Statistical analysis of corotating interaction regions and their geoeffectiveness during solar cycle 23

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[1] This is an investigation of the effects of corotating interaction regions (CIRs) in the heliosphere (<1 AU) on geomagnetic disturbances during solar cycle 23 (1996–2005). Three kinds of interplanetary structures, “pure” CIR, interaction of CIR with ICME, and “pure” ICME by transient events, are identified by using the Hakamada-Akasofu-Fry (HAF) solar wind model. Yearly occurrence of 157 “pure” CIRs has a minimum value in 2001 and a peak value in 2003 at the declining phase during the 23rd solar cycle. The maximum correlation coefficient of the daily sum of Kp indices between consecutive Carrington Rotations indicates that recurrent geomagnetic disturbances are dominant during the declining phase near solar minimum. Eighty percent of storms that are related to “pure” CIRs belong to weak and moderate storms. The statistical analysis shows that about 50% of CIRs produce classical interplanetary shocks during the descending phase and 89% of the CIR-related shocks are followed by geomagnetic storms. These results demonstrate that CIR-related shock is not a necessary condition for generating a magnetic storm, but most CIR-related shocks are related to a storm. The Dst index that corresponds to CIR-related storms has a better linear relationship with IMF Bz, Ey, and the coupling function (ε) when the Dst indices are higher than −100 nT. Finally, the geoeffectiveness of CIRs appears clearly to have a seasonal variation.


1. Introduction

[2] It is well known that two major types of interplanetary disturbances may lead to disturbances of the geomagnetic field. One is the quasi-steady corotating interaction region (CIR) where a fast stream from a coronal hole overtakes a leading slow stream associated with the closed streamer belt region. The other one is the transient, interplanetary coronal mass ejection (ICME) that is preceded by a shock wave. If there is no occurrence of solar eruption events, like flares and CMEs, the flow pattern emanating from the Sun is roughly time-stationary so that the fast and slow stream interaction regions form spirals in the solar equatorial plane that corotate with the Sun, and they are called corotating interaction regions (CIRs). If the relative speed gradients are sufficiently large, fast forward and reverse MHD shock waves are formed.

[3] Generally, within CIRs, the interplanetary magnetic field (IMF) presents a highly fluctuating southward component and small enhancement of Br, therefore, geoeffectiveness of CIRs is lower than that of transient disturbances [Alves et al., 2006]. However, during the solar minimum, CIRs play a dominant role in geomagnetic activity; 70% of geomagnetic disturbances are caused by CIRs, 20% are caused by slow solar wind, and 10% are from CME-related structures [Richardson et al., 2000]. During the declining phase of the solar cycle, polar coronal holes extending to latitudes close to the ecliptic plane result in more occurrence of CIRs [Burlaga et al., 1978].

[4] As is well known, moderate level geomagnetic activity can occur with a 27-day period. It is the corotating streams, the preceding heliospheric current sheet (HCS) crossings, or the stream-stream interaction regions that contribute to such geomagnetic activity [Tsurutani et al., 1995]. Nevertheless, in previous studies, it is also proposed that CMEs may play a central role in recurrent as well as nonrecurrent events [Crooker and McAllister, 1997; Alves et al., 2006]. Tsurutani et al. [1995] found that intense storms are mainly caused by ICMEs and were not associated with CIRs. Major geomagnetic storms, both recurrent and nonrecurrent, are the result of the combined effects of CMEs and CIRs [McAllister and Crooker, 1997]. Recent studies showed that some intense storms might be driven by CIRs [Richardson et al., 2006].

[5] Double peaks in geomagnetic activity during a solar cycle have been known since long time ago [Gonzalez et
al., 1990]. The gap between the two peaks was termed as the Gnevyshev Gap. The Gnevyshev gap plays an important role in solar activity forecasting [Storini et al., 2003]. Many studies have concentrated on this phenomenon [Kane, 2005, 2006; Feminella and Storini, 1997]. Feminella and Storini, [1997] presented results that showed that the solar background activity tends to be single peaked and the double peak appearance is related only to the growing event importance in each layer of the solar atmosphere. These results indicate that dynamical activity phenomena should be superimposed on a quasi-stationary 11-year trend. The Gnevyshev gap has been found in interplanetary parameters \( N \) (number density), \( V \) (solar wind speed), \( B \) (magnetic field). The cosmic ray (CR) modulation also showed peaks [Kane, 2005]. Gnevyshev gap was also found in the occurrence of coronal holes.

