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Applying ACE data and pressure-corrected Dst index (Dst*), annual distributions of solar wind structures detected at L1 point (the first Lagrangian point between solar-terrestrial interval) and correlations between solar wind structures and geomagnetic storms in 1998–2008 have been studied. It was found that, within the Earth’s upstream solar wind, the dominant feature was interplanetary coronal mass ejections (ICMEs), primarily magnetic clouds, during solar maximum period but corotating interaction regions (CIRs) at solar minimum. During rising and declining phases, solar wind features became unstable for the complicated solar corona transition processes between the maximum and minimum phases, and there was a high CIR occurrence rate in 2003, the early period of the declining phase, for the Earth’s upstream solar wind was dominated by high-speed southern coronal-hole outflows at that time. The occurrence rate of sector boundary crossing (SBC) events was evidently higher at the late half of declining phase and minimum period. ICMEs mainly centered on the maximum period but CIRs on all the declining phase. The occurrence rate of ICMEs was 1.3 times of that of CIRs, and more than half of ICMEs were magnetic clouds (MCs). Half of magnetic clouds could drive interplanetary shock and played a crucial role for geomagnetic storms generation, especially intense storms (\(\Delta rt > 100\) nT), in which 45% were jointly induced by sheath region and driving MC structure. Sixty percent of intense storms were totally induced by shock-driving MCs; moreover, 74% of intense storms were driven by magnetic clouds, 81% of them driven by ICMEs. Shock-driving MC was the most geoeffective interplanetary source for four fifths of it able to lead to storms and more than one-third to intense storms. The rest of intense storms (19%) were induced just by 3% of all detected CIRs, and most of CIRs (53%) were corresponding to nearly 40% moderate and small storms (\(-100\) nT < \(\Delta rt\) < \(-30\) nT). The true sector boundary crossing (SBC) events actually had no obvious geoeffectiveness, just 6% of them corresponding to small storms.

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1. Introduction

Helmet streamer and coronal hole are significant coronal features. Helmet streamers could create slow and dense solar wind in interplanetary (IP) medium, whereas coronal-hole outflows are always characterized by high-speed stream (HSS). During intense solar activity periods especially with flares and erupting filaments, fast transient streamer outflows originating from large breaking coronal loops throw gigantic plasmoids into IP medium, which were identified as flux-rope coronal mass ejections, a subset of coronal mass ejection (CME). CME and HSS are two main solar sources of IP disturbances. The IP counterpart of CME is interplanetary coronal mass ejection (ICME), and some of ICMEs can drive IP shocks. Shock-driving ICME apparently presents three subregions: shock, sheath region immediately after shock, and the following driving ejecta. One-third or one-half (Gosling, 1990; Cane et al., 1997) of ICME driving ejecta contained magnetic flux rope with large-scale smoothly rotating magnetic field, known as magnetic cloud structure (MC). Other ICMEs without smooth flux-rope structures in ejecta are usually called non-cloud ICMEs compared to MCs. Furthermore, according to the magnetic structure of MC's flux rope and the time order of detected Bz direction varying through the MC, most MCs can be identified as south-north (SN), north-south (NS), full south (FS), and full north (FN) clouds (e.g., Mulligan et al., 1998). These mentioned subdivisions of ICME facilitate the study of ICME’s geoeffectiveness (e.g., Gopalswamy, 2008; and reference therein), and if the geoeffectiveness is limited to the ability to intensify ring...
current of geospace, it mostly can be attributed to the subregions containing southward IMF Bz component (BzS) within the driving ejecta and the shear region (e.g., Zhang et al., 2007; Echer et al., 2008; and reference therein) due to the compressed or draping IMF ahead of ICME ejecta. IMF BzS can create magnetic reconnection between the IMF and the Earth’s magnetic field at dayside magnetopause, which plays the most significant role for solar-terrestrial coupling and geomagnetic storm generation for transferring enormous solar wind energy and momentum into terrestrial space (Dungey, 1961; Gonzalez et al., 1999).

HSS colliding with preceding slow solar wind forms an interaction region, corotating interaction region (CIR), between the decreased HSS and increased preceding slow wind (Smith and Wolf, 1976). The CIR can be divided into three subregions: the leading half (the increased low-speed flow), stream interface, and the trailing half (the decreased HSS), and intense storms following CIRs were generated by BzS located in those regions and Bz fluctuations of Alfvén waves in the trailing part (Burlaga, 1974; Forsyth and Marsch, 1989; Richardson et al., 2006), since the amplitude of IP Alfvén waves propagating into CIR can be largely intensified (Tsurutani et al., 1995) and the Bz fluctuations within Alfvén waves can result in intermittent reconnection at dayside magnetopause.

In IP space, the boundary between plasma with true opposite IMF polarities at their solar origins separates the heliosphere into sectors, in each sector IMF possessing uniform polarity of open field lines, and the boundary was named interplanetary sector boundary (SB). The opposite IMF can form heliospheric current sheet (HCS), but HCS could depart from SB sometimes due to the passing-by of transient streamer outflows along SB (Crooker et al., 2004a). After radial propagation, these helmet streamer outflows which encase SB will evolve into heliospheric plasma sheets (HPS) of slow and dense solar wind plasma in IP space (e.g., Crooker et al., 2004a, b; and reference therein).

