Major geomagnetic storms \( (D_{st} \leq -100 \text{ nT}) \) generated by corotating interaction regions

I. G. Richardson\(^1,2\), D. F. Webb\(^3\), J. Zhang\(^4\), D. B. Berdichevsky\(^1,5\), D. A. Biesecker\(^6\), J. C. Kasper\(^7\), R. Kataoka\(^8\), J. T. Steinberg\(^8\), B. J. Thompson\(^1\), C.-C. Wu\(^9\), and A. N. Zhukov\(^10,11\)

Abstract.

Seventy-nine major geomagnetic storms (minimum \( D_{st} \leq -100 \text{ nT} \)) observed in 1996 to 2004 were the focus of a "Living with a Star" Coordinated Data-Analysis Workshop (CDAW) held at George Mason University, Fairfax, VA, in March, 2005. In 9 cases, the storm driver appears to have been purely a corotating interaction region (CIR) without any contribution from coronal mass ejection-related material (interplanetary coronal mass ejections, ICMEs). These storms were generated by structures within CIRs located both before and/or after the stream interface that included persistently southward magnetic fields for intervals of several hours. We compare their geomagnetic effects with those of 159 CIRs observed during 1996 - 2005. The major storms form the extreme tail of a continuous distribution of CIR geoeffectiveness which peaks at \( D_{st} \sim -40 \text{ nT} \) but is subject to a prominent seasonal variation of \( \sim 40 \text{ nT} \) which is ordered by the spring and fall equinoxes and the solar wind magnetic field direction towards or away from the Sun. The O'Brien and McPherron [2000] equations, which estimate \( D_{st} \) by integrating the incident solar wind electric field and incorporating a ring current loss term, largely account for the variation in storm size. They tend to underestimate the size of the larger CIR-associated storms by \( D_{st} \sim 20 \text{ nT} \). This suggests that injection into the ring current may be more efficient than expected in such storms. Four of the nine major storms in 1996 - 2004 occurred during a period of less than three solar rotations in September - November, 2002, also the time of maximum mean IMF and solar magnetic field intensity during the current solar cycle. The maximum CIR-storm strength found in our sample of events, plus additional 23 probable CIR-associated \( D_{st} \leq -100 \text{ nT} \) storms in 1972 - 1995, is \( (D_{st} = -161 \text{ nT}) \). This is consistent with the maximum storm strength \( (D_{st} \sim -180 \text{ nT}) \) expected from the O'Brien and McPherron equations for the typical range of solar wind electric fields associated with CIRs. This suggests that CIRs alone are unlikely to generate geomagnetic storms that exceed these levels.

1. Introduction

Major geomagnetic storms are among the most important space weather phenomena. The 79 storms occurring during 1996 to 2004 with minimum \( D_{st} \leq -100 \text{ nT} \) were the focus of a "Living with a Star" Coordinated Data-Analysis Workshop (CDAW) held at George Mason University, Fairfax, VA, in March, 2005. A major aim of the workshop was to identify the interplanetary drivers of these storms, and where possible, their solar counterparts. Consistent with previous studies [e.g., Gosling et al., 1991; Tsurutani and Gonzalez, 1997; Richardson et al., 2001; Zhang et al., 2003], the majority of these storms were found to be driven by interplanetary coronal mass ejections (ICMEs) and/or the related upstream sheaths, or multiple structures of these types. The remaining events generally involved a corotating interaction region (CIR) formed ahead of a high-speed stream emanating from a coronal hole. In some cases, the CIR interacted with a preceding ICME, and compression of southward magnetic fields in the ICME intensified the geoeffectiveness. Similar events have been reported by Zhao [1992], Cane and Richardson [1997], Fenrich and Luhmann [1998] and Crooker [2000]. In another 9 cases, the CIR alone was responsible for driving the storm, with little or no evidence of ICME-like structures being involved, and no plausible association with earthward-directed coronal mass ejections (CMEs) observed by the SOHO/LASCO coronagraphs. This observation is somewhat surprising given that some previous studies [e.g., Gonzalez et al., 1999, and references therein] that have concluded that CIRs never generate storms with \( D_{st} < -100 \text{ nT} \). Three examples in 1994 were identified by Watari [1997], however, and an additional event (October 23, 1996) was reported by Zhang et al. [2003].

In Section 2, we describe solar wind observations associated with these 9 CIR-associated storms. In Section 3, we...
discuss these observations in the context of a sample of 159 CIRs during cycle 23, and examine the relationship between CIR/stream properties and the storms that they generate.

2. Observations

The nine CIR-associated $D_{st} < -100$ nT storms in 1996–2004 are listed in Table 1, where the first two columns give the time of the storm peak and minimum $D_{st}$. We also show the minimum value of the pressure corrected $D_{st}$ index, $D_{st}^* = D_{st} - 7.26 P_w^{2/3} + 4.1$ nT, where $P_w$ is the solar wind dynamic pressure in nPascals [O’Brien and McPherron, 2000]. For these storms, minimum $D_{st}^*$ and $D_{st}$ differ by $\leq 7$ nT. Evidently, the storms were not distributed evenly during this period, which extends from sunspot minimum through sunspot maximum for cycle 23 (in 2000) and into the declining phase of this cycle. There were only two events during the ascending phase of the cycle, and no events during a ~4-year interval around sunspot maximum. The remaining events occurred during the declining phase. A caveat should be added that the 2003 and later events were identified using the provisional $D_{st}$ index and may be revised when the final index becomes available.

It is well established that the dawn-dusk ($-y$) component of the solar wind electric field ($E = -V \times B$) is an important driver of geomagnetic activity [e.g., Dunlop, 1961; Peray and Akasofu, 1978; Tsurutani and Gonzalez, 1997, and references therein], including activity associated with CIRs [Burlaga and Lepping, 1977]. Hence, we have examined solar wind plasma and magnetic field observations associated with each of these storms to infer the characteristics of their drivers. For those in 1998–2004, 64-s plasma/field observations from the ACE spacecraft were used; similar 92-s WIND data were used for earlier events or when there were ACE plasma data gaps. Relevant parameters for these events are shown in Figures 1 to 4. For each event, the top black graph shows the hourly $D_{st}$ index. Other graphs show the magnetic field intensity and $x$- (north-south) component, the $y$-component of the solar wind electric field ($E_y = -V \cdot B_y$) in Geocentric Solar Magnetospheric (GSM) coordinates, the azimuthal magnetic field angle ($\phi_B$, where $0^\circ$ = directed sunward and $90^\circ$ is directed to the east), plasma proton temperature ($T_p$), density ($n$), bulk speed ($V$), and flow angle ($\phi_sw$), and the hourly-averaged ratio of solar wind oxygen ions with charges $\pm 7$ and $\pm 6$ ($O^7/O^6$) from the ACE/SWICS instrument, if available. The plasma and field data illustrated are generally from ACE. However, WIND data are used if they are more complete than the ACE data. If WIND data are displayed, we do still show $E_y$ based on ACE data — inspection of variations in $E_y$ (ACE) and $B_y$ (WIND) verifies that essentially similar structures were observed at both spacecraft (after allowing for the few tens of minutes propagation delay from ACE to WIND) and serves to “link” the ACE composition data with the WIND data.