The also well known Russell-McPherron effect is responsible for at least part of the seasonal variation in geomagnetic activity due to the changing relative orientation of the solar and terrestrial axes as Earth orbits the Sun [Russell and McPherron, 1973]. This effect enhances the geoeffectiveness of ecliptic IMF during the period, being strongest in the fall with antisunward field and in the spring with sunward field [McAllister and Crooker, 1997]. These authors also report a seasonal effect in CIR-associated activity during cycle 22. They demonstrated that this seasonal effect enhanced the geoeffectiveness of CIRs. Richardson et al. [2006] also displayed a clear seasonal effect by analyzing all the storms with \( Dst \leq -100 \) nT in 1972~2004. More general results need to be studied by extending these previous studies to another solar cycle; that is our objective here.

In the present paper, the Hakamada-Akasofu-Fry (HAF) solar wind model is introduced briefly in section 2. In section 3, we describe how to identify CIRs by using the HAF model. Statistical analysis of CIR events and their geoeffectiveness during cycle 23 are included in section 4 and section 5. Our conclusions are given in section 6.

## 2. HAF Solar Wind Model

The HAF model is a kinematic model described by Hakamada and Akasofu [1982], Fry [1985], Sun et al. [1985], and Fry et al. [2001, 2003]. It can predict solar wind conditions (speed, density, and interplanetary magnetic field) at the Earth, based upon observations of the Sun. It is a useful tool for the study of large-scale solar wind structure, especially for the investigation of the propagation of disturbances in interplanetary space. The HAF model has two components: background solar wind and event-driven solar wind. This physics-based model, as discussed in the above-mentioned references, generates the inhomogeneous back ground flow on which the event-driven shock is impressed.

### 2.1. Background Solar Wind

The background solar wind is established by the inner boundary conditions, which means the distribution of solar wind speed on a concentric solar-centered sphere at 2.5 solar radii. Distribution of solar wind speeds at 2.5 solar radii can derived from the measured line-of-sight solar magnetic field on the solar surface provided by the Wilcox Solar Observatory, Stanford University [Arge and Pizzo, 2000; Hoeksema et al., 1982, 1983]. As the Sun rotates, particles with divergent speeds move out of the source surface along the radial direction. The particles with higher speed are decelerated, while particles with lower speed are accelerated in the interaction process. In the HAF model, parameterized compression algorithms account for this view of the stream-stream interaction. If the computed velocity gradients are steep enough, CIRs and forward-reverse MHD shocks will form as discussed earlier.

### 2.2. Event-Driven Solar Wind

In general, the event-driven solar wind is generated by solar transient events (flares or CMEs). In the HAF model the solar flare information includes start, max, and end time; source location; and brilliance and importance of flares that can be obtained from the National Oceanic and Atmospheric Administration (NOAA) National Geophysical Data Center (NGDC http://www.ngdc.noaa.gov/). Solar wind velocity enhancements produced by solar transient events are superposed on the inner boundary. Such velocity enhancements are assumed to mimic the transient, locally physics-based, response of flares and CMEs. The initial coronal shock speeds \( (V_s) \) are normally derived from Metric Type II radio frequency drift rates or observations of LASCO CMEs. When those data for some events are not available, the initial shock speed can be also empirically approximated by using the flare’s brilliance and importance. Only transient events with the initial speed of greater than 400 km/s are adopted to make simulation in the HAF model. The initial speed of the events, as a most important parameter, will have significant influence on the shock arrival time (SAT) at the Earth. An extensive set of real-time studies, using HAF, has been made during solar cycle 23 by Fry et al. [2003], Sun et al. [2002a, 2002b], Dryer et al. [2004], and McKenna-Lawlor et al. [2002, 2006].

### 3. Identification of CIRs

Fry et al. [2003], using the HAF model, recognized the CIRs under both “quiet” and active periods. When only the ambient solar wind conditions, i.e., the source surface maps of \( B_r \) and \( V_r \) are input parameters in any simulation, the CIRs (and, possibly, their shocks) may form, as noted above, if the stream-stream speed differential is great enough.

