Long-term variations of solar, interplanetary and geomagnetic indices

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Abstract: The long-term variations of the 12-month running means of several solar, interplanetary and geomagnetic parameters during the last several sunspot cycles revealed that the sunspot numbers Rz showed smooth but broad maxima for 3 years in each cycle, the geomagnetic aa index showed several peaks within 5 years around the sunspot maxima, with some peaks during the declining phases of the sunspot cycles. The 11-year running means showed very good correlation between Rz, aa index and global sea surface temperature (SST). Rz and F10 (2800 MHz radio emission) showed similar 11-year fluctuations of varying amplitudes, but coronal index CI showed monotonically increasing amplitudes by almost a factor of two. The open magnetic flux emanating from the Sun showed long-term fluctuations very different at low and high solar latitudes. The variations of the fluxes at low latitude (0-45°) were almost parallel to the sunspot cycle (there was a slight N-S asymmetry), while fluxes at high latitudes (45°-90°) were almost anti-parallel to the sunspot cycle. Cosmic ray neutron monitor intensities at two different neutron monitoring stations were well anti-correlated with sunspot cycle and interplanetary magnetic field B but poorly correlated with interplanetary number density N, solar wind speed V, and geomagnetic index aa. The geomagnetic index aa was best correlated with the product VB.

Keywords: cosmic ray, solar activity, solar wind, interplanetary magnetic field.

1 Introduction

Geomagnetic activity results from the interaction (compression and magnetic reconnection) between the solar wind and the magnetosphere. It is characterized by geomagnetic indices (Mayaud, 1980), which are driven by some combination of the following solar wind variables and system parameters: 1. The interplanetary magnetic (B) flux per unit time and area, BV; 2. The solar wind momentum (nm V) flux per unit time and area, (nm V)V; 3. The angles between the Earth’s magnetic field and the IMF direction (a) and flow direction (w); 4. The time scale of interest (hours to days) and the variability within that. In early studies, interplanetary solar wind data have been used to indirectly infer the nature of solar sources of geomagnetic storms. There are in general two kinds of solar sources, CMEs and corotating interaction regions (CIRs). The CME counterparts in interplanetary space, conventionally called interplanetary CMEs (ICMEs), can be verified by various solar wind signatures including magnetic clouds (Burlaga et al. 1981; Klein & Burlaga 1982) and bidirectional electron fluxes (Gosling et al. 1987). Other solar wind features can also be used as CME signatures (Richardson & Cane 1995). ICMEs are geoeffective because of either the enhancement of an interplanetary magnetic field compressed by CME-driven shocks or the presence of strong magnetic fields carried by CMEs themselves, or both (Bothmer & Schwenn 1998; Tsurutani 2001). CIRs are compressed solar wind structures that occur when a fast-speed stream originating in open magnetic field coronal holes catches up with a preceding slow-speed stream originating from a relatively closed magnetic structure (Smith & Wolfe 1976; Gosling & Pizzo 1999). Both CMEs and CIRs contribute to minor and moderate geomagnetic storms (Lindsay, Russell, & Luhmann 1995). Nevertheless, major geomagnetic storms are found to be mainly caused by CMEs (Gosling et al. 1990; Bothmer & Schwenn 1995; Tsurutani & Gonzalez 1998).

A combination of remote sensing solar observations and in situ solar wind observations provides an integrated approach to the identification of the solar sources of geomagnetic storms. Earlier efforts to establish individual Sun-Earth connections have been based on presumed CME proxies, including disappearing solar filaments (Joselyn & McIntosh 1981; Rust 1994; Bothmer & Rust 1997), erupting features in X-ray coronal images (McAlister et al. 1996; Weiss et al. 1996), and long-duration soft X-ray flares (Sheeley et al. 1975; Landi et al. 1998). Since the advent of SOHO, a comprehensive approach has become possible due to the CME observations of the Large Angle and Spectrometric Coronagraph (LASCO; DOI: 10.7529/ICRC2011/V11/0394
Brueckner et al. (1995) and coronal observations of the EUV Imaging Telescope (EIT; Delaboudinière et al. 1995). Recent studies (Brueckner et al. 1998; Webb et al. 2000) have established the geoeffectiveness of halo CMEs. Halo-type CMEs, first discovered by Howard et al. (1982), appear with a full or partial circular shape surrounding the Sun and presumably have a component moving along the Sun-Earth line. Statistical studies have found that the CME transit time from the Sun to the near-Earth space falls in between 1 and 5 days and coarsely depends on the CMEs’ initial speed (Gopalswamy et al. 2000; Cane, Richardson, & Cyr 2000).

