URSI-RCRS 2024, ARIES/GEHU, Bhimtal, India, 22 - 25 October, 2024

Space-Weather implications of a Radio-loud CME from Sigmoidal Active Region NOAA 12473

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Abstract

Coronal mass ejections (CMEs) accompanied by Decameter- Hectometric (DH) type II radio bursts are among the most powerful CMEs responsible for various interplanetary and geomagnetic disturbances. Here, we present the near-Earth consequences of such a halo CME that erupted from the sigmoidal active region NOAA 12473 and first appeared on the *Large Angle and Spectrometric Coronagraph* (LASCO) C2 coronagraph at around 12:12 UT on 28 December 2015 with a linear speed 1212 km/s. After three days of the CME launch, signatures of an interplanetary CME (ICME), is detected in the near-Earth region in the form of drastic variations in the plasma and magnetic field measurements of solar wind at 1 AU. Variations in the interplanetary plasma/field parameters, *viz.* interplanetary magnetic field, z-component of the magnetic field, flow speed, and proton density, are examined. At the Earth, we found an intense geomagnetic storm with a Dst index of -116 nT and Forbush decrease of magnitude ~5%. This Forbush decrease shows a characteristic two-step Forbush profile decrease with magnitudes of ~2.79 % and ~5.4 %. Further, we noticed a similar variation in the time profile of cosmic ray intensity as of geomagnetic SYM/H and Dst index, indicating a good correlation (correlation coefficient is 0.7) between them. However, a time delay of ~4 hours is reported between the minima of Forbush decrease and the geomagnetic storm.

1. Introduction

Coronal mass ejections (CME) are spectacular expulsion of huge amounts of magnetized plasma from the Sun into interplanetary space. Earth-directed CMEs, i.e., halo CMEs, are known for their geo-effectiveness. CMEs form in the solar atmosphere, and all contemporary models predict that their magnetic field configuration when they leave the lower solar corona is that of a twisted bundle of the magnetic field known as a magnetic flux rope (MFR) [1]. One such observational signature of an MFR is regarded as a coronal sigmoid, which can be observed as an S-shaped (or inverse S-shaped) structure in the solar corona [2]. Previous studies have indicated that sigmoidal active regions are more likely to be eruptive [3] [4] [5].
CME and its interplanetary counterpart, i.e., ICME, are responsible for geomagnetic storms, a strong disturbance in the global geomagnetic field, which is conventionally measured by disturbance storm time index (Dst index) and Forbush decrease (FD, [6]) in cosmic ray intensity. During their travel in the corona, inner heliosphere, and interplanetary space, powerful CMEs generate shocks. The propagation of shock can be seen as a slow drifting feature in the radio dynamic spectrum, known as a type II radio burst [7]. Importantly, type II radio bursts observed in the decameter-hectometre (DH) domain, i.e., longer wavelength range, suggest the shock formation at higher heliocentric distances. CMEs associated with DH type II radio bursts are identified as radio-loud CMEs, and those which are not associated as radio-quiet CMEs [8]. It is important to note that radio-loud CMEs maintain significantly higher speeds at a large distance of 1 AU than radio-quiet CMEs [9]. Further, radio-loud CMEs are more effective in producing FD in cosmic ray intensity and geomagnetic storms than radio-quiet CMEs [8]. With this knowledge, more case studies are required to enhance our understanding towards the interplanetary and geomagnetic consequences of radio-loud CMEs.

In this article, we present the investigation of interplanetary and geomagnetic consequences of a radio-loud CME, which is caused by an eruption of a sigmoidal flux rope from the active region NOAA 12473 on 28 December 2015. In Section 2, we provide information about the data utilized in the study. In Section 3, we discuss the results of the study. Finally, the results are summarized in Section 4.

2. Data Analysis

We utilize observations from the Large Angle and Spectrometric Coronagraph (LASCO) [10] on board the Solar and Heliospheric Observatory (SOHO) for CME observations. SOHO/ LASCO observes the Sun with two coronagraphs C2 and C3 in the field-of-view 1.5 - 6 $R_\odot$ and 3.7-30 $R_\odot$, respectively. The Decameter-Hectometric type II solar radio burst is derived using the observations from the Radio and Plasma Waves (WAVES) experiment on board the Wind spacecraft [11].

