New Astronomy 53 (2017) 44–52

Contents lists available at ScienceDirect

New Astronomy

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

Study of large solar energetic particle events with halo coronal mass ejections and their associated solar flares

Hema Kharayat*, Lalan Prasad, Meena Pokharia, Chandrashekhar Bhoj, Chandni Mathpal

Department of Physics, M.B. Govt. P.G. College, Haldwani, Nainital 263 139, India

HIGHLIGHTS

- SEP events are highly associated with fast halo CMEs.
- Most SEP events are associated with the western solar flares than the eastern flares.
- SEP events are likely associated with the southern flares than northern flares.
- Maximum SEP events are associated with M-class flares than X and C-class flares.
- Most SEP events are associated with fast halo CME associated X-class solar flares.

ARTICLE INFO

Article history:
Received 10 March 2016
Revised 19 October 2016
Accepted 12 December 2016
Available online 12 December 2016

Keywords:
Sun: coronal mass ejections
Sun: flares
Sun: particle emission

ABSTRACT

The purpose of the present study is to investigate the association of solar energetic particle (SEP) events with halo coronal mass ejections (CME) and with their associated solar flares during the period 1997–2014 (solar cycle 23 and 24). We have found that halo CMEs are more effective in producing SEP events. The occurrence probability and peak fluxes of SEPs strongly depend on the halo CMEs speed (V) as follows. The highest associations, 56% for occurrence probability and 90% for average peak fluxes, are found for the halo CMEs with $V > 1400\ \mathrm{km\,s^{-1}}$ but the lowest associations, 20% for occurrence probability and 5% for average peak fluxes, are found for halo CMEs with speed range $600 \leq V \leq 1000\ \mathrm{km\,s^{-1}}$. We have also examined the relationship between SEP events and halo CME associated solar flares and found that 73% of events are associated with western solar flares while only 27% are with eastern solar flares. For longitudinal study, 0–20° belt is found to be more dominant for the SEP events. The association of SEP events with latitudinal solar flares is also examined in the study. 51% of events are associated with those halo CMEs associated solar flares which occur in the southern hemisphere of the Sun while 49% are with those solar flares that occur in the northern hemisphere of the Sun. Also, 10–20° latitudinal belt is found to be likely associated with the SEP events. Further, 45% of SEP events are associated with M-class solar flares while 44% and 11% are with X and C-class respectively. Maximum number of SEP events are found for the fast halo CME associated X- class solar flares (68%) than M and C- class solar flares.

1. Introduction

A solar flare is a sudden brightening on the surface of the Sun. The flare emits energy over a wide range of wavelengths extending from radio to gamma- rays together with particle emission (Prasad & Joshi, 2008). They eject clouds of electrons, ions, and atoms through the corona of the Sun into space. Flares are often (not always) accompanied by a spectacular coronal mass ejection (Kopp et al., 2005). A coronal mass ejection (CME) is a dynamically evolving, most energetic and enhanced phenomenon which is associated with the eruption of large scale magnetized plasma from the Sun. This plasma transports into the heliosphere and produces major disturbances in interplanetary medium. When the speed of CMEs exceeds the local Alfvén speed in the corona and in the interplanetary medium, they drive shocks. These CME-associated shocks can accelerate electrons and ions, generally, known as solar energetic particles (SEPs) (Reames, 1999). SEPs are the high energy particles coming from the Sun and have been first observed in early 1940s. They consist of protons, electrons and HZE [High (H) atomic number (Z) and energy (E)] ions having energy range from a few tens of KeV to GeV. The occurrence of these SEP events is directly related to solar flares and CMEs. There are two different physical mechanisms for the acceleration of SEPs: produced by solar flares and by CME- driven shocks. On this basis, SEPs are divided into two distinct classes: impulsive and gradual SEPs (Cane et al., 1986). Impulsive SEPs are accelerated in flares, associated with type III radio bursts, have large $^{3}He/^{4}He$ ratios and enhancement of heav-

---

* Corresponding author.
E-mail address: mailme.hema1991@rediffmail.com (H. Kharayat).

http://dx.doi.org/10.1016/j.newast.2016.12.001
1384-1076/

ier ions such as Fe/O while gradual SEPs are accelerated at CME-driven shocks, associated with Type II and IV radio bursts, have small ^{4}He/H ratios and do not exhibit ^{3}He/^{4}He or Fe/C enhancement. Reames (2002) suggested that the mixed events consisting of both particles accelerated in flares and at the shock do not exist. In the acceleration process by the flares, the particles are accelerated due to reconnection in a compact closed magnetic field loop and then confined. These particles then interact with the denser solar atmosphere and create hard electromagnetic radiation. Electron beam bouncing back and forth along the loop excite a wide spectrum of electromagnetic waves which propagate across the field and accelerate particles. This acceleration occurs for the particles with gyro-frequencies comparable to wave frequency. Thus, different waves accelerate different particles. The acceleration process includes: particle acceleration in the magnetic reconnection region above the flare loops (Craig and Litvinenko, 2002), magnetic field reconnection which accelerates newborn ions produced by ionization of neutral atoms in the lower corona (Wu, 1996), and scaling by which the process of auroral particle acceleration in parallel potential drops to the solar atmosphere.

