Solar Wind Conditions Driving Geomagnetic Activity

PH37540: Project - Literature Review

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Abstract

This document constitutes a review of the literature concerning the solar-terrestrial environment for a project on the solar wind conditions and their effect on the Earth in respect to geomagnetic disturbances. A short introduction is included, consisting of an overview of the central physical concepts and the project. Sub-sections concerning the main topics of research in the field then follow, along with a conclusion critically reviewing the literature as a whole.

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Introduction

The solar-terrestrial environment encompasses the coupled system of the Sun and the Earth in space, connected by the solar wind. Specifically, this refers to regions in the near vicinity of the Earth, such as the magnetosphere, which are in turn affected by processes occurring in the solar interior and the solar atmosphere. The field of solar-terrestrial physics has roots in the past as well as that of modern research today. The rate of progress in research on the solar-terrestrial environment in recent decades has been attributed to the availability of observational data from satellites, especially in the near-Earth environment. Interplanetary spacecraft have also observed the solar atmosphere and solar wind in detail (Kamide and Chian, 2007).

The project undertaken by the authors focuses on the nature of solar wind conditions and how these conditions influence geomagnetic activity in the near vicinity of the Earth. As the solar wind is heavily dependent on solar activity, the solar cycle likely plays a significant role in the variations seen in the solar wind. These variations in turn affect geomagnetic activity, but it is unlikely that a one-to-one relationship is present as the solar wind couples both the solar and terrestrial environments. The aim of the project is to explore the physical nature of this relationship. This aim will be achieved by studying geomagnetic disturbances measured at Earth using magnetometer data in terms of geomagnetic indices, and solar wind conditions as detected by the Advanced Composition Explorer (ACE) spacecraft. In addition, interplanetary manifestations of solar processes such as interplanetary coronal mass ejections, magnetic clouds, and corotating interaction regions and their influence on geomagnetic activity will be considered.

1 The Solar Environment

The dynamical processes that occur in the convection region of the Sun gives rise to the solar dynamo, which is responsible for the solar magnetic field that in turn controls solar activity (Kamide and Chian, 2007). The solar magnetic field creates a highly structured corona and away from the photosphere, is approximately a dipole whose axis is tilted from the rotational axis of the Sun. This tilt varies as the magnetic field evolves over the solar cycle (Gosling and Pizzo, 1999). The variation in solar activity, the solar cycle is, therefore, inherently linked to solar magnetic fields (Kamide and Chian, 2007). The most prominent cycle of solar activity of 22-years is revealed by variations of the solar magnetic field in sunspots. This cycle is broken down further into 11-year cycles that occurs with the reversal of polarity of sunspots, as shown in Figure 1 (Vasilyev and Makarov, 1996, Benevolenskaya, 1994, Cliver et al., 1996).