The correlation of ICME and CIR with geomagnetic storms has been studied for decades, and both of them were considered as the most important IP sources of IMF BzS (e.g., Gonzalez et al., 1999; Echer et al., 2004, 2008; and reference therein). Gonzalez and Tsurutani (1987) and Tsurutani et al. (1988) found that during the maximum period of solar cycle 21, half of intense storms (Dst < −100 nT) were associated with magnetic cloud, and half with compressed sheath regions led by large shocks ahead of magnetic clouds. Gonzalez et al. (2007) have studied IP causes of intense geomagnetic storms in 1997–2005 and found that the most common IP structures corresponding to the development of an intense storm-main phase were: MCs, sheath fields, sheath fields followed by a MC and CIRs in order of importance. But we still do not know if these solar wind structures kept the same weights in driving moderate and small storms, or if these structures had the same influences to each storm levels in solar cycle 23.

It had been found that the sector boundary crossing (SBC) events may lead to geomagnetic activities enhancements (Schatten and Wilcox, 1967). Echer and Gonzalez (2004) have studied the statistical relationship between SBCs andDst-storms during 1957–2001 and found that about 6% of SBCs was followed by intense magnetic storms, 20% by moderate and 25% by small. But sometimes, SBC and CIR, or SBC and ICME can be jointly observed by the passing-through space detectors, for IP sector boundary always being the passageway of transient streamer outflows (Crooker et al., 2004a, b) and the local warps of cold and dense sector boundary being able to create CIRs as interacting with faster ambient solar wind (Kunow et al., 1999). And so the question is these remarkable intense and moderate storms were really induced by SBC events or actually induced by the adjacent ICMEs or CIRs, and it needs to be figured out.

At sunspot minimum, the solar coronal displays a simple structure with huge circumpolar coronal holes sitting on high heliolatitudes and emitting persistently fast and tenuous flows, and helmet streamers confined to low heliolatitudes forming huge streamer belt with slower but more variable solar wind. At solar maximum, the solar activities are extremely intense and the solar coronal turns into a mixed solar wind source with smaller and discrete coronal holes, active regions and helmet streamers found at all heliolatitudes. The rising phase and declining phase of solar cycles are transition intervals of maximum and minimum periods. The Earth’s upstream solar wind, confined in the regions around the ecliptic plane, is dominant for solar-terrestrial energy coupling, and the regularity of near-Earth solar wind perturbation is important for understanding the condition of the Earth’s magnetosphere disturbances. As the most common IP sources of geomagnetic storms, it is important for space weather research and forecasting to find out the distributional patterns of occurrence rate and geoeffectiveness of ICMEs and CIRs in the Earth’s upstream solar wind and how they vary with solar activity in a solar cycle.

The continual data of ACE nearly covers the whole solar cycle 23, and it is an advantage for comprehensively studying the control effects of the near-Earth upstream solar wind (Stone et al., 1998) to terrestrial space conditions. So ACE data in 1998–2008 were used to study the geoeffectiveness of those solar wind structures, their different weights to each storm level and the yearly distributions of those structures and their geoeffectiveness at L1 point (the first Lagrangian point between solar-terrestrial interval) for figuring out the above-mentioned concerns.

2. Identification of solar wind structures and magnetic storms

In solar cycle 23, the sunspot number was smaller than previous two solar cycles, and meanwhile solar wind dynamic pressure was also obviously smaller (McComas et al., 2003) leading to an unusual cycle (Richardson et al., 2001). For establishing the most general correlation between a variety of solar wind structures and geomagnetic storms, in this study, the pressure-correctedDst (Dst*) index, which removes the effects of solar wind dynamic pressure from Dst index (Burton et al., 1975; Gonzalez et al., 1989; O’Brien and McPherron, 2000), were used to define geomagnetic storms and measure their intensities.

\[
\text{Dst*} = \text{Dst} - b\frac{P_{dyn}}{c} + c
\]

where \( b = 7.26 \text{nT/(nPa)}^{1/2}, P_{dyn} \) is solar wind dynamic pressure in nPa, and \( c = 11 \text{nT} \) (O’Brien and McPherron, 2000). We applied the Gonzalez et al. (1994) classification scheme to the Dst* index, and the Dst*-storms can be classified as the following:

Quiet: \(-30 \text{nT} < \text{Dst*}\)
Small storms: \(-50 \text{nT} < \text{Dst*} \leq -30 \text{nT}\)
Moderate storms: \(-100 \text{nT} < \text{Dst*} \leq -50 \text{nT}\)
Intense storms: \(\text{Dst*} \leq -100 \text{nT}\)

Note that due to the occasionally unavoidable missing data, if the solar wind dynamic pressure is missed, Dst* cannot be computed and then these data periods are removed for the consistency of analysis.

The following were typical properties of various solar wind structures. The plasma and magnetic signatures of ICMEs include: stronger IMF than ambient medium, abnormally low proton temperatures and plasma beta value, low electron temperatures,
and bidirectional suprathermal electron (e.g., Gosling et al., 1990, and reference therein). Magnetic clouds are characterized by: (1) larger field strength than average field within driving ejecta, (2) the large-scale smooth and continuous rotation of magnetic field (Burlaga et al., 1981), (3) unusually lower proton temperature and low plasma beta than the surrounding (Klein and Burlaga, 1982; Burlaga et al., 1987; Burlaga, 1991; Osherovich and Burlaga, 1997), and (4) bidirectional suprathermal electron stream (e.g., Zwickl et al., 1983; Gosling et al., 1987) in most cases. For shock-driving MC (abbreviated as SC MC), the features of sheath region (SH) are enhanced magnetic field strength, rapidly varying field direction, and increased particle temperatures, density, and speed (Tsurutani et al., 1988). Therefore, using various leading boundaries of the sheath regions: shocks, shock-like structures, pressure pulse, or a sharp rise in density, temperature or velocity (Wu and Lepping, 2002), and the boundary characteristics between preceding SH and MC ejecta: the initial rotation of the elevation angle, the intensified magnetic field strength, and the initial start of the relatively low proton temperature, low proton density, and low plasma beta (Lepping et al., 1990; Wei et al., 2003), the forward SH and MC can be differentiated. As a subset of ICMEs, when MC list is deleted from ICMEs with its significant characteristic of large-scale and smooth field rotation (Burlaga et al., 1987), the remainder is non-cloud ICMEs (e.g., Tsurutani et al., 1988; Gonzalez et al., 1999), and the possible SH ahead of non-cloud ICME also could be identified. In-situ observation, when the trajectory of spacecraft had just gone through the flank region of shock-driving ICMEs missing driving gases, the single shock or shock sheath profile without trailing driving gas could be observed (e.g., Gopalswamy, 2006, and reference therein).

