Journal of Atmospheric and Solar-Terrestrial Physics 107 (2014) 12–19

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

Why have geomagnetic storms been so weak during the recent solar minimum and the rising phase of cycle 24?

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ARTICLE INFO

Article history:
Received 6 March 2013
Received in revised form
15 October 2013
Accepted 1 November 2013
Available online 8 November 2013

Keywords:
Geomagnetic storms
Interplanetary coronal mass ejections
Solar wind
Solar cycle

ABSTRACT

The minimum following solar cycle 23 was the deepest and longest since the dawn of the space age. In this paper we examine geomagnetic activity using *Dst* and *AE* indices, interplanetary magnetic field (IMF) and plasma conditions, and the properties and occurrence rate of interplanetary coronal mass ejections (ICMEs) during two periods around the last two solar minima and rising phases (Period 1: 1995–1999 and Period 2: 2006–2012). The data is obtained from the 1-h OMNI database. Geomagnetic activity was considerably weaker during Period 2 than during Period 1, in particular in terms of *Dst*. We show that the responses of *AE* and *Dst* depend on whether it is solar wind speed or the southward IMF component (B_S) that controls the variations in solar wind driving electric field (E_Y). We conclude that weak *Dst* activity during Period 2 was primarily a consequence of weak B_S and presumably further weakened due to low solar wind densities. In contrast, solar wind speed did not show significant differences between our two study periods and the high-speed solar wind during Period 2 maintained *AE* activity despite of weak B_S. The weakness of B_S during Period 2 was attributed in particular to the lack of strong and long-duration ICMEs. We show that for our study periods there was a clear annual north–south IMF asymmetry, which affected in particular the intense *Dst* activity. This implies that the annual amount of intense *Dst* activity may rather be determined by the coincidence of what magnetic structure the strong ICMEs encountering the Earth have than by the solar cycle size.

1. Introduction

The deep and long transition from solar cycle (SC) 23 to SC 24 has drawn a large amount of attention in the space physics community. Sunspots were practically absent during nearly two years (2008–2009), and Sun's polar magnetic fields were about 30–40% weaker than during the three previous minima (e.g., Wang et al., 2009). The solar magnetic field possessed a significant multipole component and long-lived coronal holes were observed frequently in low- and mid-latitude regions (e.g., Abramenko et al., 2010; Wang et al., 2010). These drastic changes in the Sun's global magnetic field magnitude and configuration have been reflected in the sources and properties of the ecliptic solar wind (e.g., Lee et al., 2009; Tokumaru et al., 2009; Jian et al., 2011).

The extensive comparison of solar wind properties during 1-year periods around the four most recent sunspot minima by Jian et al. (2011) showed that during the SC 23/24 minimum the interplanetary magnetic field (IMF) intensity and solar wind density were about 30% lower than during the three previous minima. The weak IMF and low densities resulted in weak solar wind dawn–dusk electric field (approximated here as $E_Y = -V_X B_Z$, where V_X is the X-component of the solar wind velocity and B_Z IMF north–south component) and low dynamic pressure ($P_{dyn} = \rho V^2$, where ρ is solar wind density and V solar wind speed). E_Y induces the large-scale magnetospheric and ionospheric convection and its variations correlate relatively well with the variations in geomagnetic activity indices (e.g., Dungey, 1961; Burton et al., 1975; Crooker and Gringauz, 1993; Ballatore, 2002; Kane, 2005). The solar wind–magnetosphere coupling efficiency may also depend on whether variations in E_Y are caused primarily by southward IMF component (B_S) or solar wind speed (Pulkkinen et al., 2007). High P_{dyn} further enhances solar wind–magnetosphere coupling leading to more intense activity (e.g., Murayama, 1982; Crooker and Gringauz, 1993; Fenrich and Luhmann, 1998; Kessel et al., 2003; Wang et al., 2003; Palmroth et al., 2004).

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1364-6826/$ - see front matter
http://dx.doi.org/10.1016/j.jastp.2013.11.001

Table 1
Thresholds for moderate and intense *Dst* and *AE* activity and (positive) solar wind driving electric field and IMF north–south component.

Parameter	Moderate	Intense
Dst	$-50\ \text{nT} < Dst \leq -100\ \text{nT}$	$Dst < -100\ \text{nT}$
AE	$500\ \text{nT} \leq AE \leq 1000\ \text{nT}$	$AE > 1000\ \text{nT}$
E_Y	$2.5\ \text{mV/m} < E_Y \leq 5\ \text{mV/m}$	$E_Y > 5\ \text{mV/m}$
$\lvert B_Z \rvert$	$5\ \text{nT} < \lvert B_Z \rvert \leq 10\ \text{nT}$	$\lvert B_Z \rvert > 10\ \text{nT}$

As a consequence, geomagnetic activity has been at a record low. Richardson and Cane (2012) showed that in 2009 the annual number of storms was at its lowest since the beginning of the *Kp* index recordings in 1932. Tsurutani et al. (2011) studied two years of low *ap* activity (2009 and 1997) and concluded that in 2009 exceptionally low *ap* values were related to the disappearance of equatorial and low latitude coronal holes leading to slow solar wind speeds, which reduced the solar wind–magnetosphere coupling. In addition, for the periods investigated by Jian et al. (2011), the *Dst* values were significantly lower during the SC 23/24 minimum than during the three previous minima. Richardson (2013) also showed that weak *Kp* activity has continued through the rising phase of SC 24 and there have been considerably fewer *Dst* storms than during the previous four solar cycles. This paper concluded that the lack of severe storms was due to the lack of fast ICMEs with intense southward fields/large values of E_Y. The weak magnetic fields in ICMEs when compared to previous solar minima was also reported by Jian et al. (2011), Kilpua et al. (2011, 2012a). In addition, Jian et al. (2011) showed that the slow-fast stream interaction regions (SIRs) were weaker.

