ICME and CIR storms with particular emphasis on HILDCAA events.

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Abstract. During the 11-year solar cycle, the dominant geoeffective features of the Sun and of the interplanetary medium change significantly. Around the solar maximum phase, the predominant features are coronal mass ejections (CMEs), and their interplanetary counterparts, ICMEs. During the descending and solar minimum phases, the coronal holes in the Sun become the most important geoeffective features. From these coronal holes emanate high speed solar wind streams, which interact with the slow solar wind, forming interplanetary structures called Corotating Interaction Regions (CIRs). Both these CIRs and ICMEs, if they have significant southward Bz components (Bs), may lead to geomagnetic storms when these structures reach the Earth's magnetosphere. The characteristics of CIR and ICME storms are different, depending on the type of the driving interplanetary structure and Bs profile. In this paper, we address the main differences and similarities in the Dst profile and auroral shape of these storms, and compare them with another kind of geomagnetic activity: HILDCAA events. These HILDCAA events, although without intense and remarkable interplanetary causes, such as those leading to storms, show low, continuous levels of geomagnetic activity in the auroral region and are the ultimate cause the acceleration of relativistic electrons. The low levels of geomagnetic activity are quite significant, however. Because they are continuous, the accumulated energy deposition supersedes that of ICME magnetic storms during the solar maximum phase.

Index Terms. Coronal Mass Ejection, Corotating Interaction Region, Geomagnetic Storm, High Speed Stream, HILDCAA.

1. Introduction

The term "geomagnetic storm" was first used by Chapman and Bartels (1940) to describe the magnetospheric and ionospheric disturbances intermittently occurring. Those authors believed that storms were caused by sporadic solar streams. Later it was showed that the solar wind is continuously emitted (Parker, 1958), and that its interaction with the geomagnetic field forms the magnetosphere. During these storms, the whole current system of the magnetosphere and ionosphere is intensified, leading, consequently, to changes in the geomagnetic field measured on the Earth's surface.

In the magnetosphere, during geomagnetic storms, several plasma regions are affected and suffer strong modifications. Such changes are associated with intensifications in the current systems, mainly in the equatorial ring current region, where they can cause telecommunication disturbances (Akasofu and Chapman, 1972; Lanzerotti, 1979; Echer et al., 2005). Also, during these periods, particle acceleration and precipitation may occur, mainly in the auroral region, leading to aurora occurrences. The more intense the storm, the more intense the energy of particles involved, and more equatorward and wider the aurora.

The main causes of storms are related to plasma and magnetic field structures in the interplanetary medium. If the Bz component of the interplanetary magnetic field (IMF) is southward oriented (Bs), and if this orientation is sustained for long time (hrs), one has the necessary conditions for significant storm development. More details about storms may be found in Gonzalez et al. (1994), Gonzalez et al. (1999), Kamide et al. (1998), and Tsurutani et al. (2006). In a general way, a Bs field with intensities higher than 10 nT maintained for, at least, 3 hours, is enough to cause a "major" storm (Dst < -100 nT) (Gonzalez and Tsurutani, 1987).

The Dst index is obtained from low-latitude ground-based measurements of deviations in the H-component of the geomagnetic field (Sugiura, 1964; Rostoker, 1972). This field depression is proportional to the kinetic energy transported by particles encircling the Earth in a ring current around 2-6 Re in the equatorial plane (Dessler and Parker, 1958).

The main process for energy transfer from the solar wind to the magnetosphere is the magnetic reconnection (Dungey, 1961). By this process, when the IMF is southward oriented, its field lines merge with the field lines of the Earth's magnetic field, transferring energy and energetic particles. More details about this process are in Dungey (1961), Petsheck (1964), and Rostoker and Falthammar (1967).

In this work, we briefly compare storms caused by intense Bs fields present in coronal mass ejections in the interplanetary medium and storms related to corotating interaction regions. Further, these storms are compared with High-Intensity, Long-Duration, Continuous AE Activity (HILDCAA) events, which are another significant type of energy deposition into the magnetosphere/ionosphere. This comparison is done in Dst profiles and auroral shapes.

2. ICME and CIR storms

2.1. ICME storms

During the solar maximum phase, the main structures emanating from the sun are interplanetary remnants of coronal mass ejections - CMEs (Burlaga et al, 1981; Klein and Burlaga, 1982). These ejections, which in the interplanetary medium are named ICMEs, have a structure similar to the schematic in Fig. 1.