Scientists (Scholer and Morfill, 1977; Jones and Ellison, 1991) have also suggested that a shock can accelerate particles via three processes which are shock drift acceleration, diffusive shock acceleration and stochastic acceleration. In shock drift acceleration the particles gain energy due to grad-B drift along the $\vec{v} \times \vec{B}$-field in the shock front, where $\vec{v}$ is the velocity of particles and $\vec{B}$ is the magnetic field. Hence, it dominates for the quasi-perpendicular shocks where the induced electric field is largest. In diffusive shock acceleration the particles are scattered back and forth in the plasmas converging at the shock front. It works best in quasi-parallel shocks and requires a sufficient amount of scattering. Stochastic acceleration works in the turbulence behind the shock front. All these processes have a fundamental problem that particles can escape from the shock front after gaining a sufficient energy in the acceleration process and lost from the acceleration process and cannot be accelerated any further. Therefore the energy gain is limited. So, for particle acceleration up to higher energies relatively strong scattering upstream of the shock is required to feed particles back into the acceleration process (Malkov and Diamond, 2001; Bessho and Ohsawa, 2002). Wild et al. (1963) was the first who proposed the shock acceleration of SEPs and interpreted the metric type II burst as evidence for a coronal shock wave. A metric type II burst is a sufficient condition for a SEP event in interplanetary space (Svestka and Svestka-Fritzova, 1974). Later, Kahler (1982) and Kallenrode et al. (1991) suggested that the metric type II burst is neither a sufficient nor a necessary condition. Today, the metric type II burst is less used as an indicator for particle acceleration at a shock. Cane et al. (2002) suggested that a class of type III radio burst is reliably associated with intense SEP events.

A close association of SEP events with CMEs is first pointed out by Kahlar et al. (1978). Gopalswamy et al. (2003), Kahlar et al. (1984) and Kahlar (2001) suggested that the speed of CMEs is well correlated with the intensity of the associated SEP events. The intensity of SEP events is also well correlated with the apparent width of CMEs (Kahlar et al., 1984). This suggests that the kinetic energy of CMEs is an important factor in deciding the intensity of SEP events. Sometimes, solar flares also cause the acceleration of particles. Following Archimedes spiral of interplanetary magnetic fields, these SEPs reaches the earth rapidly much before interplanetary shocks reach the earth orbits (Kane, 2008). When intensity of SEP events exceeds 10 pfu in the energy channel >10 MeV, then events are known large SEP events. Large SEP events attracts attention because of their high energy releases, their importance for increasing the near earth radiation environment and the corresponding effects on the earth's magnetosphere and ionosphere (Tsurutani et al., 2009). The SEPs with energy > 10 MeV have significantly large effects on space weather, therefore these events are taken in the study. SEPs play an important role in the study of understanding the fundamental processes in space plasmas. As these particles propagate to the near earth space they carry information in their energy spectra, elemental composition and acceleration process. An important practical value of statistical analysis of SEPs is for space weather forecasting. SEP events constitute a hazardous condition in interplanetary and near-earth space. SEPs can damage electronic components on satellites (Feynman and Gabriel, 2000), pose a radiation threat for astronauts (Hoff et al., 2004) and crews of high-flying aircraft and commercial airlines in polar routes (Beck et al., 2005), can impact the polar ionosphere, causing absorption of high-frequency radio waves and affecting long distance radio communication and radar systems. Hence, a pre-warning system is required in order to predict the occurrence SEP events. Laurenza et al. (2009) developed a technique to provide short-term warnings in SEP events which is based on flare location, flare size and evidence of particle acceleration/ escape as parameterized by flare longitude, time-integrated soft X-ray intensity and time-integrated intensity of Type III radio emission at 1 MHz respectively.

The purpose of this paper is to study the large SEP events in association with halo CMEs and their associated solar flares. In this paper, authors want to find the relationship between occurrence probability and peak fluxes of SEP event, halo CME speed, solar flare class and solar flare location. As the SEP events, halo CMEs and solar flares are activities of the Sun and the Sun is a major component in affecting the space-weather, thus the study of these activities of the Sun may be important for understanding the space-weather phenomena. The study of SEP events is also of interest because they can endanger life in outer space. The structure of the paper is of the type: Section 2 contains data selection and method, Section 3 contains the results and discussion of the study and at last, conclusions are given in Section 4.

2. Data analysis and method

First of all we have identified all major SEP events from the website http://cdaw.gsfc.nasa.gov/CME_list/sepe/ during the period 1997–2014 (solar cycle 23 and 24). This list includes major SEP events, observed by GOES (Geostationary Operational Environmental Satellite) with energy > 10 MeV and proton intensity > 10 pfu (Gopalswami et al., 2003). Here, they had also given the CME and solar flare features which occur during that period and are responsible for the large SEP events. The GOES system supports weather forecasting, severe storm tracking and meteorology research. It uses geosynchronous satellite which has been a basic element of united state weather monitoring and forecasting. Since, the major SEP events with intensity > 10 pfu in the > 10 MeV energy channel are more significant in causing space weather effect, therefore, we have used major SEPs with this energy channel. During the study period we have found 142 SEP events. Out of 142 events, 104 were associated with halo CMEs, 24 with non-halo CMEs and remaining 14 events were not associated with any type of CMEs. We have considered only those events which are associated with halo CMEs (104 events). For 104 events associated with halo CMEs, source location and associated flare class of 13 halo CMEs were not known. Therefore, these events are excluded from our study. Finally, we have selected only 91 events for which complete features are known. A list of 91 SEP events in the GOES >10 MeV channel with complete features is given in appended table. The second and third column represents the onset date and peak fluxes of SEPs. Column 4 gives the associated halo CME speed (V). Column 5 and 6 represents the location and class of halo CME associated solar flares respectively. We have also checked the halo CME characteristics from SOHO/LASCO halo CME catalogue (Gopalswami et al., 2009) from http://cdaw.gsfc.nasa.gov/CMElist/halo/ halo.html. We