As an example, Figure 1 shows the solar wind data and IMF parameters from OMNI data (black and green) together with simulations by the HAF model (blue, prior to two solar flares, and red after these flares) during March and April 1995. Figure 1, from the top to bottom, shows \( \beta \), Theta and Phi, \( B \) and \( B_z \) (green), flow angle, \( T \), \( V \), \( P_t \), \( P_d \), SSI, and \( Dst \), respectively, where \( \beta \) is the ratio of plasma thermal pressure to the magnetic pressure; Theta and Phi are the azimuthal and polar angles of IMF, respectively; \( B \) and \( B_z \) are magnitude and z-(north-south) component of IMF, respectively; flow angle is the azimuthal (east-west) flow angle; \( T \) is the proton temperature; \( V \) is the solar wind speed magnitude; \( N \) is the proton number density; \( P_t \) is the sum of the magnetic pressure and plasma thermal pressure perpendicular to the magnetic field; \( P_d \) is the dynamic pressure; and SSI is the shock search index (used in the
above-mentioned, real-time-modeled, shock arrival predictions) and is defined by the equation 
\[ SSI = \log \frac{P_{d}(t)}{P_{d}(t-1)} \]
where \( P_{d} \) is the dynamic pressure; \( Dst \) is hourly \( Dst \) index. [13] All blue curves in \( V, N, P_{d} \) in Figure 1 show the simulated results when only the background solar wind exists without transient eruptions. The CIRs may be formed, as noted above, where the speed gradient is great enough. Each increase in the blue curves probably corresponds to a CIR. Two small blue arrows in the upper part of the SSI panel indicate shock arrival times at L1, that were initially predicted to be caused by the CIRs prior to the occurrence of two solar flares (discussed below). The red curves in Figure 1 show the simulated responses when the two transient flare events are also estimated together with the background solar wind. The black curves indicate observations of solar wind plasma and IMF from OMNI data. Three
cases in Figure 1 (from this series of events) are discussed below. These cases are used to define what we will refer to as “pure” CIRs, interaction of CIRs with ICMEs, and “pure” ICMEs.

[14] 1. There are, initially, increases in $V$, $N$, and $P_p$ in the blue curves but, obviously, no jump in the red curves at the same time. Those CIRs without simultaneous ICMEs from two solar transient eruptions are recognized as “pure” CIR as indicated by the second blue arrow in SSI at 2000 UT on 5 April. Meanwhile, observations of solar wind density showed an abrupt increase around 1300 UT on 6 April as indicated by the left dashed vertical line (marked “a”), followed by a speed enhancement on the next day as indicated by the blue vertical line. This blue line indicates a MHD CIR’s fast forward real shock arrival at the Earth. Considering errors of simulation and the Carrington rotation’s averaged source surface map at 2.5 $R_S$, the simulated CIR in the blue curve is consistent with the observed shock within an error window of 20 h according to the previously noted real-time experience. This kind of CIR is referred to as a “CIR-SHOCK” in order to be distinguished from those CIRs without simultaneous observed shocks (CIR-NOSHOCK), that is, “pure” CIRs without a developed shock. In the latter case, the speed, and hence momentum, gradient was insufficient to produce the fast forward MHD shock. It should also be noted that the earlier modeled red HAF curve (simulating the two shock arrivals from the two flares) had blended back, as time progresses, into the blue background curves for these physical parameters.

[15] 2. The compound simulated and actual event is reviewed as follows. First, a background increase, preflare shock arrival, in solar wind density in the blue curve appeared at 0000 UT on 30 March as indicated by the first blue arrow in SSI. However, after the second solar flare took place, a jump in the red HAF curves signaled its shock arrival at 0600 UT on 29 March as indicated by the second red arrow in SSI. Although there is a time shift of 18 h, we believe that the simulated and actual shocks are consistent within an error window of 24 h. This kind of CIR is referred to as “CIR-ICME” which means that a CIR interacted with the shock associated with a flare-generated ICME. In the present example, this ICME event was caused by a solar flare, located at S11E37, that occurred at 1600 UT on 26 March 1995.

[16] 3. Earlier, a simulated shock arrival at Earth at 1600 UT on 25 March appeared in the red curve in Figure 1 as indicated by the first red arrow in SSI. The observation demonstrated the predicted shock arrival within a root mean square error window of ±11 h [McKenna-Lawlor et al., 2006]. However, there was no jump in the blue curves around the time. This is a case of an ICME event, i.e., a “pure” ICME, without a CIR. The shock was caused by a solar flare that occurred at 1400 UT on 22 March and was located at S15, W22.

[17] Figure 2 shows simulated IMF lines in the ecliptic plane during the same period as that in the above mentioned three cases. Blue lines show IMF lines with sunward direction, and those with antisunward direction are red. Location of the Earth is indicated by a small circle. The left panel shows the Earth’s first shock arrival at 1600 UT on 25 March that was caused by the “pure” ICME. The middle panel shows the second shock arrival around 0600 UT on 29 March that may be the result from the interaction of an ICME (and its shock) with a CIR (CIR-ICME) for this part of the event. The right panel shows the third shock arrival by the “pure” CIR. It also can be seen that the “pure” CIR is formed at the sector boundary between the red and blue compressed field lines, the latter representing the faster coronal hole stream.