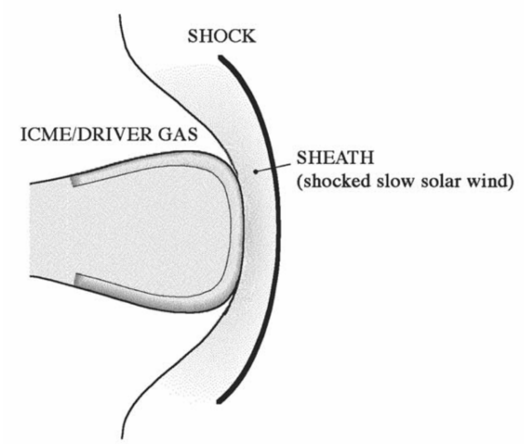

Fig. 1. Schematic of an Interplanetary Coronal Mass Ejection (ICME), taken from Tsurutani et al., 2003.

If the ICMEs are faster enough, such as its relative velocity to the ambient solar wind is higher than the magnetosonic speed, a fast shock can form ahead of it (Kennel et al., 1985). Strong, shocked fields can be found in the region between the shock and the ICME driver – the sheath region (Tsurutani et al., 1988). In addition, if the ICME has a well organized magnetic field structure, such as in magnetic clouds, further sources of Bs can be found (Burlaga et al, 1981; Klein and Burlaga, 1982).

When these structures reach the front of the magnetosphere, the first effect is dynamic, caused by the compression of the magnetosphere due to the relatively high density and increased velocity of the sheath plasma. This compression leads to an intensification of the Chapman-Ferraro current, appearing as a positive, sudden impulse in the Dst index (Nishida, 1978). Such sudden impulses, when preceding geomagnetic storms, are called storm sudden commencements (SSC). The enhanced Dst period that follows the SSC is the storm initial phase, which can last for a few hours (although this initial phase is not a necessary feature of a storm).

The interval during which the Dst index is decreasing is the storm main phase, which can last for tens of hours. This phase is caused by a sustained southward interplanetary field reaching the magnetosphere. If the high amplitude Bs is maintained for a sufficiently long time, it produces large particle injections in the ring current, and causes the decrease of the Dst index (see Gonzalez et al. (1994) for the necessary conditions for each storm intensity).

After the passage of the southward oriented part of the IMF structure, the recovery phase begins. During this phase, the trapped particles in the ring current region start to dissipate through several mechanisms (such as wave-particle interactions, Coulomb scattering, Joule heating) and the Dst index slowly returns to its pre-storm condition (Daglis et al., 1999). Fig. 2 shows a typical profile of an ICME storm.

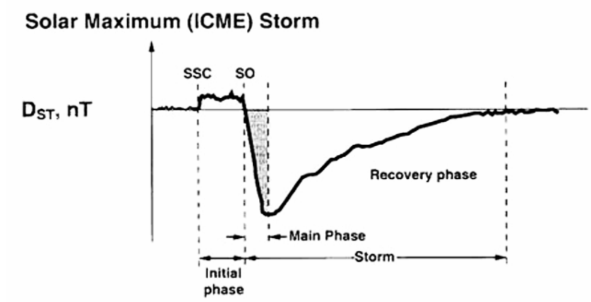

Fig. 2. Typical profile of the Dst index during storms caused by ICMEs. This figure was adapted from Tsurutani, 2000.

Generally, the most intense storms are caused by ICMEs. The Dst index during such events may decrease by hundreds of nT. Also, it is during ICME storms that the most intense auroral emissions are noted. These emissions can extend over almost all local times. The auroral oval also expands, and can reach middle and low latitudes in extreme events.

Fig. 3 shows the auroral emission observed by the POLAR/UVI instrument (Torr et al., 1995) during the storm of July 14, 2000, also known as the Bastille Day storm. This storm is considered a "great" storm which reached a peak Dst of -301 nT.

Through the image in Fig. 3 a wide aurora is seen, with high intensity levels (reaching more than 100 photon cm^{-2} s^{-1}). This aurora is distributed at almost all longitudes, although the dayside is not completely visible. The aurora is very broad in latitude and located well equatorwards of the main auroral zone. This latter feature is a characteristic of very strong events. This configuration occurred during the main phase of the storm, and lasted for some hours.