A list of CIR events were identified based on their typical signatures: (1) the solar wind velocity changes from less than 350 km/s to more than 550 km/s, (2) plasma density peaks slowly but drops suddenly at the stream interface, typically indicated by a relatively abrupt depression in the density, increases in velocity, proton temperature and flow shear in the solar wind (Forsyth and Marsch, 1999), (3) the magnetic field is compressed and remarkably larger than ambient IMF. When propagating far away 1 AU in IP space, well developed CIR structure can drive forward and reverse shock. But less than 1 AU, the possible forward shock evidently plays no role in storm generation (e.g., Richardson et al., 2006).

The local current sheet created by local IMF reversal was always seen as synonym with interplanetary sector boundary, yet this method fails actually when the field lines are substantially kinked (Kahler and Lin, 1994; Crooker et al., 2004a). Kahler and Lin (1994, 1995) first illustrated that the behaviors of electrons continually streaming away from or toward the Sun along magnetic field lines can give incontrovertible remote information about the direction of field lines when they leave the Sun, namely parallel streaming to the field implies the field line is connected to the Sun with away polarity and antiparallel streaming indicating toward polarity of magnetic field, even though these open field lines were locally inverted. Therefore, the sector boundary crossing (SBC) can be clearly identified and differentiated from the local current sheet, using the mentioned suprathermal electron pitch-angle criterion (Crooker et al., 2004a, b). Meanwhile, Kahler and Lin (1994, 1995) found some detected sector boundaries without magnetic field reversals, but they were paired to nearby local field reversals, which were created by the transient streamer outflows (Crooker et al., 2004a). Crooker et al. (2004b), Fig. 1 illustrated that 33% of detected SBC events were accompanied by the transient streamer ejecta. Thus, the sector boundary is often the sites of transient streamer ejecta. Meanwhile, 50% of SBS could be surrounded by HPSs (heliospheric plasma sheets) (Crooker et al., 2004b) of slow and dense solar wind, and the local warps of HPS or streamer belt could form CIRs (Kunow et al., 1999). The SBC, ICME, mostly represented as a transient streamer outflow, and CIR sometimes can be jointly observed by passing-by detectors.

For the veracity of identifying a true SBC event (Crooker et al., 2004b), suprathermal electrons pitch-angle spectrum data were used to distinguish a SBC event from other field and plasma disturbances in this paper, namely electrons pitch-angle changing from 0° to 180° or vice versa is identified as a SBC (Kahler and Lin, 1994, 1995; Crooker et al., 2004a, b). ACE/SWEPAM-E/STEA Electron Pitch Angle spectrum data of 272 eV electrons are available from Las Alamos National Laboratory. Since electrons at 272 eV are generally well within the suprathermal range and the distribution at this energy had very little contamination from the core population, and so measured count rates at 272 eV provide excellent statistical significance.

The storm-main phase is the primary characteristic of a storm (Gonzalez et al., 1994), standing for the creation of intensified terrestrial ring current, thus the main phase was chosen to represent a storm in this paper. Dst* index has erased the effect of solar wind dynamic pressure, so the frame of storm-main phase is set from the initial decreasing point to the minimum. Solar wind structures or their subregions within the certain solar wind interval ahead of 1 h to the storm-main phase frame, for the necessary average time-lag of solar wind propagation from the L1 point to the terrestrial space, were identified as the IP causes of this storm-main phase, based on the special IMF and plasma characteristics and identification methods of different solar wind structures mentioned above.

Table 1 lists solar wind structures identified as the IP sources of Dst*-storm main phase and their abbreviations used in this paper for concise expression. MC stands for magnetic cloud structure which did not drive IP shock. In Fig. 1, the MC possesses larger magnetic field strength (>8 nT) than ambient solar wind, long-duration (>23 h) smooth-rotation flux-rope structure, low proton temperature (<1.0 × 10^5 K) and plasma beta value (<0.3), but has not driven preceding IP shock and sheath region. The following storm generation is resulted by the grey subregion with long-duration BzS field more than 15 h in MC structure. The strength of subregion magnetic field and BzS field are all less than 10 nT, but a time-duration of more than 15 h is enough for intense storm generation. It should be noted that the solar wind data have been shifted 1 h backward according to the average time-lag to match the time of Dst*, and all the displayed case study figures of solar wind structures in this paper and the Supplementary Figs. were processed in the same way.

The corresponding storm generation with SC MC could be induced by the sheath region, MC structure, or both of them together. SH(MC) represents the type of SC MC in which just the sheath region was responsible for the storm generation and the MC structure is not involved in main-phase generation. In Supplementary Fig. 1, the storm-main phase (grey region of last panel) was resulted by the sheath region within the grey zone. The high-speed (~600 km/s) driving MC structure drove evident preceding shock forming sheath region with intense (~20 nT) and long-duration (>7 h) BzS mostly due to the trajectory of detector across through the draped IMF around the leading boundary of driving MC. On the contrary, (SH)MC stands for the category of just the driving MC structure responsible for the storm generation and the preceding SH not involved in storm generation. In Supplementary Fig. 2, SH was obvious but not related to the storm generation.