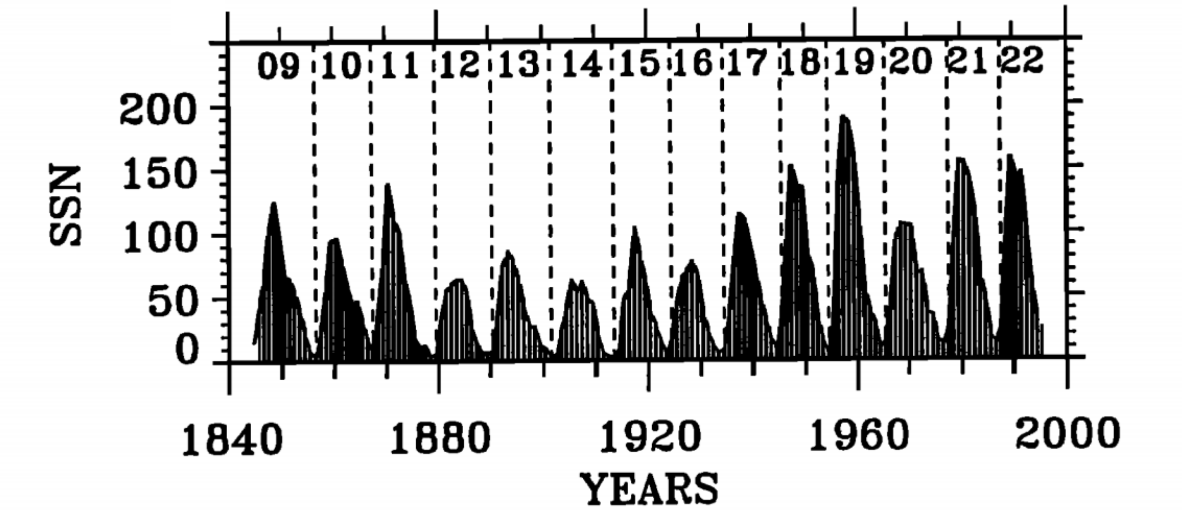

Figure 1 – *Graph illustrating the 11-year solar cycle with yearly averages of sunspot number (SSN) from 1844-1994. Typically, there are more sunspots in a preceding odd cycle than its successive even one in the 22-year solar magnetic cycle (Cliver et al., 1996).*

The solar atmosphere is very structured and quite dynamic in nature with several phenomena being associated with solar activity (Kamide and Chian, 2007). In particular, coronal holes are observed as dark regions in X-ray and EUV images because they are cooler and less dense than surrounding coronal layers. Coronal holes are most prevalent during the declining phase of the solar cycle (Kutiev et al., 2013, Le Mouel et al., 2012, Gopalswamy, 2008, Kamide and Chian, 2007, Tsurutani and Gonzalez, 1997). Another form of solar activity are coronal mass ejections (CMEs). These are large-scale magnetized plasma structures originating from closed field regions such as active regions, filament regions, and active region complexes, propelled outward into interplanetary space in huge loops. CMEs are dominant during solar maximum (Mustajab and Badruddin, 2011, Badruddin and Singh, 2009, Gopalswamy, 2008, Kamide and Chian, 2007).

2 The Solar Wind

Due to the nature of solar atmospheric plasma and the frozen-in magnetic field, both are highly coupled to each other, affecting the dynamics of the plasma (Kamide and Chian, 2007). The solar wind arises from the expansion of the solar corona, forming a supersonic flow of plasma and magnetic flux that infiltrates the interplanetary medium. Its variation directly controlled by the solar magnetic field (Gosling and Pizzo, 1999, Kamide and Chian, 2007). The interplanetary magnetic field (IMF) at Earth's orbit is an extension of the large-scale solar magnetic field connected by the solar wind (Georgieva et al., 2005). Solar wind conditions are considerably affected by the heliospheric current sheet (HCS), with speed increasing and density decreasing away from the HCS (Gosling and Pizzo, 1999, Tsurutani and Gonzalez, 1997). The solar wind is strongly coupled with solar activity and thus the solar cycle, allowing for the transmission of solar variability to the Earth (McComas et al., 2003). The rotation of the Sun causes solar wind magnetic field lines to wind up into a spiral shape, displaying a recurrent 27-day pattern, as shown in Figure 2 (Kamide and Chian, 2007).