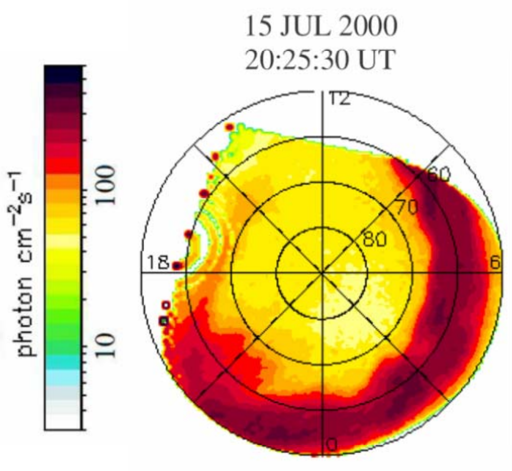

Fig. 3. Polar/UVI image for July 15, 2000, taken at 20:25:30 UT. This image shows the auroral emission during the main phase of the Bastille Day storm.

2.2. CIR storms

During the descending and minimum phases of solar cycles, flares and CMEs become less frequent and another type of solar structure occurs more often: coronal holes. Coronal holes, which appear as dark regions in x-ray images of the Sun, are confined to the solar poles during the solar maximum phase, but in the descending phase, they expand in size and move toward the solar equator (Hundhausen, 1972; Eddy, 1976).

These coronal holes are open magnetic field regions, from which emanate high-speed solar wind streams (Sheeley et al., 1976; Sheeley et al., 1978; Sheeley and Harvey, 1981; Harvey et al., 2000). High-speed streams have velocities much higher than the typical velocities observed in the solar wind, forming an interface region between the slow and fast streams. At large heliocentric distances (typically larger than 1 AU), these stream interface/interaction regions are bounded by a pair of shocks (Smith and Wolf, 1976).

Since coronal holes are long living structures, they can persist for more than one solar rotation, and the high-speed streams, originated from a same region, reappear at intervals of approximately 27 days (Smith and Wolf, 1976). This reappearance leads to the term "recurrent streams". The spiral-like structure formed by these streams, distorted due to the solar rotation and its interaction regions with slower streams, is known as Corotating Interaction Regions (CIRs). Since at Earth (1 AU) the shocks in these structures are not developed, the structure in this region is also named proto-CIR, or PCIR (Balogh et al., 1999).

Fig. 4, on the left side, illustrates a high-speed stream flowing from a solar coronal hole and forming a compressed region in front of it. The right side of this figure shows a schematic of a CIR, with the slow and fast streams marked, respectively, as "A" and "B". Both forward (FS) and reverse (RS) shocks are marked, as well as the interface region (IF).

One important aspect of fast streams is that they are imbedded with Alfvén waves (Tsurutani et al, 1995). These Alfvén waves are believed to be remnants waves generated in the photosphere by supergranular circulation (Hollweg, 1978).

When a CIR (or PCIR) reaches the Earth, it can cause a geomagnetic storm. The profile of storms caused by CIRs is different from that observed in CME storms. Since the Bz component within CIRs have large fluctuations, the consequential storms are not intense, but only weak or moderate. A schematic with the typical profile of a CIR storm is shown in Fig. 5.

In general, storms caused by CIRs have initial, main and recovery phases. The initial phase is an increase in the Dst index. It is caused by the high density plasma region associated with the heliospheric plasma sheet (HPS) in front of the high speed stream. This density increase is gradual and causes a gradual initial phase, not one beginning with a sudden commencement (Tsurutani et al., 1995).