To illustrate some of the features of a representative event, consider the storm of March 10, 1998, shown in Figure 1. We conclude that this storm was associated with a CIR based on its association with a region of compressed plasma, indicated by enhanced plasma densities (reaching ~60 /cc) and magnetic field intensities (reaching ~24 nT), lying at the leading edge of a high-speed stream — note that the solar wind speed increases from ~300 km/s at the start of the plot to nearly 600 km/s during the second half of March 10. Typical plasma and magnetic field signatures of interaction regions and high-speed streams at ~1 AU are discussed for example by Belcher and Davis [1971] and Schwenn [1990]. The unusually high density associated with the heliospheric plasma sheet [e.g., Winterhalter et al., 1994; Bavassoano et al., 1997; Crooker et al., 2004a, and references therein] encompassing the heliospheric current sheet that was crossed at ~02, 05 and 09 UT on March 10. WIND/SPD and ACE/SWEPAM solar wind suprathermal electron pitch-angle distributions (not illustrated here) show reversals of the anti-solar plasma flux relative to the magnetic field direction at these times, suggesting that these were true current sheet crossings rather than current sheets associated with folded field lines. See e.g., Kahler and Lin [1995] and Crooker et al. [2004a, b], and references therein, for a discussion of using solar wind electron flows to identify true heliospheric current sheet crossings.

The stream interface, a wave structure (often a discontinuity) separating accelerated slow solar wind and decelerated fast stream plasmas, is a prominent feature of CIRs [e.g., Burlaga and Lepping, 1977; Gosling et al., 1978; Schwenn, 1990; Forsyth and Marsch, 1999, and references therein]. The interface is typically is identified by a relatively abrupt depression in the plasma density, increases in $V$ and $T_p$, and the solar wind flow direction $\phi_sw$ changing from $>90^\circ$ to $<90^\circ$. We suggest that the interface was crossed at ~12 UT on March 10, as indicated by the vertical green line in Figure 1. The decrease in the solar wind $O^7/O^6$ ratio at this time is consistent with this interpretation [Wimmer-Schweingruber et al., 1997]. The overlaid (red) line gives the ($V$-dependent) $O^7/O^6$ ratio expected for “normal” (non-ICME) solar wind [Richardson and Cane, 2004], and suggests that the observed $O^7/O^6$ ratios are consistent with normal solar wind. In particular, there is no clear evidence of ICME-related material, which typically has higher than expected $O^7/O^6$ ratios [Richardson and Cane, 2004, and references therein]. The absence of enhanced ion charge states observed by ACE/SWICS [e.g., Leprì et al., 2001] supports this conclusion, as does the absence of abnormally low proton temperatures which can be indicative of ICME material [e.g., Richardson and Cane, 1995] — the expected temperature is overlaid on the $T_p$ panel in Figure 1. Rather, as is typical of CIRs, $T_p$ was slightly enhanced above normal values, presumably as a result of compressional heating resulting from the stream-stream interaction.

The driver of the March 10, 1998 storm was a ~6-hour interval of nearly persistent southward magnetic field that reached ~17 nT during the trailing half of the CIR (“F’ region” of Belcher and Davis [1971]). The transverse solar wind electric field reached ~9 mV/m at this time. Figure 5 summarizes the $z$-components of the magnetic field and solar wind velocity during the structures that drive this and the other storms in Table 1. For the March 10, 1998 storm, correlated variations in $B_z$ and $V_z$ indicate the presence of Alfvén waves moving southward. Such waves are a common feature of CIRs and high-speed streams [e.g., Belcher and Davis, 1971; Smith et al., 1995] and may be amplified when they propagate into the CIR [Tsurutani et al., 1995a]. In particular, the interval of predominantly southward field responsible for this storm commenced with large-amplitude Alfvén waves at ~14 UT. Nevertheless, there have been a non-Alfvénic component since the persistent southward field, extending to ~17 UT has no apparent counterpart in $V_z$. The origin of this strong southward field is unclear. As noted above, there are no clear signatures suggesting the presence of an ICME. In addition, the last halo/partial halo CME observed by SOHO/LASCO was on February 28 according to the LASCO catalogue (http://cdaw.gsfc.nasa.gov/CME_list/), far too early to be involved in this storm. A further argument against an ICME structure being involved in the production of this storm is that the solar wind that drives the storm is on the high-speed, coronal hole flow side of the interface.

Crooker et al. [2004a, b] suggest that fields that deviate from the expected Parker spiral direction in longitude and latitude can arise in looped structures formed by interchanges reconnection at the heliospheric current sheet. However, there is little evidence of such structures on March 10 since,
as noted above the magnetic and energetic electron polar- 
ity changes occur together suggesting the presence only of 
true current sheet crossings. Furthermore, the heliospheric 
plasma sheet was on the opposite side of the stream inter-
face from the geoeffective structure. Hence, it seems unlikely 
that the storm driver is related to the heliospheric plasma 
sheet.

The likely solar source of the stream was an equatorward 
extension of the southern polar coronal hole indicated by 
the arrow near central meridian in the SOHO EIT Fe XX 
observation for March 7, 1998 shown in Figure 6. By March 
10, this coronal hole would have rotated to ~ 40° west, 
consistent with the location of footpoints of field lines in 
the high-speed stream observed at Earth. The sunward mag-
netic field direction in the high-speed stream is consistent 
with the direction of the field in the southern polar coronal 
hole prior to the maximum of Cycle 23.