SH+MC represents SH and MC structure leading to the storm generation jointly. In Fig. 2, the driving MC with very high-speed (>1000 km/s) drove huge IP shock, the total magnetic field, speed,
plasma density and temperature all undergoing big jumps. Meanwhile, both plasma temperature and beta value within sheath region were remarkably high. The magnetic field in SH disturbed markedly and the intensity of following storm was very significant ($< -300 \text{nT}$). Compared to SH(MC) and (SH)MC cases, it is obvious that the speed of driving MC and detected magnetic field $B_z$ orientation and strength within SH and MC structure are all important for intense storm generation.

The category SH was the sheath region following ICME-driven IP shock but without trailing driving-gas in in-situ observation data because the detector just had gone through the flank regions of shock-driving ICME missing the driving ejecta. In Fig. 3, the frame of sheath region is from after the shock through flank region of driving ICME to the rear of ICME, nearly up to 2 days, and meanwhile, it was accompanied by disturbed magnetic field, high plasma temperature and beta value through the whole interval. For the highly disturbed $B_z$ field of this region, the single sheath region could induce intense geomagnetic storms.

### Table 1

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Interplanetary sources of geomagnetic storms</th>
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<tr>
<td>MC</td>
<td>Magnetic cloud without preceding IP shock</td>
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<tr>
<td>SH(MC)</td>
<td>The sheath region lying between the MC-driven IP shock and the driving MC</td>
</tr>
<tr>
<td>(SH)MC</td>
<td>The driving ejecta with flux rope structure within shock-driving MC</td>
</tr>
<tr>
<td>SH+MC</td>
<td>The sheath region and the driving MC</td>
</tr>
<tr>
<td>SH</td>
<td>The sheath region following the ICME-driven IP shock but without trailing ICME in in-situ observation data</td>
</tr>
<tr>
<td>E</td>
<td>Ejecta without flux rope and preceding IP shock or non-cloud ICME without preceding IP shock</td>
</tr>
<tr>
<td>SH+E</td>
<td>Sheath region and driving ejecta</td>
</tr>
<tr>
<td>CIR</td>
<td>IP corotating interaction region</td>
</tr>
<tr>
<td>SBC</td>
<td>IP sector boundary crossing</td>
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<tr>
<td>A</td>
<td>IP Alfven wave</td>
</tr>
<tr>
<td>DISTURB</td>
<td>IP disturbance for unknown origin</td>
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**Fig. 1.** The grey zone is the main phase of the intense storm and its corresponding IP cause, a subregion of a MC structure between the two vertical dashed lines. In last panel, four horizontal dotted lines mark the bounds of each storm level: 0, $-30$, $-50$ and $-100 \text{nT}$. 
For the non-cloud ICME, E stands for non-cloud ejection not driving preceding IP shock and sheath region, SH+E for the SH and following ejection collectively responsible for the storm generation. Compared to SH(MC) and (SH)MC, SH(E) and (SH)E should be reasonable categories for storm generation, but in this statistical research, none of storms was generated by the SH(E) or (SH)E. So, they were not listed in Table 1 as IP sources of storm generation. In Supplementary Fig. 3, the non-cloud ICME within vertical dashed lines did not drive IP shock for larger solar wind velocity before the ejecta, but its long-duration internal Bzs field can be responsible for the moderate storm-main phase in the last panel of Supplementary Fig. 3, even the Bzs field just around $-10\, \text{nT}$. In Supplementary Fig. 4, the storm-main phase, covered by grey zone, was induced by the subregion in sheath region with nearly down to $-10\, \text{nT}$ Bzs and the trailing E.

CIR is corotating interaction region between high-speed solar wind and preceding slower flow. Less than 1 AU, the forward shock of CIR does not always emerge, and the forward shock at CIR leading edge plays no role in storm generation (e.g., Richardson et al., 2006). CIR is mainly characterized by the larger magnetic field, remarkably rising velocity with increasing temperature, and slowly increasing but suddenly dropping of density at stream interface. In Fig. 4, within the leading half between the forward shock (the first vertical dashed line) and the stream interface (nearly after 06:30 of 4 April), the Bz field is almost positive thus without geoeffectiveness, but in leading half after stream interface, Bzs field fluctuated and induced moderate storm generation.

The spectrum of suprathermal electron pitch angle is used to identify sector boundary between plasma with truly opposite IMF at their solar origin. In the SBC case of Fig. 5, when the detector passed through the sector boundary between vertical dashed lines, the electron pitch-angle changed from $0^\circ$ to $180^\circ$ illustrated in the first panel, namely the detector moving from an outward-directed IMF sector to an inward-directed IMF sector. The HCS (heliospheric current sheet) had a little departure from the SBC.
due to the direction change of Bx after SBC in the third panel. The sector boundary was jointly detected with CIR, which should be created by the warp of the sector boundary, but the SBC event still did not correspond to geomagnetic storms.