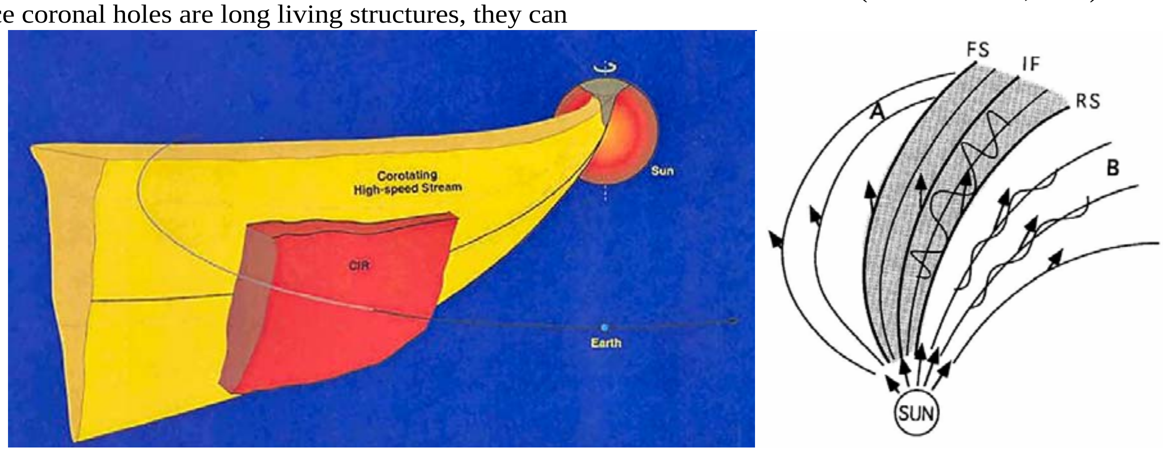

Fig. 4. In the left side, an illustration of a high speed solar wind stream flowing from a solar coronal hole (taken from Tsurutani et al., 2006). In front of the stream there is a compressed region of slow plasma. In the right side, a schematic of a Corotating Interaction Region (CIR), where "A" represents the slow solar wind, and "B" is marking the high-speed stream. The shocks are marked as FS (forward shock) and RS (reverse shock), and IF marks the interface region (taken from Tsurutani et al., 1995).

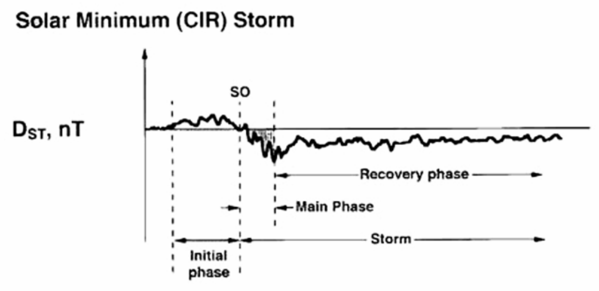

Fig. 5. Typical profile of the Dst index during storms caused by CIRs. This figure was adapted from Tsurutani, 2000.

The CIR recoveries have duration that can be much longer than those observed during ICME storms. The causes are the southward component of Alfvén waves that are present in the high speed streams. So, these events can also transfer large amounts of energy from the solar wind to the magnetosphere due to their long duration character.

2.3 HILDCAAs

When CIR storms have long recovery phases, they can fall into another category: High-Intensity, Long-Duration, Continuous AE Activity, or HILDCAA (Tsurutani and Gonzalez, 1987). During these events the AE index must reach, at least, 1000 nT, and never fall bellow 200 nT for more than 2 hours at a time. These conditions must last for at least 2 days, and must occur outside main phases of magnetic storms.

HILDCAA events can occur after CME storms as well as after CIR storms, or even without any storm occurrence. However, recent studies (Guarnieri, 2005) showed that most of these events occur after CIR storms, when the occurrence of Alfvén waves is more frequent. So, HILDCAA occurrence is higher in the descending and minimum phase of the solar cycle.

Recently, Tsurutani et al. (2004), Guarnieri et al. (2004), and Guarnieri (2005) showed that the auroral intensifications during HILDCAAs are not substorm expansion events, and neither are they convection bay events, constituting a new form of geomagnetic and auroral activity.

One example of a HILDCAA event is in Fig. 6, where interplanetary data from the ACE spacecraft and geomagnetic indices are shown. The panels are, from top to bottom: the solar wind velocity, density, pressure, IMF magnitude and components, Bx, By, and Bz, and the geomagnetic indices Dst, AU/AL, and AE.

In this event, a CIR storm is visible starting late in day 113 (April 23, 1998). The main phase starts around midnight of day 114. By the end of day 114 and beginning of day 115 (April 25, 1998) the HILDCAA event starts. Bx, By, and Bz panels show high amplitude fluctuations (Alfvén waves, verified by Guarnieri, 2005). During this time, the decrease in Dst is weak or, at most, moderate. Both AU/AL indices show intense activity, and the AE values are always high. This condition lasted for ~ 60 hours (~2 days 12 hours), until day 117, ~ 06 UT.

