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Characteristics of active regions associated to large solar energetic proton events ☆

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Abstract

The relationship between properties of active regions (ARs) and solar energetic particles (SEP events, protons with energy ⩾10 MeV) is examined. For this purpose we study 84 SEP events recorded during the SOHO era (1996–2014). We compare properties of these SEP events with associated ARs, flares and CMEs. The ARs are characterized by McIntosh classification. Statistical analysis demonstrates that SEP events are more likely to be associated to the ARs having complex magnetic structures and the most energetic SEPs are ejected only from the associated ARs having a large and asymmetric penumbra. This tendency is used to estimate intensities of potential SEP events. For this purpose we express a probability of occurrence of an SEP event from a given AR which is correlated with fluxes of associated SEPs. We find that SEP events associated with ARs from eastern longitudes have to be more complex to produce SEP events at Earth. On the other hand, SEP particles originating from mid-longitudes ($30^\circ <$ longitude $< 70^\circ$) on the west side of solar disk are associated to the least complex ARs. These results could be useful for forecasting of space weather.

Keywords: Sun: activity; Sun: coronal mass ejection (CMEs); Sun: particle emission; Sun: flares

1. Introduction

Coronal mass ejections (CMEs) are large expulsions of magnetized plasma from the Sun which are potentially harmful to advanced technology. Energetic CMEs can generate geomagnetic storms and solar energetic particles (SEPs) (e.g. Gopalswamy et al., 2007). Large SEP events, with intensity ⩾10 pfu (pfu = 1 particle $cm^{-2}\,s^{-1}\,sr^{-1}$) in the 10 MeV energy channel, cause immediate concern because they can reach Earth's vicinity in about an hour after their acceleration near the Sun. Understanding the mechanism by which SEPs are accelerated is a long-standing problem in solar physics (Cliver, 2009a,b). There is evidence for particle acceleration by two different processes (e.g. Reames, 1999): a flare reconnection process (for impulsive SEP events not accompanied by a CME) and a CME driven shock (for gradual SEP events and energetic storm particles). There were many attempts to identify a basic accelerator. The studies were based on determination of statistical correlation between SEP parameters, especially their peak intensity, and the basic attributes of flares or CMEs (Kahler, 2001; Gopalswamy et al., 2003; Cane et al., 2010; Cliver et al., 2012; Richardson et al., 2014). Results of these considerations were not conclusive because similar correlations were found for flare X-ray peaks and CME speeds as well. Therefore is widely accepted that large SEP events are usually associated with large flares and CME-driven shocks (Gopalswamy et al., 2015). Both flare and shock processes may contribute to the particle flux but the relative contribution is unclear (Cliver, 2009a; Klecker et al., 2007).

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Recently, Trottet et al. (2015) have been used the partial correlation analysis to determine the relation between the properties of CME (speed) and flares (peak flux and fluence of soft X-ray (SXR) emission, fluence of microwave emission) and the large SPE events. This analysis shown that the only parameters that affect significantly the SEP intensity are the CME speed and the SXR fluence.

It is well known that the source of solar eruptions (flares or CMEs) is the free energy stored in nonpotential magnetic field. This energy can be suddenly released through magnetic reconnection when evolution of magnetic field leads to unstable configurations. Frequently photospheric flows, flux emergence or canceling are responsible for building up energy and triggering eruption. These processes produce highly sheared (complex) magnetic field. Therefore there are two factors determining the solar eruptions: magnetic free energy stored in ARs (size) and unstable magnetic field configuration (tension of magnetic field). The tight linkage between shear flows and flare (Meunier and Kosovichev, 2003) and CME (Falconer et al., 2002) productivity was established. A high correlation between complexity of ARs and intensity of flares and velocity of CMEs was found (Guo et al., 2006). Therefore complex active regions, including highly sheared magnetic field, tend to produce large flares and CMEs (e.g. Zirin and Liggett, 1987; Sammis et al., 2000). It is also widely accepted that complex active regions tend to produce large flares and CMEs (e.g. Zirin and Liggett, 1987; Sammis et al., 2000). The most energetic CMEs and flares originate from large active regions (ARs) that have closed magnetic structures and sufficient stored magnetic energy (Liu et al., 2006; Michalek and Yashiro, 2013). If these large eruptive events (flares or CMEs) originate from the western hemisphere they may accelerate SEPs (see e.g. McCracken, 1962). Recently, many statistical studies have investigated the types of solar events which produce solar energetic particles. These studies mostly concentrated on the dependence of SEP events on various parameters of the associated flares or CMEs (e.g. Kahler, 2001; Gopalswamy et al., 2008; Richardson et al., 2014; Dierckxsens et al., 2015).