Two other storms generated by intervals of southward 
field extending from the vicinity of the stream interface to 
the CIR trailing edge are shown in Figure 1. The storm 
of September 4, 2002 (Dst = -109 nT) was driven by a 
similar ~ 4 hour period of < ~ 20 nT southward field and 
transverse electric fields ~ -7 mV/m in the vicinity of, 
and following, the stream interface, though with less evi-
dence of Alfvénic fluctuations (Figure 5). The suggested 
interface, bounded by the two vertical green lines in Fig-
ure 1, is a structure encompassing the start of the increase 
in $T_p$ and decrease in $O^+/O^0$ to the deflection of the flow 
age through the radial direction and an abrupt decrease in 
density. The proximity of the strongest southward fields 
to the interface suggests that the stream-stream interaction 
may have been involved in the production of the out-of-the-
 ecliptic fields. Ahead of the stream interface, the smooth 
rotation in magnetic field direction on September 3 (which 
includes a slow sector boundary) and enhanced field inten-
sity resemble the features of the subset of ICMEs known as 
“magnetic clouds” [Klein and Burlaga, 1982]. Furthermore, 
bidirectional suprathermal electron flows, often a signature 
of ICMEs [e.g., Gosling, 1990] were present, and the Gene-
iss spacecraft on-board solar wind algorithm [Neugebauer et 
al., 2003] classified the interval from ~ 04 to 16 UT as likely 
ICME material. Thus, it is possible that ICME material was 
present. On the other hand, enhanced $O^+/O^0$ and low $T_p$ 
are absent, and this structure is not identified by the auto-
mated magnetic cloud identification scheme of Lepping et al. 
[2000]. In this case, this structure had a northward-directed 
magnetic field and did not contribute to the geomagnetic 
storm. The last preceding, catalogued LASCO halo/partial 
halo CME was ~ 4 days earlier at 0306 UT on August 30 
but the high CME speed (1111 km/s) and strong asymme-
try towards the west suggest that this CME was unlikely to 
be associated with the structures related to the September 
4 storm. A weak inhomogeneous outflow at a wide range 
of position angles starting at 1506 UT on August 29 that 
is not included in the CME catalogue might be an alterna-
tive source candidate. A reverse shock was present at the 
CIR trailing edge (red vertical line) but clearly had no role 
in the storm. The outward magnetic field direction in the 
high-speed stream is consistent with an association with the 
southern coronal hole indicated in the SOHO/EIT observa-
tions for August 30, 2002 (after the solar polar field reversal 
at solar maximum) in Figure 6.

The storm in Figure 1 driven by the trailing half of a 
CIR, October 23, 1996, reached Dst = -105 nT, and was 
generated by a 7-hour interval of nearly persistent, south-
ward magnetic fields that reached ~ 12 nT, together with 
transverse electric fields of ~ 7 mV/m. Figure 5 suggests 
that these southward fields were associated with Alfvén 
waves. The available WIND data show little evidence of 
ICME-like signatures, such as low $T_p$. Another point to note 
is that the heliospheric plasma sheet was not crossed in this 
CIR. A partial halo CME with a speed of 480 km/s was ob-
served by LASCO at 1717 UT on October 19. Although the 
~ 3-day interval between the CME and storm onset is rea-
sonably consistent with the CME speed, EIT and Yokoh- 
osh STX observations show that the related activity was in 
the south-east quadrant of the solar disk, outside the trailing-
edge of the coronal hole that gave rise to this CIR, indicated 
in the observations for October 20, 1996 in Figure 6. Thus, 
it is unlikely that this CME would have been detected at 
Earth at the leading-edge of the stream.

A second group of three storms were driven by intervals of 
southward fields that largely preceded the stream inter-
face (‘S’ region). These storms are shown in Figure 2, in 
order of decreasing time interval between the storm peak 
and interface crossing.

The storm on February 11, 2004 (Dst = -109 nT) 
was caused by an ~ 9 hour period of southward magnetic 
fields reaching ~ 15 nT and transverse electric fields 
~ -6 mV/m. Recovery commenced when the field turned 
northward ~ 8 hours before the interface. While the en-
hanced southward field following northward fields might 
indicate the presence of a magnetic cloud-like structure, there is 
no evidence of unusually high ion charge states (cf. $O^+/O^0$) 
or abnormally low $T_p$ at this region, which is not selected by 
the automatic cloud detection scheme. Also, no LASCO 
halo/partial halo CMEs were reported after January 26.

Figure 5 suggests that the solar wind on February 11, 2004 
was dominated by Alfvénic fluctuations. In particular, 
the smaller-scale north-south field variations that influence 
geoeffectiveness are largely reflected by $V_t$. The elevated 
densities in the southward field region together with crossings 
of the heliospheric current sheet suggest that this region 
is associated with the heliospheric plasma sheet. However, 
ACE/SWEPAM electron distributions suggest that the only 
true sector boundary crossing occurred near the beginning 
of February 11. The origin of the high-speed stream is a 
large, low latitude coronal hole with a thin extension to the 
north pole (see observations for February 10, 2004 in Fig-
ure 6). The sunward magnetic field direction is consistent 
with the inward field direction above the north pole.

The driver of the Dst = -115 nT storm on October 7, 
2002 was ~ 1-day period of modest (<10 nT) southward 
field, and $E_y$ ~ -3 mV/m ahead of the interface. Varia-
tions in $B_z$ are largely associated with Alfvén waves (Fig-
ure 5), and there are no ICME-like signatures. Dst was 
already at ~ -50 nT before the CIR arrived. Thus, it is 
likely that this CIR with modest plasma/field signatures 
would not have produced a major storm without this ongo-
ing “pre-conditioning” activity. The probable stream source 
is the equatorward southern coronal hole extension indicated 
in the observations for October 4, 2002 in Figure 6.

The storm of October 14, 2002 (Dst = -100 nT) was 
driven by a ~ 10 hour interval of nearly persistent 
southward-directed field, associated with the heliospheric 
plasma sheet, that reached ~ 16 nT, was accompanied by 
transverse electric fields of ~ 5 mV/m, and terminated at 
the stream interface. Both ACE/SWEPAM and Genesis 
show evidence of bidirectional suprathermal electron distri-
butions within this structure, suggesting the possible pres-
ence of a looped field structure that might be indicative of 
an ICME. On the other hand, there are no clear signatures 
of ICME-like material in $T_p$ and $O^+/O^0$. There were partial 
halo CMEs on October 9, but frontside activity was at low 
levels, suggesting that they were probably backside.

The high-speed stream most likely emerged from the coronal hole 
indicated in the EIT observations for October 12, 2002 in 
Figure 6.