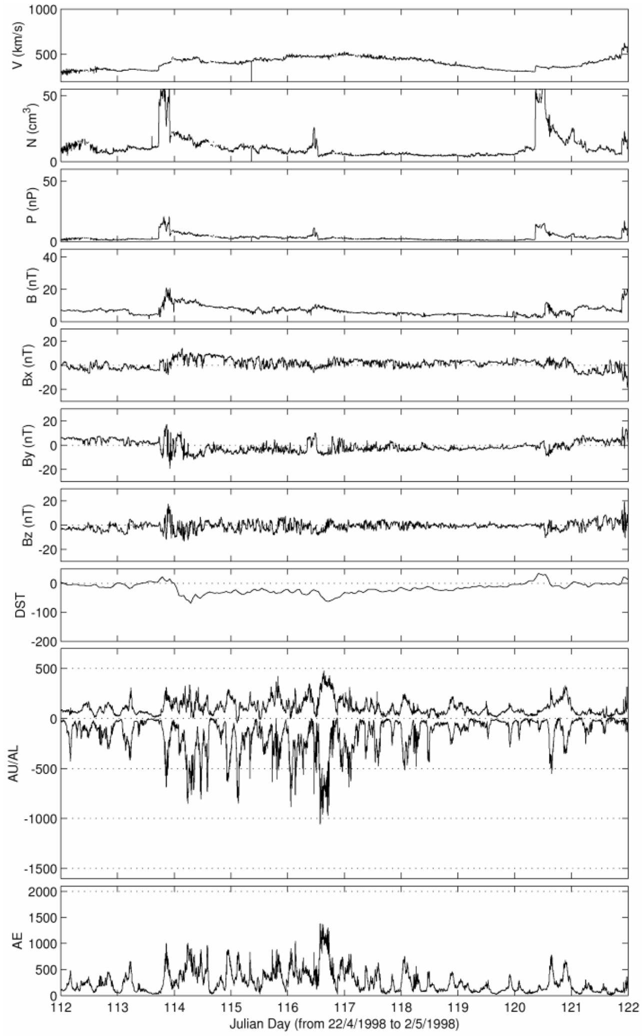

Fig. 6. Interplanetary data from ACE spacecraft and geomagnetic indices for the interval from April 22 to May 5, 1998. This interval shows a CIR storm followed by a HILDCAA event (figure taken from Tsurutani et al., 2006).

In order to verify the auroral emission (proportional to particles precipitation), we used a set of POLAR/UVI images for April 26, 1998. These images are in Fig. 7. By this sequence of images it is possible to observe that auroral emissions are much fainter than those observed during storms, however, the auroral forms are well distributed along almost all local times as a spatially continuous aurora. These intensifications lasted also for several days. During some intervals, HILDCAA auroras cover even the polar cap.

There is still a question of what is more significant for emissions: high intensity emissions observed during a short time interval, as occur during ICME storms, or the integrated effect of these moderate emissions occurring along several