The interplanetary parameters such as IMF (B), z-component of magnetic field (Bz), solar wind speed (v), and proton density; and geomagnetic activity data (SYM/H and Dst index) are obtained from NASA/GSFC's Space Physics Data Facility's OMNIWeb service and OMNI data with 5-min and 1-hour time resolution (https://omniweb.

gsfc.nasa.gov). The efficiency and pressure corrected cosmic ray count rate is obtained from Oulu Neutron monitor (http://cosmicrays.oulu.fi/) with temporal resolution of 5-min and 1 hour. Oulu NM is situated at Geographic coordinates 65.05° N 25.47° E with effective vertical cut-off rigidity ~0.8 GV.

3. Results and Discussion

We study the space-weather implications of a radio-loud CME that occurred from the active region NOAA 12473 on 28 December 2015 caused by the eruption of an active region sigmoidal flux rope. A detailed examination of magnetic evolution of the active region 12473 using a time-dependent and data-driven magnetofrictional Simulation is presented by Price et. al. in 2020 [12]. They have found that the eruption of flux rope started as a result of torus instability. During its rise, the core of the flux rope gets increasingly twisted and pushes overlying fields and neighboring slightly twisted arcade-like loops to get erupt out. Muley et al. in 2021 have reported the thermodynamic evolution of an on-disc sigmoidal flux rope observed during 24-28 December 2015 [13]. They have found multithermal (3-12.5 MK) characteristic of sigmoidal flux rope during the flaring activity. The erupted flux rope then observed in the LASCO/C2 coronagraph in the form of CME.

The CME was first appeared in the C2 coronagraph at around 12:12 UT on 28 December 2015. It was a halo CME of high speed and acceleration of ~1212 km/s and ~4.6 m/s^2, respectively. Figure 1a represents the sigmoidal active region observed in 94 Å channel of *Atmospheric Imaging Assembly* (AIA) on board *Solar Dynamics Observatory* (SDO) prior to eruptive event. Figure 1b

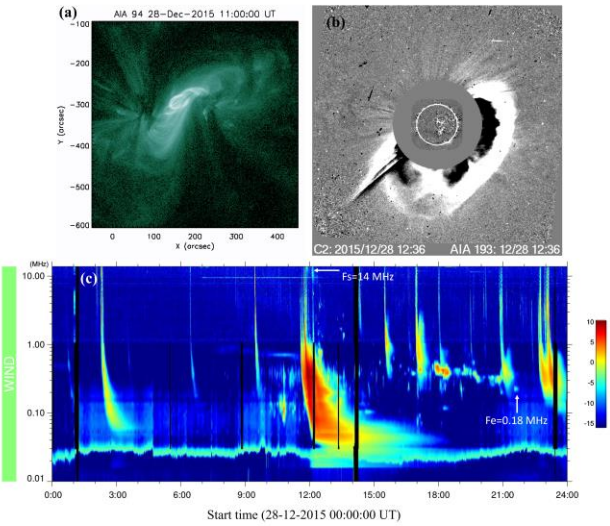

Figure 1. (a) Representation of Sigmoidal active region prior to the eruptive activity in AIA/SDO 94 Å channel. **(b)** Radio-loud CME observed is SOHO/LASCO C2 coronagraph. **(c)** Dynamic spectrum of DH type II radio burst observed by Wind/WAVES spacecraft. Starting (Fs) and ending (Fe) frequencies are marked as 14 MHz and 0.18 MHz, respectively.

shows the observation of CME in C2 coronagraph at 12:36 UT. In panel (c), we present the dynamic spectrum of DH type II radio burst associated with the corresponding CME. The radio burst started at 11:50 UT on 28 December 2015 with the starting frequency (Fs) of 14 MHz (marked in horizontal white arrow). This radio burst lasted at around 21:45 UT of the same day with ending frequency (Fe) of 180 kHz (marked by white vertical arrow).