Around the ecliptic plane, large-amplitude Alfven waves can be observed in HSS and CIR structures. Alfven wave is characterized by the highly correlated magnetic field and velocity disturbances in in-situ observation and could lead intermittent reconnection at dayside magnetopause and then significant magnetosphere disturbance including intermittent substorm activity and sporadic injections of plasma sheet energy into the outer portion of the ring current (e.g., Gonzalez et al., 1999), probably responsible for the generation of geomagnetic storms. A is short for Alfven wave in this paper. At second-fourth panels of Fig. 6, the Bx, By and Bz turbulences highly correlate with Vx, Vy, Vz turbulences respectively, displaying an Alfvenic disturbance in IP medium. Although the plasma velocity is less than 500 km/s and the total magnetic field is just around 8 nT, the BzS disturbances within Alfven wave still induce storms even for moderate storm. In this statistical research, some unknown small IP disturbances containing BzS could be responsible for several small storm generation, they were classified into the category of DISTURB.

3. Results and discussion

Rudolf Wolf was independently one of the first to show the coincidence between sunspot cycle and geomagnetic activity in 1852, and now the sunspot number is one of the indicators of the solar activity levels. For avoiding confusion in this paper, the studied interval is separated into rising phase (1998–1999), maximum (2000), post-maximum (2001), declining phase (2002–2007), and minimum (2008) of solar cycle according to the sunspot number trendline shown in Fig. 7. Fig. 7 illustrates annual distributions of all Dst*-storms in each level and monthly smoothed sunspot number trendline in 1998–2008. Most of the
intense storms concentrated on 1998, 2000–2002, and 2004–2005, but the top occurrence rate was in 2002, the early declining phase. Meanwhile, in 1999 and 2003, the intense storms were unexpectedly smaller. The top numbers of moderate, small, and all storms were all in 2003. The solar maximum 2000 and 2002 have the top number of significant Dst*-storms ($\text{Dst}^*$). For the non-linear correlation of Dst*-storms to solar activity levels, the near-Earth investigation of the solar wind is important for solar-terrestrial relation.

Table 2 displays the detailed information about the correlation of 1630 detected solar wind structures and disturbances at L1 point with Dst*-storms in 1998–2008. In Table 2, data from the third to the fifth column are the numbers of each Dst*-storm level and their different IP sources in the first column, illustrated in Fig. 8. For each solar wind structure category, the following Dst*-storms measure its geoeffectiveness in this paper, namely the contributions of caused disturbances in inner magnetospheric current systems to near-Earth disturbance field, since the transition from Dst to Dst* had removed the contribution of magnetopause current sheet to near-Earth disturbance field at moderate and low latitudes. The geoeffectiveness of each solar wind structure is clearly illustrated in Fig. 9.

The MC structures were identified in Burlaga criteria: (1) stronger IMF than ambient medium, (2) smoothly and continuously long-duration large-scale magnetic field rotation, (3) unusually lower proton temperature and plasma beta value, and
meanwhile, through the whole visual inspection process, the quantitative limits about internal magnetic field intensity (> 8 nT) and time-duration (> 8 h) and lower plasma beta value (< 0.3) within Lepping’s criteria (Lepping et al., 2005; Gopalswamy, 2006) for magnetic cloud-like structure automatic identification were adopted. The number of identified MCs is larger than Lepping’s list (http://lepmfi.gsfc.nasa.gov/mfi/mag_cloud_pub1.html) since some of our MCs do not strictly fulfill the force-free flux-rope criterion. Meanwhile, the extremely lower proton temperature (< 1.0 x 10^5 K) was considered as the primary character of ICMEs, and the non-cloud ICMEs were identified with the same magnetic field and plasma properties requirement as magnetic cloud-like structure’s identification (Lepping et al., 2005; Gopalswamy, 2006) except for the smoothly large-scale internal field rotation. Thus part of non-cloud ICMEs of this survey did not possess cloud-like magnetic field. Furthermore, since this survey covered longer time period (1998–2008) than Gopalswamy (2006) which covered a time period of 1996–2003, so our ICMEs number was larger than that of Gopalswamy (2006) where magnetic clouds, cloud-like events and shock-driving ICMEs were considered.

Bidirectional electron is a significant signature for magnetic flux-rope identification within magnetic cloud ejecta. However, bidirectional electron signature was absent in some MCs whose magnetic field interactively reconnected with ambient IMF and then lost streaming in one direction (Gosling et al., 1995), especially those MCs propagating along the interplanetary sector boundary (Crooker et al., 2004a). Besides, electron distributions could be disturbed by the mirroring streaming at magnetic field enhancement (Gosling et al., 2001). Meanwhile, some bidirectional electrons were not associated with ICMEs (e.g., Richardson and Cane, 1993). Thus, the bidirectional electron signature was not primarily adopted in MCs or ICMEs identification.

**Fig. 5.** The two vertical dashed lines indicated a SBC event. The electron pitch-angle changed from 0° to 180°, hence the outward IMF turned into inward IMF through the sector boundary. The sector boundary merged within a CIR structure in this case.
3.1. The weights of inducing $\text{D}st^*$-storms and geoeffectiveness of solar wind structure categories

For intense storms in Fig. 8.1, nearly one-fifth (19%) was resulted by CIRs and the rest four fifths (81%) was all induced by ICME-related structures in IP medium, therein 45% induced by SH+MC, 13% by MC, 12% by (SH)MC, 7% by SH, 3% by SH(MC) and 1% by E. As a whole, 60% were induced by SC MC (shock-driving MC), involving SH+MC, SH(MC) and (SH)MC, and 73% by magnetic cloud, including MC and SC MC. Therefore, magnetic cloud was the most common structure for leading to geomagnetic storms.

For moderate storms in Fig. 8.2, 40% were induced by CIR, 31% by magnetic cloud, 15% by non-cloud ICME, ICME-related structures accounted for more than one-half (51%) of these moderate storms. Alfvén wave could responsible for 8% of moderate storms, and 1% was led by DISTURB. Except for CIR, MC and E categories were the most frequent sources in IP medium for leading to moderate storms, responsible for 14% and 13% respectively.