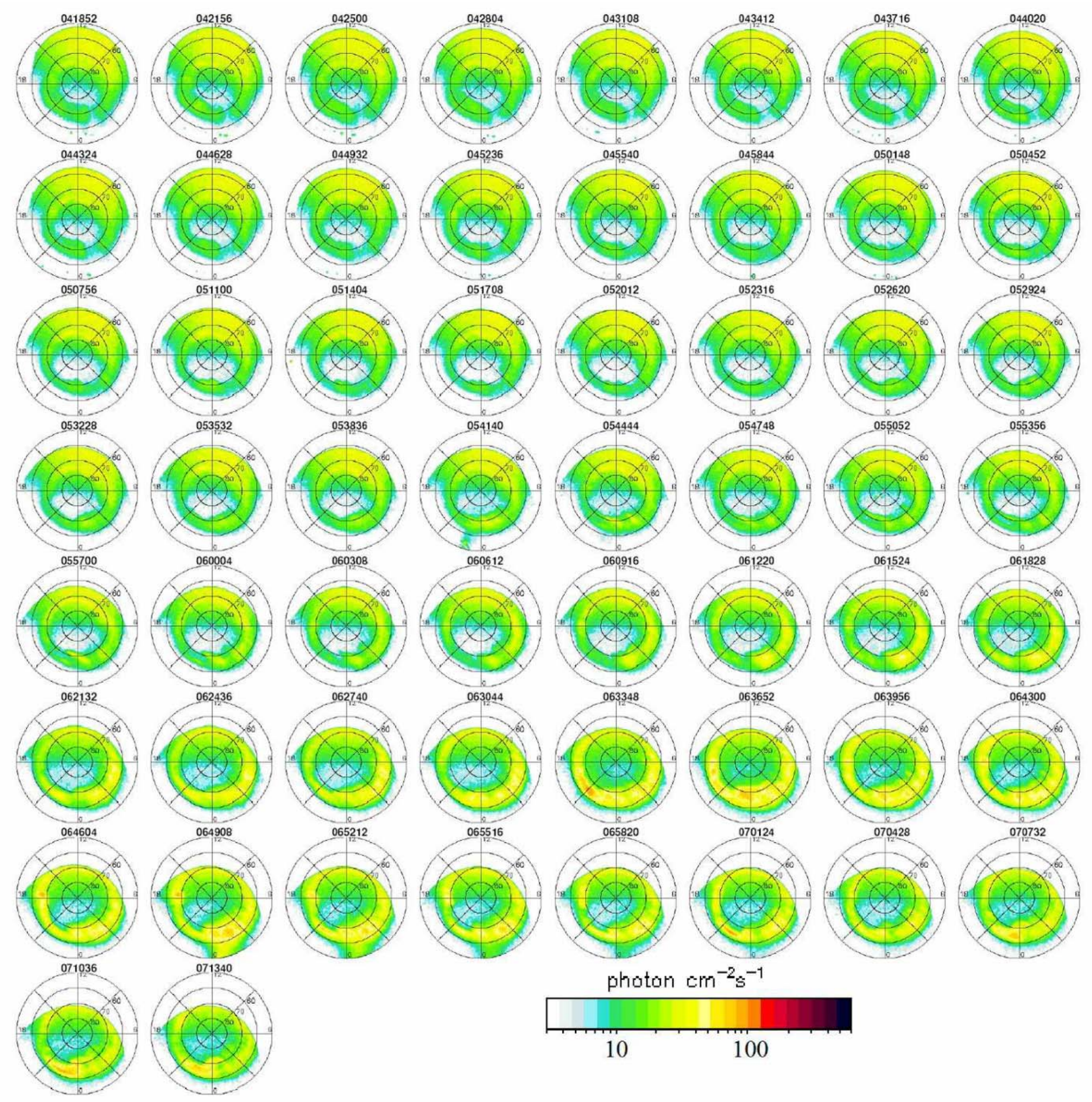

Fig. 7. Sequence of POLAR images during a HILDCAA event, for April 26, 1998. The images start at 04:18 UT and last until 07:13 UT. Figure taken from Guarnieri, 2005.

days, as in HILDCAA events. To answer this question, Guarnieri (2005) used an integration over sectors of POLAR/UVI images, for both classes of events, and showed that the integrated emission over 4 days can be higher during HILDCAA events than those observed during some very intense (Dst < -100 nT) storms. The integration time used was 4 days, which is about the maximum duration for single step storms. However, HILDCAA events can last for several days or even weeks, making these integrated emissions even more remarkable.

Another very important aspect of HILDCAA events is the acceleration of relativistic electrons, as shown on Fig. 8. This figure, for the same event of Fig. 6 and Fig. 7, shows, from top to bottom, relativistic electrons counts, Pc5 wave amplitude, IMF Bz component, solar wind ram pressure, and geomagnetic indices AE and Dst.

In the top panel an increase in the relativistic electron concentration at L-shells between 4 and 6, during the recovery phase of the CIR storm is visible. This increase is maintained or intensified along the whole HILDCAA event. These electrons, with energies in the range from 40 to 400 keV, are also known as "killer electrons" due to its hazardous effects on electronic equipments aboard satellites.