In Figure 2, we present the variability of interplanetary parameters, geomagnetic activity and cosmic ray intensity during the period 30 December 2015 to 04 January 2016 with 5-min time resolution. The cosmic ray intensity is smoothed over five points to get the fine variation in the intensity. The information about the ICME can be obtained from the near- Earth ICME catalog Compiled by Ian Richardson and Hilary Cane [14] [15]. During the studied interval, a shock associated with the ICME arrives on 31 December 2015 00:50:00 UT (marked by vertical red line). The signature of shock is evident by the sudden fluctuations in plasma/field data. A sudden jump in IMF (B), Bz, flow speed (v), and proton density is seen. A sudden commencement of geomagnetic storm indicated by

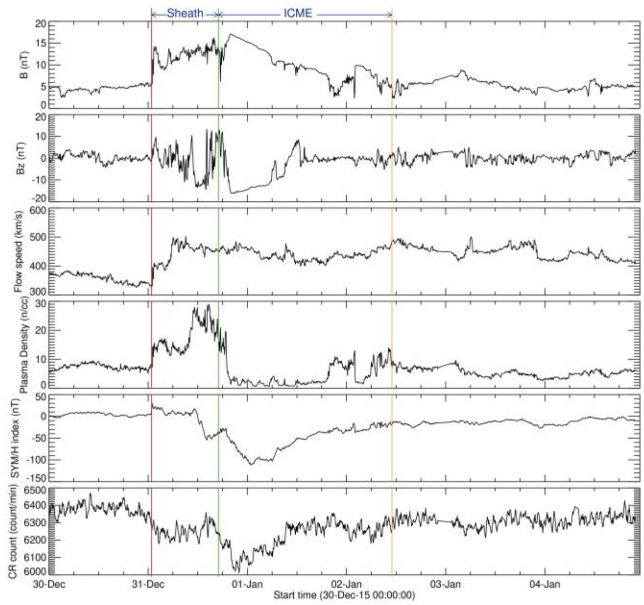

Figure 2. (Top to Bottom) Variation of interplanetary parameters *viz.* average interplanetary magnetic field (nT), z-component of magnetic field (nT), flow speed (km/s), plasma density (n/cc), SYM/H index (nT), and cosmic ray intensity (count/min). Red vertical line indicates the arrival of shock at 1 AU. The green and orange vertical lines mark the start and end time of ICME respectively.

SYM/H and Dst index (see Figure 3b) is also seen during the same time. Following the shock, the sheath region marks the fluctuation in the plasma/field parameters till about 17:00 hours of 31 December. Afterward, a further sudden enhancement can be seen in the magnetic field (B), indicating the start of ICME ejecta (marked by green vertical line). This ICME ejecta lasts till 11:00 hour of 02

January 2016 (indicated by orange vertical line). Furthermore, on the arrival of shock, we observed the start of decrease in cosmic ray counts at Oulu NM. The onset of FD is co-temporal with the arrival of shock. We noticed a small decrease in cosmic rays before the ICME arrival, however, this decrease become little bit deeper after the arrival of ICME ejecta. This points toward the two-step FD.

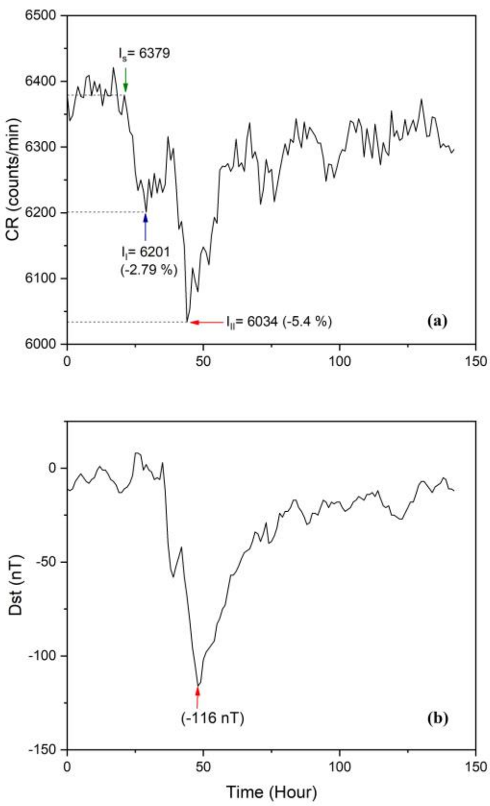

Figure 3. Hourly variation of cosmic ray (CR) counts (panel a) and Dst index (panel b). In panel (a), I_s marks the starting intensity which is considered to compute the decrease in cosmic ray. Two-step Forbush decrease is marked by blue and red arrows with magnitudes -2.79% and -5.4%, respectively. Red arrow in panel (b) marks the minimum Dst value of magnitude -116 nT.