4. Statistics of CIRs During the 23rd Solar Cycle

[18] Following the above procedures in Figures 1 and 2, we applied the HAF solar wind model to simulate all significant solar events from 1996 to 2005 during the 23rd solar cycle. This procedure, as discussed above, automatically included the continuous background inhomogeneous heliospheric flow as simulated by the solar source surface’s input to the HAF model. A total of 157 “pure” CIR and 188 CIR-ICME events have been identified. There are 64 events among 157 “pure” CIR that belong to CIR-SHOCK and 93 events that are CIR-NOSHOCK. A total of 329 events have been identified as “pure” ICME situations during the rising and maximum phase of cycle 23 by Fry et al. [2003] (173 events) and by McKenna-Lawlor et al.
[61x501]

[68x468][20] Figure 3 shows the shock search index (SSI) [Fry et al., 2001] versus \( D P_d \) for 157 “pure” CIR events. There are 64 CIR-SHOCK events among them that are indicated by black dots, and 93 CIR-NOSHOCKs are represented by black circles. We note that the SSI values of all “pure” CIR events, either CIR-SHOCK or CIR-NOSHOCK, are larger than \(-1.8\). Therefore, a threshold, SSI = \(-1.8\), is applied to determine whether or not a CIR forms.

[20] Figures 4a and 4b are histograms of the yearly number of CIRs and flares, respectively, and the thin curves show sunspot numbers during the 23rd cycle. It is very interesting to see that the variation of yearly CIR occurrence is somewhat out of phase with the variation of yearly flare occurrence during the 23rd solar cycle. The yearly CIR occurrence gradually decreased, and the yearly flare occurrence gradually increased from 1996 to 2000 during the ascending phase of the solar cycle. The yearly flare occurrence had maximum value in 2000 and the yearly CIR occurrence reached minimum value in 2001 at the maximum year of the solar cycle (although a small valley appeared in sunspot number). Then, the yearly CIR occurrence rapidly rose from 2001 to 2003 during the declining phase of the solar cycle and reached the maximum value in 2003, followed by small downward trend from 2003 to 2005. Oppositely, for the yearly flare occurrence, there was a small increase in 2002, then rapidly going down to its minimum value from 2002 to 2005 during the declining phase of the solar cycle. There was two year shift between the maximum of the yearly CIR occurrence in 2003 and the minimum of the yearly flare occurrence in 2005. The dip or valley in the CIR occurrence around solar activity maximum phase is a similar characteristic to the so-called Gnevyshev Gap [Gnevyshev, 1963] which shows a variation of solar coronal holes during a solar cycle.

5. Statistical Results on the Relationship Between CIRs and Geomagnetic Activities

5.1. Relation Between CIR Events and \( Kp \) Index During the 23rd Solar Cycle

[21] The monthly mean value of \( Kp \) index during the 17th to 23rd solar cycle is presented together with the sunspot number in Figure 5. Variations of \( Kp \) index basically follow the sunspot number. However, a Gap can be seen around the maximum phase of solar cycles 18–23 as indicated by the black arrows.

[22] In the general view, the peaks in geomagnetic activity preceding and following the solar maximum are attributed to CMEs and CIRs. That is, the gap would represent a transition from the domination of ICMEs to CIRs in geomagnetic activity. To investigate the contribution of CIRs and ICMEs to geomagnetic activity during the 23rd solar cycle, we calculated the monthly sums of \( Kp \) indices that are contributed by CIRs and ICMEs, respectively (\( Kp\text{-CIR} \) and \( Kp\text{-ICME} \)). The ICME cases are collected from Fry et al. [2003] and McKenna-Lawlor et al. [2006]. The ratio of \( Kp\text{-CIR} \) and \( Kp\text{-ICME} \) to the sum of \( Kp \) index for all storm events (R-\( Kp\text{-CIR} \) and R-\( Kp\text{-ICME} \)) is estimated for comparing the effect of CIR with that of ICME.

[23] In Figures 6a and 6b, thin blue curves show the monthly R-\( Kp\text{-CIR} \) and R-\( Kp\text{-ICME} \) during 1996–2005, respectively. The red thin curves show monthly sunspot number. Thick red and blue curves are filtered results of the

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**Figure 3.** Shock search index (SSI) versus difference of dynamic pressure (\( \Delta P_d \)) for 64 predicted CIR-SHOCKs with MHD shock observations (dots) and 93 CIRs without shock (CIR-NOSHOCK) observations (circles).