Two storms contain components driven by structures 
both before and after the stream interface (Figure 3). That 
on November 21, 2002 had two minima (Dst = -87 nT and
-128 nT). The region of southward magnetic field forming the driver of the first component shows \( \phi \) slowly reversing from sunward to outward and then back to sunward. ACE/SWEPAM (and WIND-3DP) electrons suggest that these are field loops or orbits in the vicinity of the heliospheric plasma sheet and that the true sector boundary crossing was not until ~05 UT on November 21, close to the time of the interface crossing. Large amplitude Alfvén waves were also present (Figure 5). The forward shock at the CIR leading edge evidently plays no role in storm generation. The second \( Dst \) minimum is associated with amplified Alfvén waves in the trailing half of the CIR (Figure 5) that are geoeffective because they are southward, and few strong northward, field components that reach ~20 nT, and produce transverse electric fields reaching ~12 mV/m. This second storm component does not build on the first component since activity declines during the intervening period due to a nearly 40 nT field enhancement with strong northward fields centered on a sector boundary crossing. Thus, this structure resembles a magnetic cloud/flux-ropes with a northward-directed axis, there is little supporting evidence in \( T_p \) or \( O'/O^\circ \). A halo CME was observed by LASCO at 0712 UT on November 16, but the high speed (1185 km/s) compared with the low implied transit speed (420 km/s), asymmetry, and probable bimodal source (G. Lawrence, preliminary LASCO CME report) suggest that it was not related to interplanetary structures associated with this storm. The high-speed stream most likely originated in an equatorially directed to the east. The second phase of the storm was associated with variable but predominantly southward-directed magnetic field components in most of these structures suggesting that they are unlikely to be related to CMEs. The driver of the first phase of the July 12, 2003 storm may be an exception. There are no Earthward-directed halo CMEs observed by the SOHO/LASCO coronagraphs that may be plausibly associated with these storms, although we note that CMEs can be observed at Earth in the absence of halo CMEs detectable by LASCO [e.g., Cane and Richardson, 2003]. Suprathermal solar wind electrons suggest that in several cases, the storm driving regions are associated with folded or looped fields in the heliospheric plasma sheet. Thus, it is possible that they involve transient structures, such as envisaged by Crooker et al. [2004a] to be formed by interchange reconnection. Such structures are unlikely to have typical ICME signatures since they form higher in the corona. Correlations between the north-south solar wind velocity and magnetic field components in most of these structures suggest that large amplitude Alfvén waves are present and can contribute to, if not provide the dominant source of, the southward fields.

The importance of the time variation of \( B_z \) (and \( E_y \)) in determining storm size is illustrated by the CIR on January 27, 2000 (Figure 7). Although southward fields reach \( \sim 25 nT \), these are brief and interspersed with northward fields that reach similar intensities such that the storm only reaches \( Dst = -41 nT \). Note also the initial large positive excursion in \( Dst \) (reaching +46 nT, or +20 nT if pressure-corrected) caused by compression of the magnetosphere at the time of the exceptionally large densities in the CIR. Figure 7 illustrates that a reasonably high-speed stream (\( \sim 750 \text{ km/s} \) with a change in speed of \( \sim 400 \text{ km/s} \)) including a well-developed CIR at the leading edge and a sector boundary crossing may not necessarily lead to a major geomagnetic storm.

To quantify this discussion of the conditions that generate CIR-associated storms, we have used the \( O'Brien \) and \( McPherron \) [2003] (OM) equations that relate the pressure-corrected \( Dst \) index to the solar wind driver given by \( V_Bz \), where \( V_Bz \) is the rectified value of \( V_Bz \) that is positive when \( B_z \) is southward and zero when \( B_z \) is northward. These equations are:

\[
\frac{d}{dt} Dst^* = Q(V_Bz) - \frac{Dst^*}{\tau(V_Bz)^3},
\]
The rate of change of $D_{st}^*$ is assumed to be proportional to $V_B$, $Q$ representing injection into the ring current, less a long-term represented by the recovery time $\tau$ that depends on the strength of the ring current and is assumed to be proportional to $D_{st}$. O'Brien and McPherron [2000] estimate that $\alpha = -4.4$ nT m/(mV h)$^{-1}$, $E = 0.5$ mV/m, $\tau_{\infty} = 2.4$ hours, $V_0 = 0.9$ mV/m, and $V_f = 4.7$ mV/m. Note that the recovery time $\tau$ depends on the incident $V_B$ and ranges from a maximum of 18.9 hours (for $V_B = 0$) to ~4–5 hours for typical values of $V_B$ (~5–10 mV/m) associated with the CIR events discussed above.

In Figures 1–4, we have plotted in the upper panels the time variation of $D_{st}$* “predicted” by the OM equations for each of the CIR-associated storms. The calculation uses the ACE 64-s or WIND 92-s GSM $V_B$ and $B_z$ as input, and starts well ahead of each event so that the solution has stabilized by the time of the storm. Note that we compare in the figures the predicted $D_{st}$* with $D_{st}$ rather than $D_{st}$. Although the difference between $D_{st}$ and $D_{st}$* can be significant within the dense plasma inside CIRs, it is typically only a few nT at storm maximum (cf., Table 1). Overall, the observed variations in $D_{st}$ are replicated fairly successfully with the exception of some details, such as the faster recovery between the components of the November, 2002 storm, suggesting that the physical assumptions of the OM equations together with the observed interplanetary conditions can largely account for the generation of these major storms.

To place the storms in Table 1 in context, we have examined the geomagnetic activity (as measured by $D_{st}$) for a total of 159 CIRs/high-speed streams in the near-Earth solar wind during 1996–early 2005 that did not involve any ICMEs (as identified for example by Cane and Richardson [2003]). This sample includes the vast majority of such CIRs that encountered Earth during this period, including those associated with the major storms discussed in this paper. (A few streams were excluded, for example, at times of ongoing ICME-associated storms). The top panel of Figure 8 shows the minimum $D_{st}$ in each of these streams (typically associated with the passage of the CIR) plotted as a function of time (events in Figure 8 prior to 1996 will be discussed below). It is clear that the streams with $D_{st} \leq -100$ nT are exceptional, and the majority are associated with weaker storm conditions. Figure 9 shows a histogram of the number of events vs. minimum $D_{st}$. The distribution peaks at $D_{st} \sim -40$ nT, with a tail extending to lower $D_{st}$ values. In this sample of events, ~6% generate storms with $D_{st} \leq -100$ nT, the strongest storm having $D_{st} = -128$ nT. The mean $D_{st}$ is -46 nT. For comparison, Figure 9 also shows the distribution of minimum $D_{st}$ for 281 ICME-associated storms in 1996–2005, updated from the list of Cane and Richardson [2003]. Interestingly, the distribution for ICMEs also peaks at ~ -40 nT, suggesting that the most probable ($D_{st}$) activity is similar for CIRs and ICMEs. However, ICMEs clearly have a more extended tail to low $D_{st}$ values reaching (in this sample of events) nearly -500 nT and resulting in a lower mean (~76 nT). There are relatively fewer CIRs than ICMEs associated with $D_{st}$ near 0 nT, suggesting that CIRs are rarely associated with geomagnetically quiet conditions. A probable explanation is that the combination of large-amplitude Alfvén waves, which are likely to include some southward field components, and high-speed flows mean that most CIRs/high-speed streams are likely to be geoeffective to some extent. On the other hand, ICMEs and sheath plasma can occasionally include persistent northward fields that are not geoeffective. Again we caution that storm sizes for events in 2003 and later may be revised when final $D_{st}$ values become available.