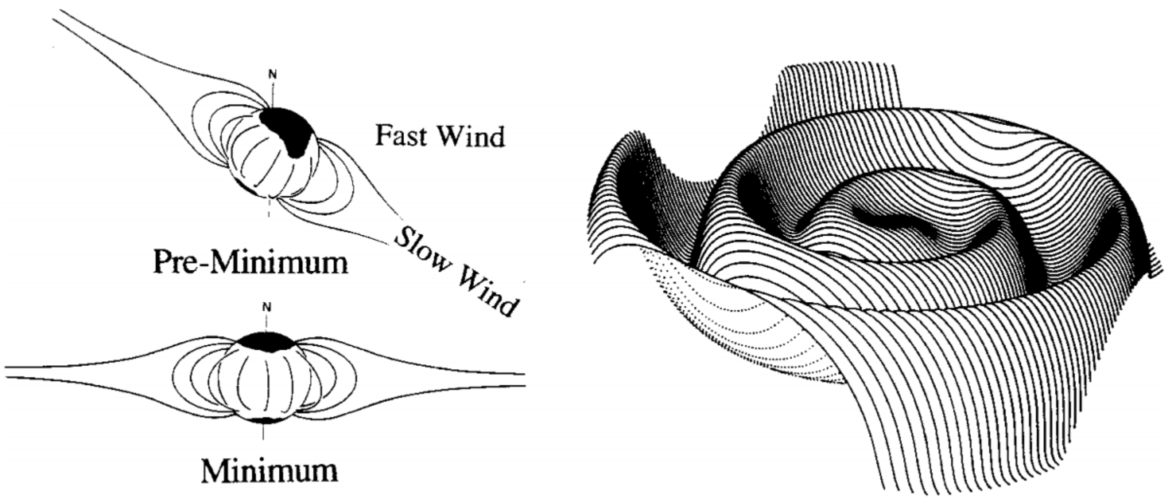

Figure 2 – *Left: image illustrating the changing tilt of the solar magnetic field and coronal structure over the solar cycle. The dark regions indicate coronal holes. Right: an idealised configuration of the HCS in interplanetary space whilst the solar magnetic field is significantly tilted (Gosling and Pizzo, 1999).*

There are two main types of solar wind. Slow solar wind is dense and usually has a velocity of 250-400 km/s. During solar minimum, slow wind originates from regions near the HCS at the solar magnetic equator. During solar maximum, slow wind tends to initiate from coronal helmet streamers in active regions near the magnetic equator where magnetic field lines are closed (Gosling and Pizzo, 1999). At high latitudes in the solar atmosphere, coronal expansion is not constrained as much by the magnetic field. This results in low density regions in the solar atmosphere, called coronal holes, where magnetic field lines are open (Krieger et al., 1973, Gosling and Pizzo, 1999, Kamide and Chian, 2007, Tsurutani and Gonzalez, 1997). In turn, these coronal holes are the sources of high-speed streams (HSS) that have low densities, and typical velocities of between 400-800 km/s (Gosling and Pizzo, 1999, Kutiev et al., 2013, Kamide and Chian, 2007, Tsurutani et al., 2011).

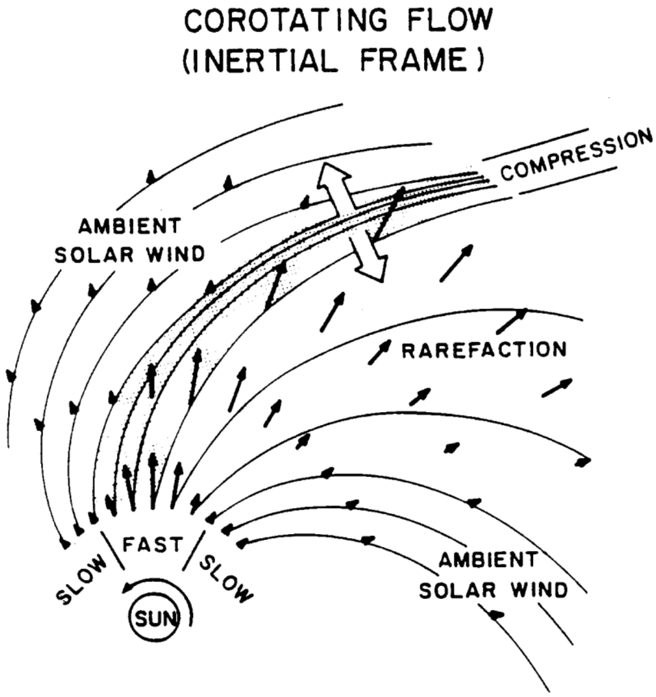

Figure 3 – *Schematic 2D diagram illustrating the structure of corotating interaction regions, in the solar equatorial plane in the inner heliosphere. These structures corotate with the rotation of the Sun (Pizzo, 1978).*