In Fig. 8.3, 39% of small storms were resulted by CIR, 14% by magnetic cloud, 14% by non-cloud ICME, and as a whole, 30% by ICME including SH category intrinsic to ICME in its IP origin. Alfvén wave could responsible for 20% of small storms, and SBC events just led to 6%, DISTURB to 4%. Therefore, CIR was common structure for driving moderate and small storms. Alfvén wave did not result in intense storms, but it was still a common IP turbulent for moderate and especially for small storms.

The geoeffectiveness of each solar wind structure, i.e., SC MC, MC, non-cloud ICME, shock-driving non-cloud ICME, SH, CIR and SBC, obviously differs from each other. For MC category, namely magnetic cloud structure which did not drive shock in IP space, in Fig. 9.1, half of them could result in geomagnetic storms, therein, 7% for intense storm, 21% for moderate storm and 22% for small storm. But for SC MC in Fig. 9.2, more than four fifths (81%) could induce storms, primarily for significant storms, 36% to intense and 29% to moderate storms, and so SC MC possesses the most remarkable geoeffectiveness in all these solar wind structures shown in Fig. 9. In Fig. 9.2(a) and (b), for the intense and moderate storms driven by SC MC, most (75% for intense, 51% for moderate)
of them were induced by SH+MC category, and the storms led only by the MC structure were more frequent than those driven only by the sheath region within SC MC.

For E category in Fig. 9.3, except one case could induce intense storm, just one-third (1/3) could lead to moderate and small storms. Though E with shock was more geoeffective, more than half corresponding to storms, but in their limited 27 cases, none of them induced intense storms. In Fig. 9.5, 51% of SH could lead to storms, 11% for intense storm, 22% for moderate storms, and it is apparent that SH category is more geoeffective than MC category.

Nearly one-fifth of intense storms in 1998–2008 were led by 3% of CIRs, and more than half of CIRs only corresponded to smaller storms, 20% to the moderate and 33% to the small. So CIR is a common IP structure, but its geoeffectiveness is mainly focus on the moderate and small storms, shown in Fig. 9.6.

It is obvious in Fig. 9.7 that just 6% of SBCs were corresponding to small storms, no larger SBC-driven storms. It has been found that about 6% of SBCs led to intense magnetic storms, 20% to the moderate and 25% to the small in 1957–2001 (Echer and Gonzalez, 2004). That list of SBC events have been obtained from Svalgaard’s criterion of identifying SBC events (Svalgaard, 1976), and the Svalgaard’s criterion defines an IMF reversal as a SBC event and just required IMF polarity keeping 4 days before reversal. Then local field line reversals can be involved in and seen as SBC events. In this study, the suprathermal electron pitch-angle criterion (Kahler and Lin, 1994, 1995) was used to differentiate true SBCs from the contaminations of IMF local reversals. Meanwhile, SBCs could be differentiated from the jointly observed transient streamer outflows (33% associated rate) and CIRs (50% association rate) along sector boundaries with this pitch-angle criterion, but the study of SBC’s geoeffectiveness also can be confused. Even so, it is apparent that the true SBC events nearly don’t possess geoeffectiveness just 6% of them corresponding to small storms.
Besides, even considering the possible upper limit of 11 nT for Dst* larger than Dst according to the transition formula of O’Brien and McPherron (2000), the SBCs still cannot be correlated with intense storms. In fact, there is no obvious difference between Dst* and Dst indices in SBC-related periods, and even at most times the Dst* indices always are smaller than Dst.

3.2. The annual distributions of solar wind structures

Around solar minimum 1996 and 1997, the solar wind displayed a simple structure with persistently fast and tenuous solar wind, emanating from huge circumpolar coronal holes, and slower, more variable and highly structured solar wind at low latitudes (McComas et al., 1998, 2000; and reference therein). The coronal helmet streamers were confined to low heliolatitudes forming streamer belt with a small dipole tilt angle (McComas et al., 2006, and reference therein). The HCS tilt was less than 10° (McComas et al., 2006), and displayed a shape of ballerina-skirt due to the modulations of transient streamer belt outflows (Crooker et al., 2004b).

From the beginning of 1998 to early 2000, the HCS became strongly tilted and warped, its tilt angle to autorotation axis being around 70° in 1999, and the streamer belt underwent a latitudinal widening (Wang et al., 2000, 2002; McComas et al., 2006). Accordingly, the low-speed solar wind spread progressively to higher latitudes as the polar holes being contracted, reaching 80°N by late 1999 and 80°S in 2000 (Wang et al., 2002). The dipolar holes were becoming smaller in area, and the magnetic quadrupole \((L = 2)\) component appeared and coexisted with magnetic dipole \((L = 1)\) component at the source surface of solar wind, especially strong from mid-1999 through early 2000 (Wang et al., 2002).

The occurrence number and geoeffectiveness of CIRs at 1999 have obviously increased from 1998, shown in Fig. 10.3. But in

**Fig. 9.** The geoeffectiveness of evident solar wind structures: MC (magnetic cloud no preceding shock), shock-driving MC, non-cloud ICME, shock-driving non-cloud ICME, SH, CIR and SBC events.