The storms in Table 1 show a tendency to be clustered around the March and September equinoxes, suggestive of a seasonal effect. Furthermore, the structures driving the storm have sunward-directed fields (neg in Table 1, column 5) in the two cases near the spring equinox, and anti-solar fields (+ve in Table 1, column 5) in those events near the fall equinox. Such a pattern is consistent with the expectations of the Russell and McPherron [1973] effect, to which other factors also contribute [e.g., Olver et al., 2000; O'Brien and McPherron, 2002]. The seasonal influence in the geoeffectiveness of our sample of CIRs is demonstrated further in Figure 10, which shows minimum $D_{st}$ for these CIRs as a function of month of the year, divided into events in which the magnetic field direction in the structure driving the activity is towards or away from the Sun. Mean values of $D_{st}$ for events in each month are also indicated. It is evident that overall activity levels are higher during the months around the fall solstice for anti-solar fields, and higher around the spring solstice for sunward fields. The difference in average $D_{st}$ between favored and unfavored field directions is as much as ~40 nT which is a significant fraction of the -100 nT major storm threshold used to identify the workshop events. Thus, we conclude that the seasonal effect is an important factor in enhancing the geoeffective of structures associated with CIRs/streams with favored field directions and hence in producing major CIR-associated storms. The only major storms which deviate from this seasonal pattern are those of July, 2003 which occur away from both solstices.

We have calculated the predicted storm size from the OM equations for each event (if essentially complete plasma and field data are available) and compare these results in Figure 11 with the observed minimum $D_{st}$* and $D_{st}$. The predicted storm sizes (for 154 events) are highly correlated both with $D_{st}$* ($cc = 0.862$) and $D_{st}$ ($cc = 0.872$). Note that the observed geomagnetic activity during the largest CIR-associated storms (as measured by $D_{st}$ or $D_{st}$*) tends to exceed predicted levels by ~20 nT. In particular, only one storm is predicted to exceed -100 nT. A possible interpretation is that the ring current injection efficiency for CIR-associated activity, represented by $Q$, is higher than inferred by OM. In fact, Miyoshi and Kataoka [2005] conclude that Alfvén waves associated with CIRs result in repeated injections from the plasma sheet into the ring current which may increase the overall ring current injection efficiency. Figure 10 shows the storm sizes predicted by the OM equations as a function of month of year. These largely reproduce the observed seasonal effect, indicating that this predominantly originates in the solar wind driver of the ring current as given by $V_B$. Again, it is evident that the intensities of the major storms tend to be underestimated compared to observations.

The main factor controlling $V_B$ is $B_z$ since the solar wind speeds associated with typical streams only range over a factor of ~2 (say from ~400 to ~800 km/s) whereas $B_z$ has a larger range of values. Figure 12 shows the maximum southward field in the solar wind structure that drives the $D_{st}$ index to minimum values, plotted versus peak $D_{st}$ for our sample of CIR/stream-associated storms ($cc = 0.586$). Though major storms are associated with larger than average values of $B_z$ (~9–19 nT), there are also CIRs with intervals of relatively strong $B_z$ that produce weaker than expected storms since, as discussed above, the storm size also depends on the time variation in the north-south magnetic field component. To provide a comparison with ICME-related storms, we have overplotted in Figure 12 (dashed line) the Richardson and Cane [2005] result of fitting peak storm ($D_{st}$) size to $B_z$ for a sample of ~300 ICME-related
major storms, $Dst = 8.49B_x + 5.6$ nT. Overall, the dependence between $Dst$ and $B_x$ is similar for both CIR and ICME storms but, for a given $B_x$, ICMEs are typically more geoeffective by $Dst \sim -30$ nT. A possible reason is that the intervals of southward fields are typically more prolonged in ICMEs, in particular in the case of magnetic clouds that give rise to the majority of larger storms, than in CIRs. The Richardson and Cane [2005] $Dst - B_x$ relationship for ICMEs, if applicable to CIRs, suggests that since $B_x$ in CIRs rarely exceeds $\sim 20$ nT, CIR-generated storms may only be expected to reach $Dst \sim -175$ nT.

Another limit on CIR-associated storm sizes may be based on the OM equations. Minimum $Dst^*$ occurs when

$$\frac{d}{dt} Dst^* = 0,$$  \hfill (4)

and hence,

$$Q_T = Dst^*.$$  \hfill (5)

For maximum observed values of $B_x (\sim 20$ nT), and assuming a typical solar wind speed of say $V \sim 450$ km/s, transverse electric fields reaching $\sim -9$ mV/m are expected to be associated with CIRs (cp., Table 1), which then imply similar limiting minimum values of $Dst \sim -180$ nT if the storm is allowed to proceed until loss driving and loss terms balance. A caveat is that as discussed above in relation to Figure 11, the OM equations underestimate the size of CIR-associated storms by $\sim 20$ nT, so the predicted limit may also need to be reduced by a similar amount, to $Dst \sim -200$ nT. The upper values of $B_x \sim 20$ nT found in CIRs presumably result from the maximum field strengths that can typically be achieved by compressing the interplanetary magnetic field by the stream-stream interaction process, and the degree to which these fields, which on average are expected to lie near the ecliptic, are deflected southward. ICMEs can generate stronger storms because their magnetic fields are imposed during CME formation near the Sun and can include configurations (such as flux ropes in the case of magnetic clouds) that may lead to extended intervals of enhanced out-of-the-ecliptic field components. Interaction between fast ICMEs and the upstream solar wind can also lead to compressions and deflections of the sheath magnetic fields that can be highly geoeffective.