HSS, when emanating away from the sun, interact with the slow solar wind and create a co-rotating interactive region (CIR) that corotates with the Sun, as shown in Figure 3. Since coronal holes can last for longer than one solar rotation (27 days), a single one can produce multiple CIRs (Pirvutoiu et al., 2008, Mustajab and Badruddin, 2011, Kamide and Chian, 2007, Tsurutani et al., 2006, Tsurutani et al., 2011). As the plasma originates at different positions on the Sun at different times, their confined magnetic fields are different, preventing them from interpenetrating. The lack of penetration of magnetic flux leads to the formation of a compression in front of the high-speed stream and rarefaction behind it. At large distances from the Sun, these pressure waves typically become forward and reverse shocks (Gosling and Pizzo, 1999, Kamide and Chian, 2007).

3 The Terrestrial Environment

When the solar wind reaches the Earth, it impinges on the Earth's dipolar magnetic field. It is slowed down and then deflected around the Earth, creating a cavity in interplanetary space called the magnetosphere. The kinetic pressure of the solar wind compresses the dayside terrestrial magnetic field, whilst the nightside magnetic field is elongated into the magnetotail (Kamide and Chian, 2007). The physical state of the of the magnetosphere is a result of the variability of the solar wind and IMF. This is a result of the variability of processes in the corona and thus the solar magnetic cycle (Saiz et al., 2013, McPherron et al., 2008, Pulkkinen et al., 2007, Georgieva et al., 2005). The solar wind applies stress to the terrestrial magnetic field in the forms of dynamical, thermal and magnetic pressure. Two primary processes, viscous interaction and magnetic reconnection apply these types of pressure. Magnetic reconnection is relevant in the context of geomagnetic activity, and its effect on the magnetosphere heavily depends on the nature of the component of the IMF. The solar wind dynamic pressure is imperative in terms of magnetospheric configuration, dynamics and energetics (Pulkkinen et al., 2007, McPherron et al., 2008).

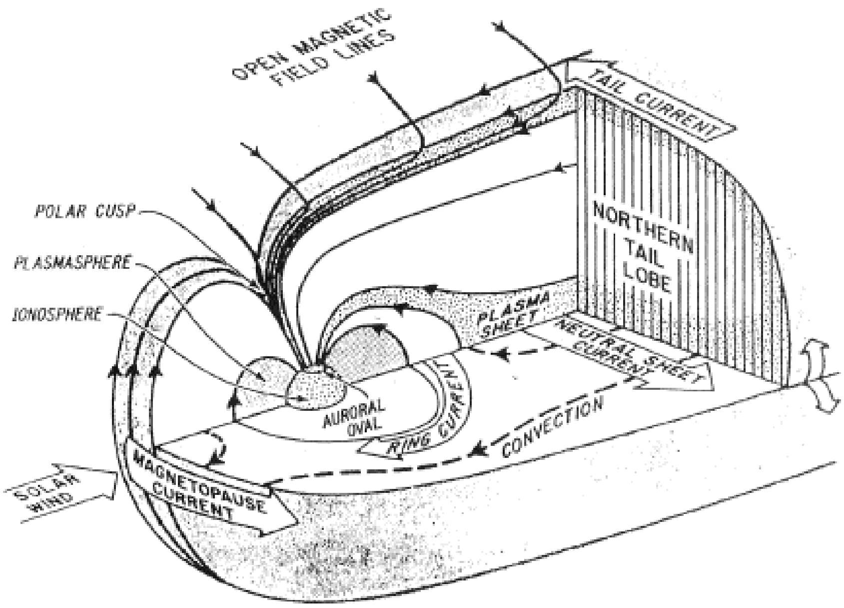

Figure 4 – *Schematic diagram illustrating the basic configuration of the magnetosphere, along with the various currents that circulate within it (Stern, 2006).*