For a clear picture of FD and geomagnetic storm, we decreased the time resolution from 5-min to one hour and further plotted the variations of two activities. The hourly values of cosmic ray counts and Dst index are plotted in Figure 3. The two-step FD is clear from the figure. In Figure 3a, we mark the starting value of cosmic ray intensity (I_s, before the start of FD) by green arrow to find the FD percent. First dip (I_I) and second dip (I_{II}) in the intensity are indicated by blue, and red arrows, respectively. Before the arrival of ICME, we found a FD of magnitude ~3%, around 4 hr later than the shock. This decrease gets stronger with the magnitude ~5% after the arrival of ICME with a time lag of ~3 hr with ICME. After this, cosmic rays undergo the recovery phase for approximately one whole day. The two-step FD is explained by two magnetic barriers, the sheath and the magnetic cloud, in an ICME event [16]. With analysis of cosmic ray data, previous studies [17] also report the start of FD before the arrival of magnetic cloud which further gives rise to characteristic two-step FD profile. Here, it is important to mention that shock-associated magnetic cloud produces larger FD than the without shock-associated ones. This is due to the fact that the shock-associated magnetic clouds are larger in spatial extent. Due to larger extent, they can scatter/block more cosmic rays than the without shock associated magnetic cloud (see e.g. [18]).

Figure 3b shows the variation of Dst index during 30 December 2015 to 04 January 2016. We noticed an intense geomagnetic storm with Dst index value of -116 nT (marked by red arrow) at 00:00 UT on 01 January 2016, approximately four hour later than the second dip in cosmic ray. This implies that the time lag between FD and geomagnetic storm is ~4 hr. Badruddin et al. [19] also reported 3-4 hours time delay between cosmic ray intensity variability and Dst index. By superposed epoch analysis Kharayat et. al. 2016, reported the zero-day time-lag between FD and geomagnetic storm [20]. It is also noticeable that cosmic ray counts and Dst index show similar variations. The Pearson correlation coefficient between cosmic ray and Dst is found to be 0.70, indicating the strong positive correlation between two parameters.

4. Summary

We presented the space-weather implications of a radio-loud CME, which first appeared on the LASCO/C2 coronagraph at 12:12 UT on 28 December 2015. The CME is associated with a shock, whose signature was observed in the form of type II radio bursts in the frequency range 14 MHz to 180 kHz, decameter-hectometric domain. This shock travels into the interplanetary space and marks the signature of the interplanetary counterpart of the CME, i.e., ICME. Strong disturbances are observed in the interplanetary plasma/field parameters *viz.* B, Bz, flow speed (v), and proton density on the arrival of ICME. At the same time, a sudden decrease is found in the geomagnetic parameters (SYM/H and Dst index). The value of the Dst index lowered up to -116 nT, indicating the commencement of an intense geomagnetic storm. Likewise, a depression is also found in the cosmic ray intensity at the high latitude Oulu neutron monitor. A characteristic two-step Forbush profile decrease is observed with a decrease of magnitudes of ~3% and ~5%. Furthermore, the time profiles of the Dst index and cosmic ray intensity show similar kinds of variations. A high correlation coefficient (0.70) is obtained between the Dst index and cosmic ray intensity. However, we found a time delay of ~4 hours between the minima of FD and Dst. Our study is crucial for understanding the near-Earth impacts of powerful, high-speed CMEs. To gain deeper insights, further analysis involving additional solar, interplanetary, and geomagnetic parameters is necessary. For examining cosmic ray variability, future analyses should incorporate data from various neutron monitors located at different latitudes.

6. Acknowledgements

We acknowledge the LASCO CME catalog and the Wind/WAVES type II burst catalog. We gratefully acknowledge use of NASA/GSFC's Space Physics Data Facility's OMNIWeb service and OMNI data. We acknowledge the use of cosmic ray data from Oulu neutron monitor.

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