While this anticipated limit on the size of CIR-associated storms is consistent with observations in 1996 – 2004, we have also examined whether it holds for an additional 23 probable CIR/stream-associated $Dst \leq -100$ nT storms we have identified between 1972 and 1995. These are listed in Table 2 and plotted in Figure 8. The availability of in-situ plasma and field data is also noted. Where such data were unavailable, to infer the presence of corotating streams we have referred to other observations, such as recurrent geomagnetic activity enhancements and recurrent cosmic ray depressions observed by neutron monitors and the Goddard energetic particle instrument on IMP 8 [e.g., Richardson et al., 1999]. The strongest such storm (September 13, 1989) reached $Dst = -161$ nT, though with the caveat that the “pure” CIR character cannot be confirmed in the absence of in-situ observations. Thus, these additional storms also lie within the expected limit.

Returning to our sample of CIR-associated events in 1966 – 2004, Figure 13 shows that the storm size is poorly correlated with the peak solar wind speed in a stream ($cc = 0.321$) or the change in speed at the stream leading edge ($cc = 0.246$), a reason being that there is essentially no correlation (Figure 14) between $B_x$ in the region that drives the storm and the peak stream speed ($cc = 0.189$). In particular, major storms are not necessarily associated with exceptionally fast streams. The correlations are not significantly improved by considering streams with seasonally favored and unfavored field directions separately.

An intriguing feature of the nine major storms in Table 1 is that four (44%) occurred over a period of less than three solar rotations in September – November, 2002. There was also a CIR-associated storm of $Dst = -98$ nT on October 24 that nearly meets the criteria for inclusion in Table 1. During this period, both CIR- and ICME-associated storms were present. Although, as noted above, the CIR storm on October 7 occurred during the decay of an intense ICME-related storm, preceding the decay, does not lead to the other major CIR-associated storms. A unique characteristic of the September – November 2002 period is that it coincides with the highest mean values of the IMF intensity and mean solar magnetic field during cycle 23. Figure 8 shows the solar cycle variations in Carrington rotation averages of the mean IMF intensity and the RMS value of daily measurements of the mean solar field from the Wilcox Observatory. The vertical line indicates the time of maximum mean IMF in cycle 23. Although an interesting possibility is that the high mean IMF, which apparently reflects the strong solar fields, contributes to the overall geoeffectiveness of CIRs and streams during late 2002, this cannot be the dominant controlling factor since major CIR storms, such as October 23, 1996, can also occur when the mean IMF is much weaker. In addition, the highest mean fields in late 2002 are also only $\sim 1$ nT higher than typical mean fields of $\sim 7 - 8$ nT during much of cycle 23, and it seems unlikely that such a small difference alone could account for the strong clustering of major storms at this time. The highest mean IMF intensities (and associated elevated solar mean fields) during the previous two solar cycles are also indicated in Figure 8. Although there is a clustering of storms around this time in cycle 22, overall the distribution of events in both cycles 22 and 21 is not strongly ordered by these field strengths, with the majority of such storms occurring as the fields decline during the descending phase of each cycle.

Considering all the $Dst \leq -100$ nT storms in 1972 – 2004, they display a clear seasonal effect, illustrated in Figure 15 where the number of storms per calendar month is given for cases where the field in the storm driver is directed away from or towards the Sun. The clear dominance of major storms driven by Sunward- (outward-) directed fields near the spring (autumn) equinox is consistent with the seasonal dependence of CIR-associated geomagnetic activity found above in cycle 23. We also note that McAllister and Crooker [1997] reported a seasonal effect in CIR-associated activity during cycle 22.

4. Summary and Conclusions

From the point of view of forecasting major storms, what is the importance of CIR-associated events? First of all, observations suggest that only a few percent of CIRs ($\sim 6\%$ in cycle 23) produce storms that exceed the $Dst = -100$ nT threshold. Based on solar wind parameters associated with CIRs and the OM equations, we estimate that the upper limit on CIR-associated storms is likely to be $Dst \sim -180$ nT. Thus, CIRs are unlikely to be a source of severe storms, at least as measured by $Dst$, that far exceed this limit. Observations since 1972 are consistent with this expectation. The size of CIR-associated storms can be estimated with limited ($\sim 1$ hour) lead time using upstream real-time plasma/field data and the OM equations, though we note that these equations tend to underestimate the size of major storms by $\sim 20$ nT. The seasonal effect clearly enhances the geoeffectiveness of CIRs near the equinoxes if the IMF direction is favorable and is an important factor in
generating storms with $Dst \leq -100$ nT. Although stream speeds can be predicted fairly successfully from a potential field model, for example [e.g., Arge and Pizzo, 2000; Arge et al., 2000], unfortunately they are poor predictors of the geoeffectiveness of streams/CIRs. The source coronal holes in Figure 6 show no unusual configuration in common that might be indicative of a particularly geoeffective stream except that they lie at low latitudes and are frequently equatorward extensions of polar coronal holes that reach low latitudes. Since the magnetic field direction in coronal holes, and hence in the associated streams, can be inferred from solar magnetograms and from knowledge of the solar polar field directions, it should be possible to forecast when CIRs with “favored” IMF configurations will be present near the Earth near the equinoxes, with a potential for generating major storms. We also note that CIRS evidently cannot be generated by CIRs alone but in conjunction with interplanetary streams (perhaps examples among the major events discussed in this paper), the most geoeffective structure might also precede the heliospheric current sheet crossing ahead of a stream, in which case, the field direction will be opposite to that in the fast streams.

Major CIR storms appear to avoid solar maximum, are most prevalent during the declining phase of the cycle, and intriguingly may occur preferentially in association with intervals of enhanced IMF intensity, and mean solar magnetic fields. The tendency for events to cluster over several solar rotations also suggests that the best predictor of an upcoming CIR-associated major storm may be the occurrence of such a storm on a preceding solar rotation. It is also important to remember that $Dst$ is only one aspect of the magnetospheric phenomena associated with geomagnetic storms. CIRs are known, for example, to have a greater influence on the strength of the dipole field than on their occurrence during major storms [e.g., Paulikas and Blake, 1976; Lam, 2004; Miyoshi and Kataoka, 2005].

Finally we note that one of the arguments of McAllister and Crooker [1997] that CMEs play a role in CIR-associated storms is that “it is generally accepted that major storms cannot be generated by CIRs alone” [Gosling, 1963; Tsurutani et al., 1995b]. Therefore, the presence of major storms (peak $Dst < -100$ nT) at the leading edges of both seasonally favored and unfavored sectors also suggests the presence of transients.” We conclude, however, that CIRs alone do occasionally produce storms that exceed this level, at least in favored sectors. We also note that CIRs evidently have a rich diversity of field configurations, and searching for the drivers of major CIR-associated storms will almost inevitably lead to the few CIRs that include regions of extended, enhanced southward fields resembling those found in geoeffective transients, even if transients are not included in these storms.