**Figure 4.** Histogram of the event occurrence of (a) “pure” CIRs and (b) flares during 1996–2005.
sunspot number and R-Kp-CIR (Figure 6a) and R-Kp-ICME (Figure 6b) by the low-pass filter. As might be expected, ICMEs make their largest contribution to sum $Kp$ (60%) at solar maximum and contribute only 17% at solar minimum. CIRs make their largest contribution to sum $Kp$ (67%) at solar minimum and contribute only 30% at solar maximum. Their contribution increases again in 2003 and reaches the second peak during the 23rd solar cycle after the ICMEs’ contribution begins to fall at solar maximum. We noted that the total $Kp$ value in Figure 5 has a similar variation to R-Kp-CIR in Figure 6a. The filtered R-Kp-CIR has values between approximately 0.2 and 0.4, and the filtered R-Kp-ICME is in the range 0.2 to 0.3. Therefore, in general, the average effect of CIRs on geomagnetic activities may be higher than that of ICMEs. A probable explanation is that the recovery phase of CIR-driven magnetic storm can last for a long period. It is caused by nonlinear Alfvén wave within high streams proper, and can have durations as long as a solar rotation (27 days) [Tsurutani et al., 2006].

### 5.2. CIRs and Recurrent Geomagnetic Activity

[24] Recurrent geomagnetic activity means that geomagnetic disturbances in the current Carrington rotation of the Sun will be recurrent in the next rotation. The correlation coefficient of the daily sums of $Kp$ indices between consecutive Carrington rotations (CCKCCR) are proportional to the level of recurrency. CCKCCR = 1 indicates geomagnetic disturbances are exactly recurrent.

[25] Figure 7 shows monthly sunspot number and CCKCCR during 1963–2005. The thick red and blue curves are filtered results. Variation of CCKCCR throughout four solar cycles appears to be out of phase with the sunspot number. Obviously, maximum CCKCCR appears during declining phase near solar minimum so that the recurrent geomagnetic disturbances occur mostly during declining phase near solar minimum.

[26] Figures 8a and 8b show the solar wind speed, density, dynamic pressure, SSI and $Kp$ index during Carrington rotations 2007 (30 August 2003 to 26 September 2003) and 2008 (26 September 2003 to 23 October 2003). Blue curves represent simulation results from the HAF model using only the background solar wind condition without transient eruptions, and black curves are observations by the ACE satellite. It is clear that the time variation of solar parameters is similar to the $Kp$ index during the two Carrington rotations.

[27] The correlation of $Kp$ index between the consecutive rotations is 0.8. The correlation of density between the consecutive rotations is 0.6. Three CIRs can be found in each Carrington rotation, which may benefit better correlation between consecutive rotations due to more CIRs.
The blue curve in Figure 9 shows CCKCCR and the red curves are correlation coefficient of density between consecutive Carrington rotations (CCDCCR) from 1996 to 2005. It is interesting that CCDCCR has its maximum during declining phase near solar minimum. Good correlation between CCKCCR and CCDCCR demonstrates also that “pure” CIRs play an important role in geomagnetic activity, in particular, and are responsible for recurrent geomagnetic disturbances during declining phase near solar minimum. When ICMEs increase during the solar maximum, “pure” CIRs correspondingly decline; thus, non-recurrent or random geomagnetic activities dominate during solar maximum.

As is well known, coronal holes are closely related to high speed streams in the solar wind, hence formation of CIRs [Sheeley et al., 1976]. Figure 10 shows the relationship between latitudes of coronal holes and CCKCCR during rising phase of the 23rd solar cycle from 1999 to 2000. From left to right, the first panel of solar image does not show any holes, and the corresponding CCKCCR at the same period has a very low value of 0.05. Holes in second image move to near the equator, and the value of CCKCCR is near 0.5. Small holes locate at high latitude in third image, and the value of CCKCCR is 0.2. The right image shows that large holes move to middle latitude, and the value of CCKCCR is 0.3.

5.3. Geomagnetic Storms, Interplanetary Shocks, and CIRs

5.3.1. CIRs and Geomagnetic Storms

Statistics show that 129 CIRs among 159 “pure” CIRs during 1996-2005 were followed by geomagnetic storms. This result means that 82% of “pure” CIRs would
generate geomagnetic storms. A total of 596 geomagnetic storms occurred during 1996–2005; this result suggests that 22% of storms during the 23rd solar cycle were caused by CIRs. Sector graph in Figure 11 shows percentage of occurrence for different level of “pure” CIR related storms. About 15% of CIR-related storms correspond to the quiet period (Dst > 30 nT); 38% for weak storms (−30 nT ≥ Dst > −50 nT); 42% for moderate storms (−50 nT ≥ Dst > −100 nT); 5% for intense storms (Dst ≤ −100 nT). Statistical results indicate that “pure” CIR related storms mostly belong to weak and moderate storms (80%) during the 23rd solar cycle. In general, the geoeffectiveness of CIRs is weaker than those of ICMEs because of the highly oscillatory nature of the GSM magnetic field z component [Tsurutani et al., 2006].