2 Data Analysis

The data used in this investigation were obtained from the NSSDC as either binary CDFs or ASCII files. For download we selected a subset of the original data corresponding to plasma and magnetic field measurements in GSE coordinates. These data were interpolated to 1-minute resolution using cubic splines. The data were then propagated to the subsolar bow shock (+17 Re, 0, 0) using a modified version of the Weiner minimum variance algorithm [Bargatze; 2005; Weimer et al., 2003]. At the chosen point the data were again interpolated to 1-minute samples and the results transformed to GSM coordinates.

3 Results and Discussion

In the 5 yr period from 1996 January to 2000 December, 38 major geomagnetic storms have been observed based on the disturbance storm time (Dst nT) index. The Dst is derived from hourly horizontal magnetic variations recorded in a network of near-equatorial geomagnetic observatories. The variations of the horizontal-component field on the ground are believed to be caused by the changes in the global high-altitude equatorial ring current, which in turn depends on solar wind conditions. A geomagnetic storm is classified as a major storm if the index at the peak time is less than or equal to -100 nT. We note that the Kp index (3 hr 09 scale index measured by middle-latitude observatories, in contrast to the Dst by near-equatorial observatories) has also been used to measure the intensity of geomagnetic storms. There are a total of 28 major Kp events with Kp 7 in the 5 yr period investigated. Among the 38 Dst major events, 20 of them are also Kp major events. Clearly, there are significant differences between sets of major geomagnetic storms defined by the two indices. at cause these magnetic storms. Instead it is the interaction region between the high-speed stream and the slow solar wind ahead of it that creates the conditions that drive geomagnetic activity (see Balogh et al. [1999] for summary of properties of CIRs). This region is centered on the interface between the two streams [Gosling et al., 1978]. Because of the interplanetary magnetic field (IMF) the two streams can not interpenetrate. Consequently the high-speed plasma is slowed and deflected east of the Sun while the slow-speed plasma is accelerated and deflected west of the Sun. The plasma and magnetic field on either side of the interface is compressed with the total pressure and total magnetic field rising to peak values at the interface. Since the Sun is rotating the stream interface is a spiral intermediate to that expected in the two streams. The peak in plasma pressure at the interface propagates outward into both streams carrying information about the presence of the interface. Inside of 1 AU these are ordinary pressure waves, but beyond this distance changes in the properties of the solar wind with distance cause these two waves to develop into shocks. The region between the two waves is called a corotating interaction region or CIR.

There are several factors associated with the CIR that cause geomagnetic activity. First is the compression of the magnetic field [Belcher and Davis, 1971]. A stronger magnetic field means a larger z-component of the magnetic field in GSM coordinates. When this component is negative the IMF merges with the Earth’s magnetic field and drives magnetic activity. Second is the possibility that there is an increase in the fluctuations of the IMF near the interface because of the shear in velocity across the interface [Belcher and Davis, 1971]. More and larger fluctuations lead to stronger GSM Bz and more geomagnetic activity. A third and more important factor is that high-speed streams tend to be filled with Alfven waves propagating away from the Sun [Belcher and Davis, 1971]. Following the interface the field contains large amplitude fluctuations, which if southward in GSM coordinates, drive activity. Finally, a fourth factor is the high solar wind velocity on the Sunward side of the interface. The actual driver of geomagnetic activity is the GSM dawn dusk electric field, VBz. The combination of large V and frequent strong intervals of southward Bz causes elevated geomagnetic activity.

The association of geomagnetic activity with stream interfaces leads to the possibility of forecasting geomagnetic activity based on predictions of the arrival of the interface. Activity is weak before the interface, very strong at the interface, and then decaying slowly after the interface. This type of forecasting has been referred to as “probabilistic forecasting by air mass climatology” [McPherron and Siscoe, 2004].

4 Conclusion

Corotating interaction regions during the declining phase of the solar cycle are the cause of recurrent geomagnetic storms and are responsible for the generation of high fluxes of relativistic electrons. These regions are produced by the collision of a high-speed stream of solar wind with a slow-speed stream. The interface between the two streams is easily identified with plasma and field data from a solar wind monitor upstream of the Earth. The properties of the solar wind and interplanetary magnetic field are systematic functions of time relative to the stream interface. Consequently the coupling of the solar wind to the Earth’s magnetosphere produces a predictable sequence of events. Because the streams persist for many solar rotations it should be possible to use terrestrial observations of past magnetic activity to predict future.
activity. Also the high-speed streams are produced by large unipolar magnetic regions on the Sun so that empirical models can be used to predict the velocity profile of a stream expected at the Earth. In either case knowledge of the statistical properties of the solar wind and geomagnetic activity as a function of time relative to a stream interface provides the basis for medium term forecasting of geomagnetic activity.

5 References