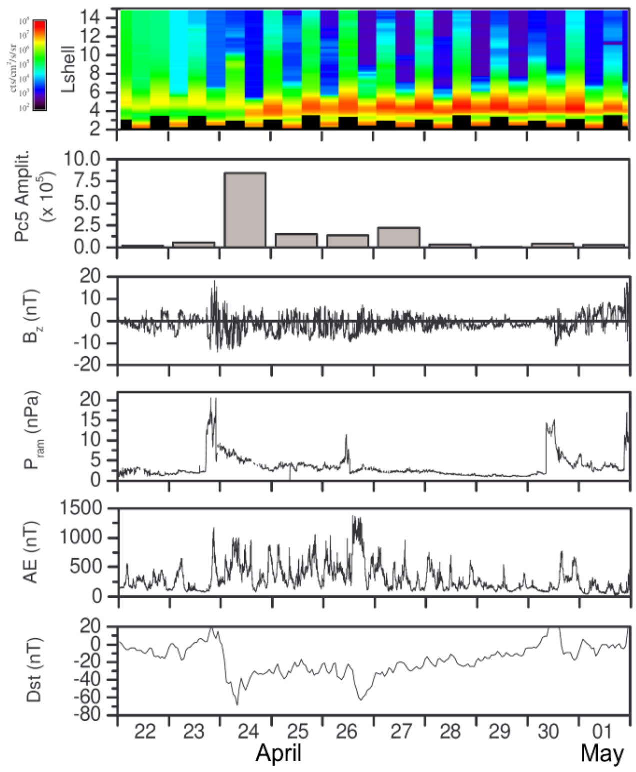

Fig. 8. Relativistic electrons and Pc5 waves observed by Polar satellite for the interval from April 22 to May 01. During this time, a CIR storm is visible and a HILDCAA event (figure taken from Tsurutani et al., 2006).

Another effect observable in this plot is the presence of Pc5 waves (second panel from the top). The maximum in wave amplitudes occurs during the main phase of the storm. However, waves of lower intensity still exist during the HILDCAA event, which finish on April 27, 1998. The wave activity disappears almost completely after the HILDCAA event.

The effects observed during HILDCAAs are not related to the dissipation of the energy from the CIR storm. Typical ring current dissipation time scales are ~10 hrs. These recovery phases last days to weeks. Soraas et al. (2004) showed that HILDCAAs are due to freshly injected particles in the ring current, as shown in Fig. 9.

By the panels in Fig. 9, it is clear that proton injections are occurring during HILDCAA events, much later than the CIR storm. These injections occur mainly in L-shells higher than 4 (second and third panels from the top). Therefore, the Dst decreases during HIDLCAA events are not dissipative effects, but fresh injections occurring along the whole event (more details in Soraas et al., 2004).

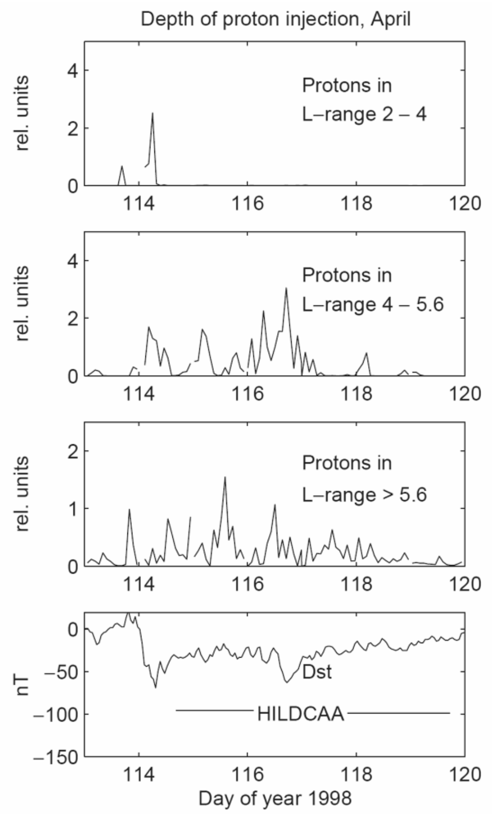

Fig. 9. Proton injection in distinct L-shells during a CIR storm followed by a HILDCAA event (taken from Soraas et al., 2004).

3. Conclusions

In general, the strongest storms are caused by ICMEs. These storms occur mainly during solar maximum, when the solar CME occurrences are more frequent. This type of storm does not always have the initial phase, but in the main phase the Dst may decrease by hundreds of nT. The recovery phase of a single-step ICME storm is, in general, shorter than the recovery phases of CIR storms.

"CIR magnetic storms" have initial, main and "recovery" phases. The initial phase is gradual and caused by the high density plasma from the heliospheric plasma sheet in front of the high speed stream. The main phases are weak to moderate in intensity, due to the highly fluctuating southward Bz components within CIRs. The "recovery" phases are not simply a "decay" of the ring current, but fresh energy is injected into the outer regions of the magnetosphere due to dayside magnetic reconnection associated with the southward component of the interplanetary Alfvén waves within the high speed streams. During these HILDCAA events, energization of killer electrons with energies in the range from 40 to 400 keV and higher occurs.

During some years in the solar cycle declining phase, there is more energy deposited into the magnetosphere than during solar maximum years, due to the long duration of the associated occurring phenomena.

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