5.3.2. CIRs and Associated Interplanetary Shocks

Observations from satellites, Wind, ACE, and SOHO identified 64 CIRs that are associated with shocks (CIR-SHOCK) among 157 “pure” CIRs at 1 AU during 1996–2005, i.e., 41% of CIRs are associated with interplanetary shocks. Figure 12a shows yearly number of CIR-SHOCK during the 23rd solar cycle. The occurrence rate of CIR-SHOCK reaches a maximum of 11 in 2003. Two minimum numbers, 4, were in 1996 and 2001. The distribution of CIR-SHOCK is similar to that of “pure” CIR in Figure 4a. About 50% of CIRs produce interplanetary shocks during the declining phase of the solar cycle. And about 16% of CIRs produce interplanetary shocks at solar maximum. Only 6% of the CIRs produced shocks at solar minimum.

We also found that 41 CIR-SHOCK events were associated with forward shocks only, 20 reverse shocks only, and 3 shock pairs among a total of 64 CIR-SHOCK events. This result suggests that the occurrence of forward shocks by CIRs is about twice that of reverse shocks during the 23rd solar cycle, which is consistent with that obtained by Jian et al. [2006]. They proposed that Wind and ACE near the ecliptic plane are expected to see more forward shocks propagating antisunward, westward, and equatorward than reverse shocks' propagating sunward, eastward, and poleward if both types of shocks form near one AU. It is very rare for spacecraft to observe shock pairs with CIRs at 1.0 AU. In the present study, only three events, i.e., 5%, are associated with shock pairs that represent the “classical” or “textbook” definition of a CIR. Figure 12b shows the distributions of forward shocks, reverse shocks, and shock pairs by CIRs during the solar cycle. We noted that forward and reverse shocks dominate the maximum and declining period in the solar cycle. It seems that the three categories of shocks randomly occur during minimum and ascending periods during the solar cycle.

5.3.3. Interplanetary Shocks and Geomagnetic Storms Related to CIRs

The relationship between interplanetary shocks and geomagnetic storms has been the concern of many researchers. As in Table 1, statistics of CIR-SHOCK and CIR-related storms shows that 57 CIR-SHOCKs in a total of 64 CIR-SHOCKs (89%) are followed by geomagnetic storms, and the others, 7 CIR-SHOCKs (i.e., 11%), had no storms. The other hand, 57 of 129 CIR-related storms (i.e., 44%) were related to CIR-SHOCKs. This result demonstrates that a CIR-SHOCK is not a necessary condition for generating a magnetic storm, but most CIR-SHOCKs are related to a storm.
5.4. Relationship Between CIR-Related Storms and IMF $B_s$, $E_y$, and $\epsilon$ Function

[34] 1. Figure 13a shows the scatterplot of IMF $B_s$ and the index $Dst$ for CIRs, where $B_s = -B_z$ if $B_z < 0$ and $B_s = 0$ if $B_z \geq 0$. The solid line shows the linear fitting result with $Dst = 4.12 B_s + 16.6$. The highest value of $B_s$ during CIRs is 17 nT. To provide a comparison with ICME-related storms, we compare this result with the fitting result for ICME-related storms with $Dst = 8.49 B_s + 5.6$ [Richardson et al., 2006]. Therefore, storms generated by ICMEs are stronger than those generated by CIRs when $B_s > 2.5$ nT, reflecting the fact that ICMEs dominate intense storms.

[35] 2. The convection electric field ($E_y = V_{sw}B_z$) plays a determinant role on geomagnetic activity. Figure 13b shows the scatterplot of $E_y$ and the $Dst$ index for CIRs, along with the linear fitting to the data. The obtained linear relation is $Dst = -11.1 E_y - 11.3$. In previous studies [Gonzalez and Tsurutani, 1987; Alves et al., 2006], an intense storm could be generated when $E_y$ is greater than 5 mV/m over a period exceeding 3 h. The average value for $E_y$ in the present study is 3.6 mV/m, which is much lower than the above criterion to drive intense storms.

5.5. Relationship Between Shock Parameters and $Dst$, IMF $B_s$, $E_y$, and $\epsilon$ Function

[36] 3. Perreault and Akasofu [1978] proposed that the development of geomagnetic storms depends primarily on the solar wind-magnetosphere energy coupling function $\epsilon V B^2 \sin^4 \theta l_0 (\text{ergs}^{-1})$, where $V$ = solar wind speed, $B$ = the IMF magnitude, $\theta = \tan^{-1} (|B_y/B_z|)$, $l_0$ = constant ($\sim 7R_E$). Figure 13c shows the scatterplot of the $\epsilon$ function and the $Dst$ index for CIR-related storms, along with the linear fitting to the data. The obtained linear relation is $Dst = -2.5 \epsilon - 25.0$. We noted that the $Dst$ values for CIR-related storms are higher than $-120$ nT so that the present linear fitting result corresponds to the part of Perreault and Akasofu [1978] result with $Dst > -120$ nT.