For a northward IMF that is parallel to the dayside terrestrial magnetic field, reconnection connects IMF field lines to open field lines in the magnetotail, driving field-aligned currents. These currents however only create weak magnetic disturbances. Therefore, times when the solar wind carries a northward IMF are considered geomagnetically quiet and hence termed quiet periods. For southward IMFs transported by the solar wind, which are antiparallel to the terrestrial magnetic field in the dayside magnetosphere, the situation is radically different. The IMF field lines connect to closed, dipole field lines near the sub-solar point of the magnetopause. Magnetic reconnection then occurs in the tail, creating a convectional system (McPherron et al., 2008). If the IMF remains southward for long periods, the magnetosphere responds in a variety of ways, where such periods are considered geomagnetic disturbances (McPherron et al., 2008, Gopalswamy, 2008, Tsurutani et al., 2011).

4 Geomagnetic Activity

As the Sun and the Earth are related through their coupling to the solar wind, geomagnetic activity results from the interaction of the solar wind with the magnetosphere. This activity is affected by solar wind parameters such as the IMF and speed. The complex interplay between the fields of the solar wind and the Earth produce electric currents and hence magnetic field variations that can be detected at the surface of the Earth (Le Mouel et al., 2012). The ring current, which flows around the Earth in a westward direction, is one of these currents that describes geomagnetic activity on a global scale. These currents are directly coupled to the dynamic pressure of the solar wind, which depends on the velocity and density of the wind, and the dusk-dawn component of the interplanetary electric field. This electric field in turn depends on the southward component of the interplanetary magnetic field. The variations in any of these parameters are the origin of disturbances in the geomagnetic field, known as geomagnetic activity (Kamide and Chian, 2007, Crooker et al., 1977).

Geomagnetic indices such as *Dst*, K_p, *aa*, *ap*, *AL*, *AU* and *AE* are a measure of geomagnetic activity over relatively short periods of time. providing information on the response of the magnetosphere to changes in solar activity (Kutiev et al., 2013, Le Mouel et al., 2012, Kamide and Chian, 2007, Gonzalez et al., 1994, Arora et al., 2014). They can be divided into two classes: mean and range, reflecting different interactions over different time scales, and hence different properties of geomagnetic activity. Mean indices have a great advantage in that they can monitor a single well-defined phenomenon whilst the range indices are widely used for precursors of solar cycle prediction (Le Mouel et al., 2012). An important mean index is the Dst index, which measures the development and intensity of the ring current and hence, magnetic storms, over time (Le Mouel et al., 2012, Szajko et al., 2013, Kamide and Chian, 2007, Fuller‐Rowell et al., 1997, McPherron, 1997). It is constructed from horizontal component recordings of the geomagnetic field for the five quietest days of the relevant month, after the removal of regular daily variations (Le Mouel et al., 2012, Kamide and Chian, 2007).

The most fundamental type of geomagnetic activity is the substorm, characterised by a high-latitude increase in current intensity (Russell, 2000, Pulkkinen et al., 2007, Kamide and Chian, 2007). In general, a substorm occurs in three stages: growth, expansion and recovery (McPherron et al., 2008, Akasofu, 1964, Pulkkinen et al., 2007, Kamide and Chian, 2007, Tsurutani and Gonzalez, 1997). Substorms typically have durations of one to three hours (Russell, 2000, McPherron et al., 2008). There is no consensus yet on how substorms are initiated (Pulkkinen et al., 2007, Huang et al., 2003, Gonzalez et al., 1994). When the coupling of the solar wind to the magnetosphere is high and extends over long periods, such as several days, it leads to a global geomagnetic storm. Magnetic storms are the dominant dynamic process in the terrestrial environment (Russell, 2000, McPherron et al., 2008, Saiz et al., 2013, Daglis, 1997, Rostoker et al., 1997, McPherron, 1997). In general, magnetic storms are characterised by three phases: an initial phase, the main phase and a recovery phase (McPherron, 1997, Gonzalez et al., 1994). A geomagnetic storm usually starts with a sudden increase in the geomagnetic field at the Earth's surface, the storm sudden commencement (SSC) (Kamide and Chian, 2007, Tsurutani and Gonzalez, 1997, Gonzalez et al., 1994). This initial phase is followed by a decrease in Dst, which is known as the storm main phase. It is followed by a rapid first recovery period followed by a long, slow second recovery phase. The main phase of geomagnetic storms is characterised by the frequent occurrence of intense substorms (Tsurutani and Gonzalez, 1997, Gonzalez et al., 1994). The variety in the development of magnetic storms is very complex (McPherron et al., 2008, Kamide and Chian, 2007, McPherron, 1997).