Acknowledgments. We thank the organizers of the “Living with a Star” CDAW at the George Mason University, Virginia, for the opportunity to meet and discuss these storms, and the members of Working Group 1 for their participation in identifying and interpreting the solar and interplanetary observations. The CDAW website is http://cdaw.gsfc.nasa.gov/geomag_cdaw/. We acknowledge the use of ACE data, available from the ACE Science Center (http://www.srl.caltech.edu/ACE/ASC/), and Genesis data, available at http://genesis.srl.nasa.gov/. WIND data were obtained from the WIND/MFI site (http://lepmfi.gsfc.nasa.gov/) and from the University of Berkeley (http://sprg.srl.berkeley.edu/wind3dp/). Data from the National Space Science Data Center and National Geophysical Data Center were also used. Wilcox Observatory data are available at http://wso.stanford.edu/~wso/. We also thank R. McPherron for helpful discussions regarding OM equations, and the referees for their constructive comments.

References


D. B. Berdichevsky, R. Kataoka, and B. J. Thompson, Code 612, NASA Goddard Space Flight Center, Greenbelt, MD, 20771 (dberdich@pop600.gsfc.nasa.gov; ryanho@mit.edu; Barbara.j.thompson.nasa.gov); D. A. Biesecker, NOAA/SEC W/NP9, 326 Broadway, Boulder, CO 80305 (doug.biesecker@noaa.gov).

J. C. Kasper, MIT Center for Space Research, 37-873 77 Massachusetts Avenue, Cambridge, MA 02139 (jck@mit.edu); I. G. Richardson, Code 661, NASA Goddard Space Flight Center, Greenbelt, MD, 20771 (richardson@lheavx.gsfc.nasa.gov); J. T. Steinberg, MS D466, Los Alamos National Laboratory, Los Alamos, NM 87545 (jsteinberg@lanl.gov); D. W. Webb, Boston College, Inst. for Scientific Research, Chestnut Hill, MA 02467 (David.Webb.ctt@hanscom.af.mil); C.-C. Wu, CSPAR/University of Alabama in Huntsville, Code 695, NASA Goddard Space Flight Center, Greenbelt, MD, 20771(wuc@cspar.uah.edu); J. Zhang, George Mason University, 4400 University Dr., Fairfax, VA 22030 (jzie@esos.gmu.edu); A. N. Zhukov, Royal Observatory of Belgium, Avenue Circulaire 3, B-1180 Brussels, Belgium (Andrei.Zhukov@oma.be).

Figure 1. Three CIR-associated Dst < -100 nT storms driven by structures (several hour duration intervals of persistent southward field) in decelerated fast solar wind following the stream interface (indicated by green vertical lines). The red vertical line in the bottom panel indicates passage of a reverse shock.

Figure 2. Three major storms driven by structures ahead of the stream interface.

Figure 3. Two major storms driven by southward field structures prior to and following the stream interface. Forward and reverse shocks are indicated by red vertical lines on November 20, 2002 and July 12, 2003, respectively.

Figure 4. A major storm driven by an interaction region between two high-speed streams. The red vertical line indicates a reverse shock.

Figure 5. North-south (z) components of the solar wind magnetic field and velocity in the vicinity of the interplanetary field (several hour duration regions of persistent southward fields (-ve Bz)) that drive the geomagnetic storms in Table 1. The pervasive correlated variations between Bx and By are indicative of Alfvén waves.

Figure 6. SOHO EIT Fe XV observations of the coronal hole source for the high-speed streams associated with the storms in Table 1.

Figure 7. A well-developed CIR including southward magnetic fields of more than 20 nT that gives rise to only a modest storm because of the large both positive and negative fluctuations in Bz due to Alfvén waves. In addition, the high plasma densities in the heliospheric plasma sheet drive Dst temporarily positive.
Table 1. CIR-Associated $Dst \leq -100$ nT Storms in 1996 – 2004

<table>
<thead>
<tr>
<th>Storm Peak (UT)</th>
<th>$Dst$ ($Dst^*$)</th>
<th>$B_x$</th>
<th>B Direction</th>
<th>$E_y$</th>
<th>$V_{slow}$</th>
<th>$V_{fast}$</th>
<th>$dV$</th>
<th>Driver</th>
<th>Heliospheric Current Sheet?</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1996 Oct. 23, 03</td>
<td>-105 (-105)</td>
<td>12</td>
<td>+</td>
<td>-7</td>
<td>450</td>
<td>670</td>
<td>220</td>
<td>F'</td>
<td>N</td>
<td>Also Zhang et al. [1996]</td>
</tr>
<tr>
<td>1997</td>
<td>No Events</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1998 Mar. 10, 21</td>
<td>-116 (-119)</td>
<td>17</td>
<td>-</td>
<td>-9</td>
<td>300</td>
<td>600</td>
<td>300</td>
<td>F'</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>1999 – 2001</td>
<td>No Events</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2002 Sept. 4, 06</td>
<td>-109 (-110)</td>
<td>20</td>
<td>+</td>
<td>-7</td>
<td>350</td>
<td>500</td>
<td>150</td>
<td>I/F'</td>
<td>Y</td>
<td>Preceding ICME with $B_x &gt; 0$</td>
</tr>
<tr>
<td>Oct. 7, 08</td>
<td>-115 (-)</td>
<td>10</td>
<td>+</td>
<td>-3</td>
<td>400</td>
<td>500</td>
<td>100</td>
<td>S'</td>
<td>N</td>
<td>Preceding storm</td>
</tr>
<tr>
<td>Oct. 14, 14</td>
<td>-100 (-104)</td>
<td>16</td>
<td>+</td>
<td>-5</td>
<td>280</td>
<td>580</td>
<td>300</td>
<td>S'</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>Nov. 21, 11</td>
<td>-128 (-133)</td>
<td>16</td>
<td>-</td>
<td>-10</td>
<td>380</td>
<td>740</td>
<td>360</td>
<td>S'+F'</td>
<td>Y</td>
<td>Preceding “flux rope” with $B_x &gt; 0$</td>
</tr>
<tr>
<td>2003 Jul. 12, 06</td>
<td>-118 (-120)</td>
<td>15</td>
<td>+</td>
<td>-9</td>
<td>350</td>
<td>700</td>
<td>350</td>
<td>S'+F'</td>
<td>Y</td>
<td>ICME-driven 1st component</td>
</tr>
<tr>
<td>Jul. 16, 13</td>
<td>-117 (-122)</td>
<td>12</td>
<td>-</td>
<td>-6</td>
<td>550</td>
<td>690</td>
<td>140</td>
<td>S'</td>
<td>N</td>
<td>In high-speed stream</td>
</tr>
<tr>
<td>2004 Feb. 11, 18</td>
<td>-109 (-116)</td>
<td>15</td>
<td>-</td>
<td>-6</td>
<td>380</td>
<td>700</td>
<td>320</td>
<td>S'</td>
<td>Y</td>
<td></td>
</tr>
</tbody>
</table>

a Maximum southward magnetic field (nT).

b Magnetic field direction in structure driving storm: + = outward; - = sunward.

c Solar wind electric field $y$-component.

d Solar wind speed in slow solar wind preceding CIR.

e Solar wind speed in fast solar wind following CIR.

f Change in solar wind speed.