In this paper we investigate interplanetary causes of low geomagnetic activity (in terms of *Dst* and *AE*) during the whole transition from SC 23 to SC 24 and the rising activity phase of SC 24, and compare the observations to the corresponding phases from the previous solar cycle. We seek answers to the following questions: (1) What were the average solar wind conditions during the recent geomagnetic quietness, in particular was it B_S or solar wind speed that caused variations of E_Y, (2) what were the large-scale solar wind structures related to enhanced B_S periods in different solar cycle phases, and (3) whether there was significant asymmetry in the north–south IMF component, which could have affected the low levels of geomagnetic activity.

In Section 2 we will summarize the data and methods used in this work. In Section 3 we will give an overview of geomagnetic activity and present the statistics of the various solar wind parameters, ICMEs and north–south IMF asymmetry. In Sections 4 and 5, we discuss and summarize our results.

2. Data and methods

We investigate two periods around the two last solar minima and the rising activity phases. Our study periods were selected based on the availability of (nearly) continuous solar wind measurements and the phase of the solar activity cycle. Period 1 extends from the late declining phase of cycle 22 (year 1995) to the end of the rising phase of cycle 23 (year 1999). Period 2 extends from the late declining phase of cycle 23 (year 2006) through 2012. The maximum of cycle 24 is expected to occur in fall 2013 (http://solarscience.msfc.nasa.gov/predict.shtml), but due to a decline in activity during 2012–2013 following a peak in the sunspot number in late 2011, there is a possibility that solar maximum has already passed, or that cycle 24 will be doubled peaked. It should be noted that it is not straightforward to compare the activity during our two study periods since the transition from cycle 23 to cycle 24 was considerably longer and had much lower sunspot numbers.

The solar wind parameters and geomagnetic activity indices we use in this study are 1-h averages obtained from the Near-Earth Heliospheric data base (OMNI). During the 1995–1999 period, the OMNI database is created using measurements from Wind, ACE, IMP-8 and Geotail, while during the 2006–2012 period the data comes from Wind and ACE. During our study periods 1-h OMNI measurements were nearly continuously available without large data gaps that could have significantly affected our annual statistics.

Hourly *Dst* and *AE* values in the OMNI database are acquired through the World Data Center for Geomagnetism at University of Kyoto. *Dst* and *AE* are derived from different magnetometer networks, and thus represent different magnetospheric current systems (e.g., Mayaud, 1980; Rostoker, 1972) and have no one-to-one correspondence. *Dst* measures low-latitude global variations in the horizontal component of the geomagnetic field, and represents the strength of the equatorial ring current, while *AE* is the auroral electrojet index, reflecting the intensity of those high latitude currents. In addition, as *Dst* measures the energy stored in the ring current, it can stay depressed even though the solar wind energy input has weakened substantially in the storm recovery phase. In contrast, *AE* recovers more quickly to quiet time levels as it measures the rate of the energy input. Furthermore, it has been shown that these indices respond differently to different types of solar wind driving (Huttunen et al., 2002; Huttunen and Koskinen, 2004; Yermolaev et al., 2010, 2012). The thresholds we have used for moderate and intense geomagnetic activity are found in Table 1 and they are based on the classification by Gosling et al. (1991) and Gonzalez et al. (1994).

3. Results

3.1. Geomagnetic activity and interplanetary conditions

In this section we examine and compare the levels of geomagnetic activity and interplanetary conditions during our two study periods. Fig. 1 shows the sunspot number and the annual hours with moderate and intense activity in *Dst* and *AE* as well as the annual hours with moderate and intense E_Y.

For both periods the lowest levels of geomagnetic activity coincided with the lowest sunspot number levels, but it is clear from Fig. 1 that Period 2 featured much longer depression in the sunspot numbers and in geomagnetic activity. During Period 2 solar minimum years (2008–2009) geomagnetic activity levels were clearly lower than during the previous minima, and in particular *Dst* activity was minimal. Some moderate *AE* activity occurred in 2008, but in 2009 *AE* activity was also distinctly low when compared with the other investigated years. In contrast, during Period 1 significant amount of *AE* activity was maintained through all the years and it is interesting to note that in 1996 (Period 1 solar minimum year) moderate *AE* activity was almost equal to the activity in 1997 although *Dst* activity was significantly weaker in 1996. Geomagnetic activity levels were also clearly lower before and after the minimum for Period 2 than for Period 1. The clearest differences are in the intensity of *Dst* activity. For Period 2 significant increase in geomagnetic activity did not occur until 2012. It is also interesting to note that in 2012 *AE* activity was about at the same level as in 1998, which was the most active year of Period 1, but the *Dst* activity remained clearly below the values recorded in 1998.

The comparison of the annual hours of enhanced geomagnetic activity indices and E_y shows that the variations of moderate (intense) geomagnetic activity roughly follows the variations of moderate (intense) E_Y. The four-year quiescence in intense