The primary causes of magnetic storms are thought to be intense, long-duration interplanetary magnetic fields in the southward direction (Barkhatov et al., 2006, Tsurutani and Gonzalez, 1997). These fields are directly coupled to the solar wind electric field (Pulkkinen et al., 2007). The sources of these fields vary over the course of the solar cycle (Tsurutani and Gonzalez, 1997). The conventional division of magnetic storms is according to their intensity, based on the minimum of Dst during the period of the main phase of a storm (Loewe and Prolss, 1997, Gopalswamy et al., 2008, Gopalswamy, 2008, Szajko et al., 2013, Barkhatov et al., 2006). Interplanetary CMEs (ICMEs) and CIRs are the two large-scale IP structures that cause geomagnetic activity when the IMF has a southward component, as shown in Figure 5 (Stauning, 2013, Russell, 2000). This interaction is different for solar wind dominated by each of these IP structures (Badruddin and Singh, 2009). The ability of IP magnetic structures in causing geomagnetic storms is referred to as geoeffectiveness (Gopalswamy, 2008, Szajko et al., 2013). Moderate and weak storms are usually caused by both CIRs and ICMEs, whilst intense ones are mostly caused by ICMEs (Gosling et al., 1991, Gopalswamy et al., 2008, Gopalswamy, 2008, Saiz et al., 2013, Fuller‐Rowell et al., 1997).

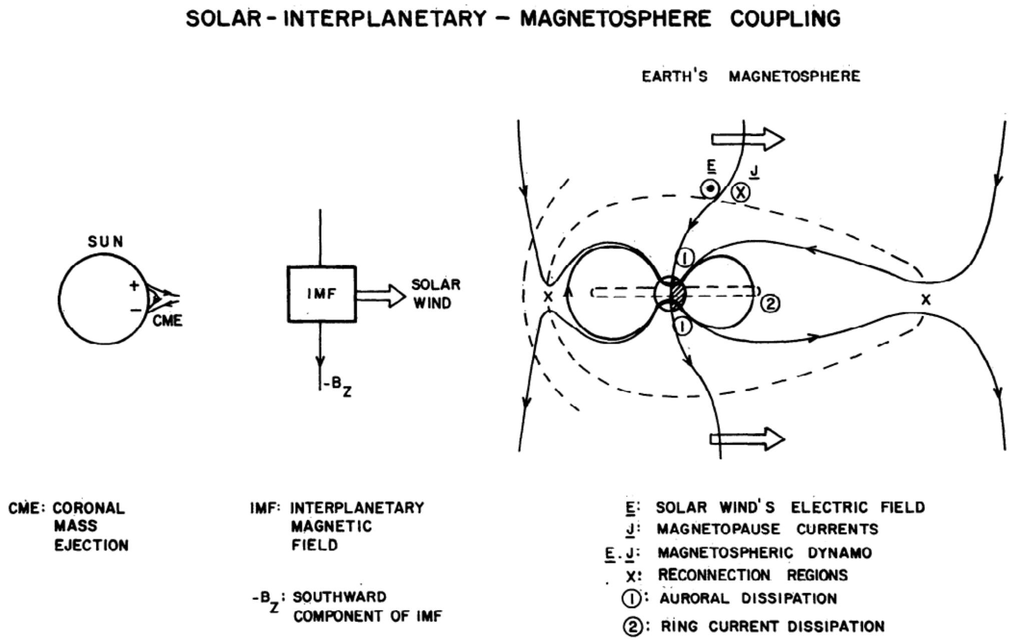

Figure 5 – *Schematic illustrating solar-terrestrial coupling in relation to ICME driven storms at solar maximum. The coupling is similar in the declining phase of the solar cycle with CIR structures possessing southward IMF components (Gonzalez et al., 1994).*