The ARs may be classified in terms of the morphology of the sunspot groups. The most common classification of ARs was introduced by McIntosh (1990). The McIntosh Sunspot Classification Scheme (MSCS) assigns three descriptive codes characterizing the size (A, B, C, D, E, F, H), penumbra (X, R, S, A, H, and K) and compactness (X, O, I, and C) of ARs. The paper by Michalek and Yashiro (2013) describes the McIntosh classification in greater detail. To improve the readability of the paper we include Table 1 that shortly explains the MSCS. The MSCS may be used as a proxy for magnetic structures in the ARs and, hence, is expected to correlate with the production of CME-driven shocks generating SEPs. Bornmann et al. (1994) showed that most ARs (35%) have simple magnetic structures classified as AXX or BXX, and they also studied the rates of transition between classes. The relation of flare rate per day with McIntosh class was considered by Bornmann and Shaw (1994). Recently, Michalek and Yashiro (2013) considered the relationship between the ARs and coronal mass ejections (CMEs). They demonstrated that speeds of CMEs are correlated with McIntosh class and the fastest CMEs can be ejected only from the most complex classes of ARs.

The dynamic pressure of the solar wind dominates over the magnetic pressure in the inner heliosphere, so the solar magnetic field is pulled into an Archimedean spiral pattern due to the combination of the outward motion and the Sun's rotation (Smith, 2001). The motion of charged particles from the Sun is constrained by this magnetic field pattern. Hence the location of the source is very important for characteristics of SEP events. Events from the western hemisphere generally have better magnetic connectivity to the Earth than those from the eastern hemisphere, so western events are more likely to produce large SEP events (Gopalswamy et al., 2014).

Falewicz et al. (2009) found that peak X-ray fluxes of flares are not significantly associated with productivity of energetic particles during the reconnection process. Michalek and Yashiro (2013) found that the velocities of CMEs, especially for halo events which are mostly associated with the large SEP events, include to significant error due to projection effects and may be significantly different from the real velocities of the CMEs.

In the present paper we propose a new approach to investigate the appearance of SEP events. We seek to identify which MSCS classes indicate a tendency to produce SEPs. The MSCS parameters serve as proxies for the magnetic structure of ARs and should be correlated with production of SEPs. We consider a set of 116 SEP events recorded during 1996–2014. We study the magnetic structure of the source ARs to see if this can account for the observed productivity and fluxes of SEPs. We propose a simple but effective method to predict the arrival of energetic particles in the Earth's vicinity. The paper is divided as follows. The data used for this study are described in Section 2. A statistical analysis of properties of ARs producing SEPs is presented in Section 3. In Section 4 we present the results of our analysis and draw conclusions.

2. Data

Our statistical study covers the SOHO era (1996–2014) of CME observations from the Large Angle and Spectrometric Coronagraph (LASCO). In the considerations we use three databases which are described in this section. The basic list of large SEP events is from the NOAA Space Weather Prediction Center (http://www.swpc.noaa.gov/ftpdir/indices/SPE.txt). This list has been compiled since 1976 and includes fluxes of protons in the $\geqslant$10 MeV channel and associated CMEs, flares, and ARs. The Space Environment Monitor (SEM) onboard the Synchronous Meteorological Satellites (SMS-1 and SMS-2) and the Geostationary Operational Environmental Satellites (GOES-1, GOES-2, etc.) have been routinely used for monitoring the