated with the CMEs created the intense geomagnetic storms with Dstmin⩽ −100 nT. The results confirm that the CMEs are the main producer of large geomagnetic storms during solar maximum.

The source distribution of above 59 Earth-directed halo CMEs on the solar disk is east-west (E–W) asymmetrical. The number of the Earth-directed halo CMEs occurring on the west is larger than that on the east by 57%, and such CME can be expected at W70ºapproximately but can not be found out of E40º. By further studying 73 Earthencountered front-side halo CMEs (EFHCMEs) during 1997–2001, such E–W asymmetry in their source distribution is also found. The E–W asymmetry is 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.

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. In parallel, mid-term quasi-periodicities in solar X-ray flares (class ⩾ M5.0) 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 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. New criteria of interplanetary parameters causing geomagnetic storms are found. For moderate storms with Dstmin⩽−50 nT, the threshold values are Bs ⩾ 3 nT, −VBz ⩾ 1 mV/m and Δt ¸ 1 hour; for intense storms with Dstmin ⩽−100 nT, the threshold values are Bs ⩾ 6 nT, −VBz ⩾ 3 mV/m and Δt ⩾ 2 hours. The importance of −VBz is much greater than that of ¢t in creating storms, and a long duration is not very helpful to further enhance a storm's intensity. An empirical formula: Dstmin = −19.01−8.43(−VBz)1.09(Δt)0.30 (nT) with the correlation coefficient of 0.95 is found. From the formula, one can conclude that a compressed southward magnetic field has a more intense geoeffectiveness. Assuming the magnetic flux Φ = −VBzΔt = constant, if Δt is shortened to a half, and −VBz enhances 1 time accordingly, the value of (Dstmin + 19.01) is therefore 1.73 times its original value.

2. The 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 firstly according to the observations, and a theoretical model is developed to describe it. 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.

Multi-MC is different from other interplanetary complex structures. It has the following five characteristics: (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.

In addition, the characteristics and propagation of double-MC are numerically studied by using fractional step scheme. 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, Bz 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.

3. The phenomena of shock overtaking preceding magnetic cloud

Two events of shock overtaking preceding magnetic cloud in October 2000 and November 2001 respectively are reported. 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 large enough. The Oct. 2000 event produced a large geomagnetic storm with Dstmin =−175 nT, and the Nov. 2001 event created a great storm with Dstmin = −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. The result suggests that the geomagnetic disturbance is the strongest when the shock arrives the distance of 0.86R0 from the cloud's center if the central magnetic field strength of the cloud is 20 nT and the following shock speed is 550km/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 Bs and −VBz (i.e., Δt) are different, though the existence of Bs is a necessary condition in causing geomagnetic storms.

Key words: Coronal mass ejection − Interplanetary magnetic cloud − Shock − Geomagnetic

storm