ICME is a general name given to various types of IP structures of the solar wind resulting from CMEs. Magnetic clouds (MCs) are a subset of ICMEs that have enhanced magnetic field and smooth magnetic field rotation (Gopalswamy, 2008, Saiz et al., 2013, Badruddin and Singh, 2009, Gopalswamy et al., 2008, Georgieva et al., 2005, Tsurutani and Gonzalez, 1997). The magnetic field often rotates from north to south or vice versa and is usually elongated along its axis, forming a flux rope (Badruddin and Singh, 2009, Georgieva et al., 2005, Tsurutani and Gonzalez, 1997). Hence, these clouds can cause magnetic storms followed by geomagnetic quiet conditions or vice versa (Tsurutani and Gonzalez, 1997). ICMEs without flux-rope structures are referred to as ejecta or non-cloud ejecta (Gopalswamy et al., 2008). CIRs often have intense magnetic fields, which is important in respect to geomagnetic activity

(Gopalswamy, 2008, Tsurutani and Gonzalez, 1997). Due to a lack of shocks with CIRs, where is often not an SSC. The actual CIR is responsible for the main storm phase. If there is a reverse shock, this is the start of the recovery phase where the magnetic field (of the CIR) decreases rapidly (Tsurutani and Gonzalez, 1997). ICMEs are more geoeffective than CIRs, however, CIR-associated geomagnetic disturbances extend for longer durations (Mustajab and Badruddin, 2011, Barkhatov et al., 2006, McPherron et al., 2008, Tsurutani and Gonzalez, 1997, Tsurutani et al., 2006).