**Fig. 10.** The annual occurrence rates and geoeffectiveness of ICMEs (including magnetic clouds), magnetic clouds, CIRs and SBCs detected at L1 point of the Earth’s upstream solar wind in 1998–2008. Blue stands for intense storms, red for the moderate, green for the small and purple for quiet conditions. In second panel, MCs stands for all magnetic clouds include MC, SH+MC, (SH)MC, and SH(MC) categories. (For interpretation of the references to colour in this figure legend, the reader to the web version of this article.)
Fig. 10.1, ICMEs and their geoeffectiveness decreased remarkably contrasting with the increasing sunspots numbers, and the effectiveness of magnetic clouds also reduced. The increasing CIRs indicated the long extensions of coronal holes from the pole to the equator at certain heliolongitudes, which is the antecedent of magnetic quadrupole component appearing at low latitude from mid-1999 to early 2000 (Wang et al., 2002, Fig. 4), even though the fast flows from northern polar coronal hole had not yet extended down to mid latitudes at all heliolatitudes (McComas et al., 2003). The ICMEs mostly originate from the transient streamer outflows, thus the decreased occurrence rate of ICME at L1 point in 1999 has shown a general reflection of the increasing tilt, dispersed areas and widening in latitude of helmet streamers. For the extension of coronal holes from double poles to the equator and then the following magnetic quadrupole component appearing and being dominant at low latitudes until the early 2000 (Wang et al., 2002), the nondipolar nature of the large-scale coronal field led to complex streamer/HCS topologies, and a four-sector structure and even a secondary, detached current sheet with cylindrical geometry was sometimes present (Wang et al., 2002). Accordingly, the larger occurrence rate of SBC events had happened at ACE (\(\pm 8\) heliolatitudes) in 1999.

At solar maximum 2000 and post-maximum 2001, the solar wind were remarkably driven by the flows originating from the mixed sources of solar surface by small coronal holes, helmet streamers, active regions at all heliolatitudes (McComas et al., 2002, 2003). The solar surface field completed its high-latitude polarity reversals in 2000–2001, and most of the open flux of the solar surface field resided in the middle and low-latitude activity zones, in which the associated coronal holes were characterized by large expansion factors and were the main sources of the predominantly slow solar wind (Neugebauer et al., 2002; Wang et al., 2002). Being coincidence with this situation, CIRs detected in low heliolatitudes in 2000–2001 had an obviously reduction down to minimum at 2001 with much weaker geoeffectiveness, shown in Fig. 10.3. Meanwhile, the significant increasing in the number and geoeffectiveness of ICMEs especially for MCs indicated what controlled low-latitudes solar coronal at this time was CMEs and associated active regions. With the rapidly decreasing after early 2000 and even disappearing in mid-2000 of magnetic quadrupole components at low latitudes (Wang et al., 2002, Fig. 3), probably due to the much smaller locations but large expansion factors of low-latitude coronal holes, and also with the high tilt of HCS and streamer belt nearly perpendicular to solar autorotation axis in this year (Smith et al., 2003), the detected SBCs at ACE has significantly decreased in 2000–2001, illustrated in Fig. 10.4.

In the early declining phase 2002, the new northern polar hole formed after the high-latitude polarity reversals during solar maximum had not yet grown to the size of those at solar minimum by September 2002 and had just paused fast coronal-hole solar wind down to \(\sim 32\) N latitude (McComas et al., 2003). Whereas, the detected CIRs at the L1 point increased and had the most geoeffectiveness in leading intense Dst*-storms during this solar cycle, shown in Fig. 10.3. The solar dipole and streamer belt were still highly inclined, the CMEs still could be observed above 45°N latitude (McComas et al., 2003, 2006), and detected ICMEs and magnetic clouds at low latitudes were also still significant, shown in Fig. 10.1 and 2.

During the declining phase, the heliosphere was generally returning to a more ordered state, in which coronal holes gradually concentrated on Sun’s two poles and formed huge circumpolar holes, the helmet streamers were confined within mid- and low-heliolatitude streamer belt, and all this could be explained as a simple tilted dipole model. But most recent declining phase seemed somewhat unusual when compared to what generally happened and could not be simply explained with tilted dipole model (McComas et al., 2006). McComas et al. (2006) found around the start of 2003 that a band of slow solar wind resided at \(-20–25\) N latitude at all heliolongitudes, and proposed that either solar wind must have been emanating from portions of the low- to mid-latitude coronal holes with low speeds comparable to that from the streamers, or that channels of slow wind must have been separating coronal-hole flow in such a way that a band of slow streamer belt wind encircled the Sun at these latitudes.

In 2003, what happened at L1 point was obviously decreasing number and geoeffectiveness of ICMEs and also magnetic clouds and the nearly top occurrence number of CIR and geoeffectiveness, and seems to keep coincidence with the second case proposed by McComas et al. (2006) mentioned above, namely, in early 2003, a band of slow streamer belt encircled the Sun at \(-20–25\) N latitude and at lower latitudes (\(< 20^\circ\) N), furthermore, the dominant flow switched polarity and was driven by coronal-hole flows that were largely present in the southern hemisphere (McComas et al., 2006). During September and October of 2003, when Ulysses was at 6–8°N heliolatitude, the spacecraft encountered another slow streamer belt (McComas et al., 2006) just like the above-mentioned belt, and the ACE spacecraft was coincidently circling within the same latitudinal zone at the same time. Therefore, from the beginning to August of 2003, ACE has moved within a zone dominated by high-speed southern coronal-hole flows (McComas et al., 2006, Fig. 1), then after that, ACE moved into the slow stream belt again at 6–8°N heliolatitude just like what happened to ACE from June to September of 2002 (McComas et al., 2006). Hence during 2003, the magnetic clouds number was unusually small but the number of CIRs was very large. Also due to these special processes, the SBC events detected at ACE were remarkably low also down to the minimum of this cycle.