Table 1. Correlation Between Shock and Storm for CIRs

<table>
<thead>
<tr>
<th>Type</th>
<th>Number of Events</th>
<th>Percent</th>
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<tbody>
<tr>
<td>CIR-NOSHOCK — storm</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>CIR-SHOCK — storm</td>
<td>57</td>
<td>89</td>
</tr>
<tr>
<td>CIR-SHOCK — no storm</td>
<td>7</td>
<td>11</td>
</tr>
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</table>

[37] In this paper, correlation analysis between shock parameters and the $Dst$ index is made in relation to “pure” CIRs, CIR-ICMEs, and “pure” ICMEs for solar minimum and maximum and the results are presented in Table 2. It is found that density variation is poor correlated with $Dst$ peak, correlation coefficients being 29% for CIRs at solar minimum, 31% for CIR-ICMEs, and 15% for “pure” ICMEs at solar maximum, respectively. Temperature vari-
ation is not statistically significant correlation for “pure” ICMEs and CIR-ICMEs during solar maximum (10%), but it is significant for “pure” CIRs during solar minimum (94%). Speed variation has better correlation with $D$st peak (87%) during solar minimum than for “pure” ICMEs during solar maximum (60%), but it is not correlated with $D$st peak for CIR-ICMEs at solar maximum (6%). Correlation of dynamic pressure with $D$st peak is better for CIR-ICMEs (60%) and it is significant (14%) for “pure” ICMEs during maximum, but it is bad correlated with $D$st peak for “pure” CIRs at solar maximum (5%). The correlation for all shock parameters indicates that the shocks were probably not associated with geoeffective southward magnetic field structures.

[40] In Figure 14, shock strengths estimated by the jump in dynamic pressure. The red, blue, and black curves show the variation of shock strength in relation to “pure” CIRs, CIR-ICMEs, and “pure” ICMEs respectively from 1996 to 2005. In this period, the mean values of shock strength in relation to “pure” CIRs, CIR-ICMEs, and “pure” ICMEs respectively from 1996 to 2005. In this period, the mean values of shock strength in relation to “pure” CIRs, CIR-ICMEs, and “pure” ICMEs are 1.6 nPa, 2.0 nPa, and 3.1 nPa, respectively. It is suggested that ICMEs have greater impact on shocks than CIRs.

[41] Figures 15a, 15b, and 15c show the scatterplots of shock strength (jump in dynamic pressure) versus $B_s$, $E_y$, and the $\epsilon$ function for CIRs, respectively. They indicate poor relations between $B_s$, $E_y$, $\epsilon$ and shock strength. The result indicates that these parameters, which have effects on geomagnetic storms, were not associated with the shocks.

### 5.6. Seasonal Effect of Geomagnetic Activity Associated With CIRs

[42] Two panels in Figure 16 show the distribution of monthly mean $D$st values for 129 “pure” CIR-related storms. The mean values of $D$st in each month with error bars are indicated by open diamonds. It is evident that a higher level of geomagnetic activity occurs during August–September for antisunward fields and March–April for sunward fields. The difference of $D$st values between favored and unfavored field directions is ~40 nT for sunward field and antisunward field. It is clear that a significant fraction of major storms mainly occurs at favored field directions. During equinox periods (September–October and March–April), 68% and 45% of CIRs are geoeffective considering intense and moderate magnetic storms, respectively. About 30% of CIRs are geoeffective during the solstice periods (November–February and May–August), using the same criterion. The present result is similar to that by Richardson et al. [2006], i.e., seasonal variance enhanced the geoeffectiveness of CIRs near the equinoxes if the IMF direction is favorable.