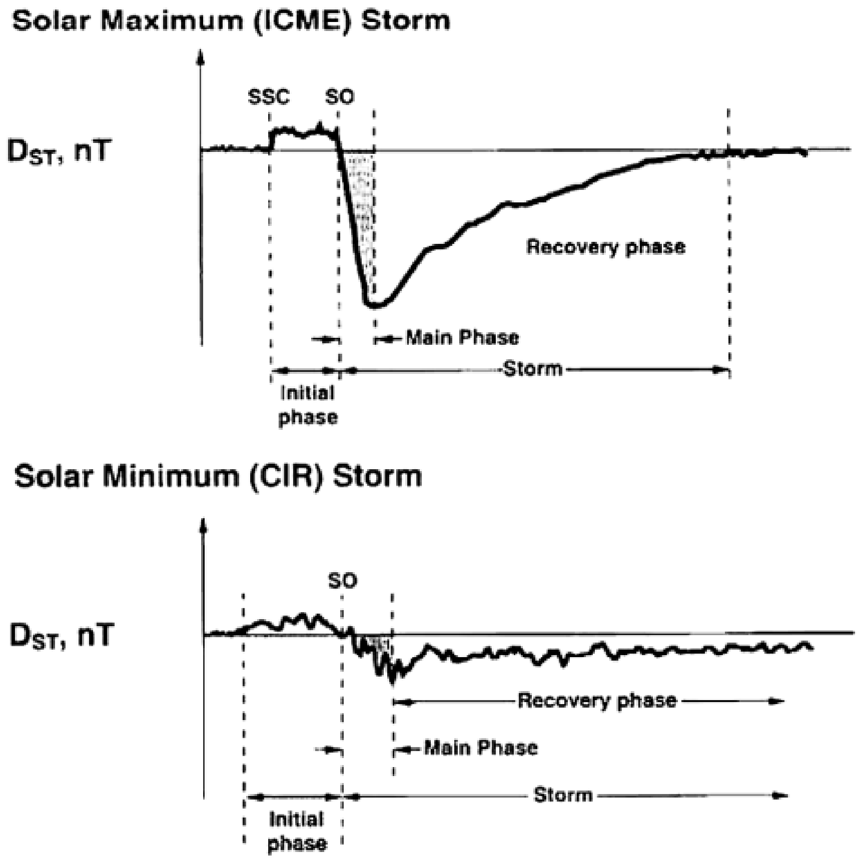

Figure 6 – *Schematic comparing the variation in the Dst index for ICME and CIR driven geomagnetic storms. ICME driven storms are much more geoeffective than their CIR counterparts (Tsurutani et al., 2006).*

Gradual commencement magnetic storms have no SSC or initial phase and are primarily caused by CIRs. These storms are usually quite weak but are long-lived. These storms most commonly occur in the declining phase of the solar cycle when recurrent high-speed streams are common. Sudden commencement storms are mostly caused by ICMEs. ICMEs are most common during solar maximum. ICME produced storms are much larger than their CIR counterparts, as shown in Figure 6 (McPherron et al., 2008, Barkhatov et al., 2006, Tsurutani and Gonzalez, 1997). CIRs often cause recurring geomagnetic storms (Le Mouel et al., 2012, Tsurutani and Gonzalez, 1997, Tsurutani et al., 2006, Cliver et al., 1996). Geomagnetic activity is understood to vary over a 22-year cycle, with high activity during the latter half of even-numbered solar cycles and during the former half of odd-numbered cycles (Cliver et al., 1996).

Conclusion

From the review of the literature regarding the solar-terrestrial environment in respect to geomagnetic activity, it is quite clear that the magnetosphere is directly connected to the solar atmosphere through the coupling of the solar wind. Due to this connection, it is quite logical to expect that geomagnetic activity has some inherent link to solar magnetism and activity, and thus will show some variation over the 22-year and 11-year solar cycles. The 11-year variation has been verfied by numerous papers concerned with this topic, for example, Echer et al. Unfortunately, the 22-year variation has only been investigated by a few, such as Cliver at al. However, as the solar wind mediates the connection between the solar and terrestrial environments, its intense variability creates a complex relationship that is very difficult to understand. Whilst some studies have managed to deduce certain details about this relationship, such as ICME dominated geomagnetic activity at solar maximum and CIR dominated activity during the declining phase of the cycle, a full description of this relationship is far from complete.

Global geomagnetic indices are more relevant in respect to the undertaken project, due to the study of average global conditions over a long period. The *Dst*, *aa* and A_p indices are most commonly found in literature analysing some aspect of geomagnetic activity over the solar cycle. The *Dst* index reflects the evolution of the IMF whilst *aa* and A_p reflect the solar wind dynamic pressure and thus inherently the solar cycle. In respect to the project, a combination of these indices will be useful in addressing the research aim. In respect to different solar wind structures, it is expected that ICMEs are the cause of a peak in geomagnetic indices, that follow the cycle, near solar maximum and that CIRs are the result of a secondary maximum during the declining phase of a solar cycle.

One of the major issues in the literature that arose during this review was the fact that the relationship of geomagnetic activity with the solar over odd and even cycles was not appropriately addressed, with just Cliver et al. researching into this matter. As the solar magnetic field undergoes polarity reversals over the 22-year magnetic cycle, solar wind IP structures are likely affected, since magnetism controls significant aspects of solar activity. Due to this, it is expected that the relationship may differ for odd and even cycles. This difference is a possibly for exploration in the project. Another subject not sufficiently covered in the literature was the geoeffectiveness of different types of geomagnetic storms, in terms of their intensity. Less intense storms may have a better correlation with the solar cycle, which in turn may be due to their related interplanetary structures. Conversely, he opposite may be the case, with more intense storms correlating better with the solar cycle. This could be a way in which the project could be expanded, if time permits.

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