S'=accelerated slow solar wind ahead of stream interface; F'=decelerated fast solar wind following stream interface; I=stream interface.

h Heliospheric current sheet (sector boundary) encountered in vicinity of CIR?
Table 2. "CIR-Associated" $Dst \leq -100$ nT Storms in 1972 – 1995

<table>
<thead>
<tr>
<th>Date</th>
<th>Dst</th>
<th>Magnetic Field</th>
<th>Plasma B Direction</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>(UT)</td>
<td>(nT)</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>1973 Feb 21</td>
<td>-121</td>
<td>Yes</td>
<td>Yes</td>
<td></td>
</tr>
<tr>
<td>1975 Nov 9</td>
<td>-110</td>
<td>No</td>
<td>Partial</td>
<td></td>
</tr>
<tr>
<td>1977 Dec 11</td>
<td>-112</td>
<td>Yes</td>
<td>Yes</td>
<td>+</td>
</tr>
<tr>
<td>1983 Mar 12</td>
<td>-112</td>
<td>No</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>1984 Mar 28</td>
<td>-105</td>
<td>Partial</td>
<td>Partial</td>
<td>–</td>
</tr>
<tr>
<td>1984 Aug 1</td>
<td>-112</td>
<td>Partial</td>
<td>Partial</td>
<td>+</td>
</tr>
<tr>
<td>1985 Oct 13</td>
<td>-101</td>
<td>Partial</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>1989 Apr 26</td>
<td>-132</td>
<td>Yes</td>
<td>Yes</td>
<td>–</td>
</tr>
<tr>
<td>1991 Aug 2</td>
<td>-114</td>
<td>Yes</td>
<td>Yes</td>
<td>+</td>
</tr>
<tr>
<td>1991 Aug 30</td>
<td>-107</td>
<td>Yes</td>
<td>Yes</td>
<td>+</td>
</tr>
<tr>
<td>1991 Nov 22</td>
<td>-139</td>
<td>Partial</td>
<td>Partial</td>
<td>+</td>
</tr>
<tr>
<td>1992 Sep 17</td>
<td>-140</td>
<td>No</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>1992 Sep 29</td>
<td>-118</td>
<td>No</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>1993 Mar 9</td>
<td>-137</td>
<td>Yes</td>
<td>Yes</td>
<td>–</td>
</tr>
<tr>
<td>1993 Sep 13</td>
<td>-161</td>
<td>No</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>1993 Nov 4</td>
<td>-129</td>
<td>No</td>
<td>Partial</td>
<td></td>
</tr>
<tr>
<td>1995 Dec 3</td>
<td>-117</td>
<td>Yes</td>
<td>Yes</td>
<td>+</td>
</tr>
<tr>
<td>1994 Feb 6</td>
<td>-126</td>
<td>Partial</td>
<td>Partial</td>
<td>+</td>
</tr>
<tr>
<td>1994 Mar 7</td>
<td>-109</td>
<td>Yes</td>
<td>Yes</td>
<td>–</td>
</tr>
<tr>
<td>1994 Apr 4</td>
<td>-111</td>
<td>No</td>
<td>No</td>
<td></td>
</tr>
<tr>
<td>1994 Nov 26</td>
<td>-117</td>
<td>Yes</td>
<td>Yes</td>
<td>+</td>
</tr>
<tr>
<td>1995 Mar 26</td>
<td>-107</td>
<td>Yes</td>
<td>Yes</td>
<td>–</td>
</tr>
<tr>
<td>1995 Apr 7</td>
<td>-149</td>
<td>Yes</td>
<td>Yes</td>
<td>–</td>
</tr>
</tbody>
</table>
Figure 8. Minimum $Dst$ in CIRs during 1972 – mid-2005 (events with $Dst \leq -100$ nT only are shown prior to 1996) plotted together with the mean interplanetary magnetic field strength at Earth (solar rotation averages) and the solar mean magnetic field strength (specifically solar rotation root mean squares of daily values) measured at the Wilcox observatory. Vertical lines indicate times of maximum mean interplanetary field in solar cycles 21 – 23.

Figure 9. Histogram of minimum $Dst$ values associated with 159 CIRs and 281 ICMEs in 1996 – 2005.

Figure 10. Seasonal variation in CIR-associated geomagnetic activity observed (left) and predicted by the OM equations (right) for cases where the magnetic fields in the activity driver are directed away (top) or towards (bottom) the Sun. Monthly averages are also indicated.

Figure 11. Predicted minimum $Dst^*$ from the OM equations for CIR-associated activity plotted versus observed minimum $Dst$ and $Dst^*$.

Figure 12. Minimum $Dst$ vs. maximum $B_s$ in CIRs during 1996 – 2005. For comparison, the dashed line indicates the $Dst$–$B_s$ relationship inferred for ICMEs by Richardson and Cane [2005].

Figure 13. Minimum $Dst$ vs. maximum solar wind speed and change in solar wind speed at the stream leading edge for CIRs/streams in 1996 – 2005, showing little correlation between $Dst$ and these stream parameters.

Figure 14. Maximum stream speed vs. $B_s$ in the structures driving minimum $Dst$ for CIRs/streams in 1996 – 2005.

Figure 15. Number of $Dst \leq -100$ nT storms in Tables 1 and 2 per calendar month, divided into those driven by sunward or anti-solar fields, demonstrating the clear seasonal dependence.
35
40
c0
tijn
z
S
W
c2
c0
tijn
z
5
30
25
20
15
10
5
n
-400 -300 -200 -100 0

Number of Events

159 CIRs

Number of Events

281 ICMEs

Dst(nT)
Outward Field

Sunward Field