### 6. Summary and Conclusions

[43] With the aim of analyzing the geoeffectiveness of CIRs, the HAF model is employed to simulate the propagation of the solar wind including all significant solar

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**Table 2. Correlation Coefficients Between Shock Parameter Variations and $D$st Peaks in Relation to “Pure” CIR, CIR-ICME, and “Pure” ICME During Solar Minimum and Solar Maximum**

<table>
<thead>
<tr>
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<tbody>
<tr>
<td></td>
<td>“Pure” CIR</td>
<td>CIR-ICME</td>
</tr>
<tr>
<td>$\Delta N \times D$st peak</td>
<td>29</td>
<td>*</td>
</tr>
<tr>
<td>$\Delta V \times D$st peak</td>
<td>87</td>
<td>*</td>
</tr>
<tr>
<td>$\Delta T \times D$st peak</td>
<td>94</td>
<td>*</td>
</tr>
<tr>
<td>$\Delta B_s \times D$st peak</td>
<td>5</td>
<td>*</td>
</tr>
<tr>
<td>$\Delta P_d \times D$st peak</td>
<td>5</td>
<td>*</td>
</tr>
</tbody>
</table>

*During solar minimum, CIR-ICMEs and ICMEs rarely occur, while “pure” CIRs rarely occur during solar maximum. Therefore, the statistical correlation cannot be obtained for the above conditions. Then, the correlations are identified by asterisks.*
events. Three kinds of interplanetary structure are identified as (1) “pure” CIR; (2) interaction of a CIR with an ICME; and (3) “pure” ICME by transient events. The statistical results are as follows:

1. There are 157 “pure” CIRs in a total of 345 CIR events identified during the 23rd solar cycle.

2. During solar cycle 23, the yearly occurrence of CIRs has a minimum value at 2001 near the solar maximum and a peak value at 2003 during the declining phase. It is much different from flares that have a similar variation to sunspot number.

3. The monthly sum of the $K_p$ index during the 17th to 23rd solar cycles from 1933 to 2006 appears to have a gap near each solar maximum. Two peaks are at both sides of the gap. This result is like the so-called Gnevyshev Gap in variation of solar coronal holes during a solar cycle. The $K_p$ index which is related to CIRs and ICMEs, appears to have a similar variation to the occurrence of CIRs rather than ICMEs during the solar cycle.

4. CCKCCR is calculated to represent the level of recurrent geomagnetic disturbances. The maximum CCKCCR appears during descending phase near solar minimum so that recurrent geomagnetic disturbances are dominant during this period. Meanwhile, CCDCCR has a similar variation to CCKCCR during the 23rd cycle, which indicates that CIRs play an important role for recurrent geomagnetic disturbances.

5. Statistical results indicate that 80% of storms which are related to “pure” CIR mostly belong to weak and moderate storms during the 23rd solar cycle.

6. Statistics also show that about 50% of CIRs produce interplanetary shocks during the descending phase of the solar cycle. And about 16% of CIRs produce shocks at solar maximum. Only 6% of CIRs produce shocks at solar minimum. About 64% of CIR-SHOCKs are associated with forward shocks; 31% are reverse shocks; and 5% are shock pairs. The 57 CIR-related shocks (CIR-SHOCK) in the total of 64 CIR-SHOCKs (89%) are followed by geomagnetic storms. On the other hand, the 57 storms among the total of 129 CIR-related storms (44%) are related to CIR-SHOCK. This result demonstrates that CIR-SHOCK is not a necessary condition for generating a magnetic storm, but most CIR-SHOCKs are related to storms.

7. The $Dst$ index which corresponds to CIR-related storms ($Dst > -120$ nT) has a better linear relationship with IMF $B_z$, interplanetary $E_y$, and the coupling function ($\varepsilon$), when the $Dst$ indices are higher than $-100$ nT.

8. The correlations between the shocks parameters variations and the $Dst$ peaks in relation to “pure” CIRs, CIR-ICMEs, and “pure” ICME during solar maximum (2000) and solar minimum (1996) are analyzed, respectively. Solar wind speed ($V$) and temperature ($T$) were the parameters with higher correlations with peak $Dst$ index for “pure” CIR during solar minimum.

9. The shock strength of CIRs has a poor correlation with IMF $B_z$, interplanetary $E_y$, and the coupling function ($\varepsilon$).

10. The geoeffectiveness of CIRs appears clearly to have seasonal effects due to the changing relative orientation of the Earth and the Sun. We found that a significant

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**Figure 14.** The variation of shock strength (jump in dynamic pressure) in relation to “pure” CIRs (blue), CIR-ICMEs (red) and “pure” ICMEs (black) from 1996 to 2005.

**Figure 15.** Scatterplots of shock strength (jump in dynamic pressure) and (a) $B_s$, (b) $E_y$, (c) $\varepsilon$. 
fraction of major storms mainly occurs at favored IMF directions. Moreover, the overall geomagnetic disturbance levels are higher at high latitude for antisunward direction of IMF and spring equinox for sunward direction. Similar results have been recently discussed by Richardson et al. [2006].

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References

Figure 16. Seasonal variation in “pure” CIR-associated geomagnetic storms: (a) IMF directed away from the Sun; (b) IMF directed toward the Sun. The open diamonds show mean values of Dst with error bars.


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