In 2004, the arising magnetic clouds and ICMEs, especially for their significant geoeffectiveness in driving intense Dst*-storms comparable to what had happened in solar maximum was an indication of ACE spacecraft must be intermittently emerging into a gradually formed low-latitude streamer belt. And so the detected SBCs had undergone a rising, whereas the geoeffectiveness of CIRs decreased significantly.

For 2005–2006, the late declining phase of solar cycle 23, with obviously reducing solar activity and the further evolution toward the awfully ordered dipole model at solar minimum, ICMEs and magnetic clouds reduced as well, but the transient streamer belt ejecta along the interplanetary sector boundary (Crooker et al., 2004b), had strongly modulated the topological feature of streamer belt and sector boundary into a so-called ballerina-skirt shape. SBC events largely increased even up to the top number within this solar cycle when ACE spacecraft crossed through local warps of the sector boundary, and also for the contribution of the part of CIRs formed by these local warps, the occurrence rate of CIRs still keep high. In 2005, CIRs possessed significant geoeffectiveness especially in inducing intense storms.

In 2007–2008, the solar activity has gradually changed into relatively quiet conditions, and then the occurrence rates and geoeffectiveness of ICMEs and MCs decreased to the minimum. CIRs and SBCs had high occurrence rate in 2007, even though the geoeffectiveness of CIRs decreased obviously, and until minimum 2008, for the less modulation of ICMEs to sector boundary, CIRs and SBCs decreased accordingly.

4. Conclusion

For these solar wind structures detected by ACE, the occurrence rate of ICMEs is 1.3 times of that of CIRs (625/475 in Table 1),
so within the Earth’s upstream solar wind, the disturbances induced by transient solar wind outflows (ICMEs) are more frequent and geoeffective than that induced by stream interactions of fast and slow solar wind. Of all detected magnetic clouds, nearly one-half (141/298 in Table 2) could drive IP shocks, but for the non-cloud ICME, just about 10% (27/272 in Table 2) could drive shocks. Besides, discounting the 55 solely detected sheath regions (SH), the proportion of magnetic clouds was still more than one-half in the whole ICMEs.

Geomagnetic storms in 1998–2008 did not strictly keep in line with the sunspot number, and so Earth’s upstream solar wind conditions played a key role in solar-terrestrial coupling. The three-dimensional structure of the heliosphere is different from one solar cycle to another (McComas et al., 2006), the Earth’s upstream solar wind, therefore, vary with different solar cycles and also with the evolutions of the heliospheric three-dimensional structures during a solar cycle. In 1998–2008 of solar cycle 23, the annual-distribution profiles of the main solar wind structures reflected the dominant features within the Earth’s upstream solar wind, shown in Fig. 10. At the solar maximum, the dominant feature was ICME, primarily magnetic cloud, whereas at solar minimum, the dominant feature was CIR. In rising phase and declining phase of the cycle, the dominant features became unstable due to the special and complicated transition evolution between solar maximum and minimum phase. During the rising phase of the cycle, the low-latitude extension of coronal holes and gradually tilted streamer belt led to an increase in CIRs and a decrease in ICMEs in 1999. Whereas during the declining phase, especially in 2003, two special reconstructed streamer belts above 8 N heliolatitude and the Earth’s upstream solar wind was dominated by high-speed southern coronal-hole outflows resulting an abnormal low MCs and SBCs number but remarkably high CIR numbers. For CIR, both number and geoeffectiveness focused on all the declining phase. SBC events kept low during solar maximum period but obviously increased and topped at the late half of declining phase and minimum due to crossing-through local warps in sector boundary. ICMEs, especially MCs, obviously focused on the maximum and post-maximum period, and got top occurrence rate and geoeffectiveness at solar maximum 2000. Meanwhile, they were significant for leading intense storms in 2000–2002, 1998 and 2004.

As the main solar wind features, CIRs and ICMEs had different weights in inducing each storm level. To intense storms, near one-fifth (19%) of intense storms was resulted by CIRs and the rest four fifths (81%) all was induced by ICME-related structures, magnetic clouds accounting for 73% in particular. Furthermore, 60% of intense storms were induced by SC MCs, and 45% of intense storms were jointly induced by sheath region and driving MC structure (SH+MC category) pertained to SC MCs. Therefore, magnetic clouds were the most important IP source of intense storms, especially the SH+MC category. Forty percent of all moderate storms were led by CIRs, and ICMEs accounted for 51%, magnetic clouds for 31%. Thirty percent small storms were led by CIRs, 30% by ICMEs (14% by magnetic cloud). CIR played a more significant role for leading moderate and small storms than magnetic clouds. Moreover, IP Alfvén waves could account for 8% moderate storms and 20% small storms, thus, the Bz5 disturbance within Alfvén wave is a common IP source for smaller storms, and the induced intermittent dayside reconnection at magnetopause is still a remarkable solar-terrestrial coupling process for storm generation, not only for obvious storm activity.

Magnetic cloud with shock was the most geoeffective structure, more than four fifths (81%) inducing storms, specifically near two-thirds (65%) corresponding to intense and moderate storms and more than one-third (36%) to intense storms. For CIR, its geoeffectiveness was focused on smaller storms, and more than half of them lead to moderate and small storms.

The suprathermal electron pitch-angle distributions facilitated identifying the true SBC events and then figuring out the correlation between SBC events and geomagnetic storms. The result is the SBC events did not induce any intense or moderate storm, and just 6% of them were corresponding to small storms. So the sector boundary itself nearly was not a geoeffective structure in IP medium.

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Supplementary data associated with this article can be found in the online version at doi:10.1016/j.pss.2009.07.015.

Reference
