m-to-DH type II bursts associated solar eruptions and their relation to SEP events

A brief introduction

I have joined as a postdoctoral scientist under **Prof.W.Q.Gan** in "Purple Mountain Observatory (CAS)", Nanjing on 15 June 2015. I have an interest to study the type II radio bursts associated with solar flares and CMEs and their space weather events. This time, we have planned to study the particle acceleration and their effects on the near-Earth space. Hence, we choose to study a statistical analysis on the characteristics of m-to-DH type II bursts associated with solar flare and CMEs in relation with SEP events. Many authors have pointed out that the observation of the type II bursts in the corona is the earliest indicator of space weather events. In our first paper, we have discussed characteristics of m-to-DH type II bursts associated solar eruptions and their SEP and non-SEP events. Later, this paper has been accepted for the publication in *Astrophys. Space Sci.*. After that, we moved to our main objective work, which is whether the CME-CME interaction plays an important role in the particle acceleration or not. Therefore, we have decided that to do one more statistical study to compare the differences in the key ingredients between the single CME-SEP events and twin CME-SEP events. We believe that this study may reveal the important clues on the particle enhancement for the single halo CME and CME-CME interactions. We also compared the basic parameter of solar flares and CMEs and their associated type II and type III bursts. Generally, twin-CMEs associated DH type II bursts shock intensity is much stronger than the single CMEs associated DH type II bursts which are observed by the Wind/WAVES onboard instrument. Hence, we have extensively studied the duration, peak intensity, integrated intensity and slope of the DH type II and DH type III bursts for both sets of events. Apart from this, we also derived the abundance of the seed particles (Fe/O ratio) for the both sets of events. Hopefully, this paper is expected to submit the journal in the mid of July 2017.

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A detailed description of the work have been done

Motivations and the background of the work

Solar energetic particle (SEP) events are considered to be produced from solar flares and/or coronal mass ejections (CMEs) [Cane et al.(1981), Reames(2012)]. In general, these particle events are classified into two categories: impulsive SEP events typically last a few hours, and are closely associated with solar flares [Klein & Posner(2005)]; on the other hand the large gradual events typically last a few days and are associated with energetic CME-driven shocks [Kahler(2001), Cane & Lario(2006)]. Furthermore, the large fraction of SEP-associated CMEs is closely related with solar flares. Hence, some recent studies were demonstrated to add one more category, that is hybrid SEP events in which, both solar flares and CME-driven shocks accelerate the particles that contribute to large SEP events. Several authors have pointed out that the importance to study the SEP events associated with solar flares and CMEs (hybrid events). These hybrid SEP events seem to be gradual SEP events but have impulsive-like properties.

An earlier study [Kahler(1996)] demonstrated that both the maximum energy and the intensity of energetic particles in SEP events is closely related to shock speed.In an another following study, [Kahler(2000)] also suggested that the ambient energetic particle intensity prior to the event may be an important factor in causing a large SEP event. This seed population may be from previous flare remanent materials or ambient corona materials [Gopalswamy et al.(2004), Li et al.(2012), Ding et al.(2013)]. Firstly, [Gopalswamy et al.(2002)] demonstrated that interaction with pre-CMEs was a powerful discriminator for predicting SEP events, in addition to other properties of primary CMEs. They also suggested that type II associated CMEs are good electron and proton accelerators. But, [Kahler & Vourlidas(2014)] concluded that the higher SEP peak intensity values with pre-CMEs may not be primarily due to CME interactions, such as the "twin-CME "scenario, but they were explained by a general increase of both background seed particles and more frequent CMEs during solar maximum. Therefore, the relevance of CME interactions for larger SEP event intensities remains unclear.

The type II radio bursts observed in the corona (in metric wavelength) and in the interplanetary (IP) medium (in Deca-Hectometric wavelength) are considered to be produced by the acceleration of non-thermal electrons. They occur at the local plasma frequency and/or its harmonic. By assuming a coronal/IP density model, the frequency of emission can be converted into the heliocentric distance at which the radio emission originates. The m type II radio bursts occur in the frequency range of 150 – 15 MHz and the shocks excited in the distance range 1– 3 $R_\odot$ ($1R_\odot = 6.96 \times 10^5$ km). The lower limit 15 MHz is the ionospheric cutoff frequency. On the other hand, DH type II radio bursts originate roughly in the outer corona within the heliocentric distance of about 2 – 10 $R_\odot$. DH type II radio bursts are also observed as a continuation of m type II radio bursts (hereinafter m-to-DH type II radio bursts). DH and km type II radio bursts are recorded in the frequency ranges 14 – 1 MHz and 1 MHz – 20 kHz by RAD2 and RAD1 instruments respectively. These instruments are part of the Radio and Plasma Wave (WAVES) experiment on board the Wind spacecraft. Radio emission can be observed in the spectral domain of metric (m) or Deca-Hectometric (DH) or kilometric (km) or in any of the two domains or in the entire radio spectral domain (hereinafter we refer to them as m-to-km type II bursts). Shocks are formed when CME speed exceeds Alfven speed. A close relationship between kinetic energy of CMEs and the wavelength range of associated type II radio bursts has been reported by a few authors [Lara et al.(2003), Prakash et al.(2014)].

Whereas type III radio burst is a fast drifting signature, are associated with solar flares (Nicholson et al. 1978). In the beginning, the intense and complex type III radio bursts (DH type III bursts) were studied using the data from ISEE-3 spacecraft [Cane et al.(1981)]. Later, [MacDowall et al.(1987)] statistically demonstrated that these DH type III bursts were associated with m type II radio bursts, so-called as shock associated (SA) events. Cane et al. (2002) was analyzed this type III bursts observed from the coronal and IP region using the ground-based and Wind/WAVES data. They proposed that these type III events were always associated with energetic CMEs and it could be a new source of electron acceleration. Recently, [Winter & Ledbetter(2015)] extensively analyzed 123 DH type II radio bursts from the Wind/WAVES and their associated SEP and non-SEP events during 2010-2013. They found that the high degree peak intensity of SEP events are nearly associated with both DH type II and DH type III radio bursts. They derived a new radio index from the principle component analysis to forecast the SEP events from the derived properties of DH type III and DH type II radio bursts. They pointed out that the peak intensity and duration of DH type III radio bursts also a dominant factor along the properties of DH type II radio bursts. Finally, they concluded that the DH type III radio bursts occurred along with DH type II bursts are shown to be an important diagnostic used to forecast the SEP events. Hence, m-to-DH type II and DH type III bursts associated solar eruptions and their relation to SEP events are important to forecast the space weather conditions.

In our first paper, we have particularly made the list of events in which DH type II radio bursts is continuation of m type II bursts (m-to-DH type II bursts) associated with hybrid SEP events and we preformed a comprehensive comparative studies for these solar eruptions into SEP-associated and non-SEP-associated events. The mainly results are as follows: 65% of m-to-DH type II bursts associated with CMEs and flares produced SEP events. The SEP-associated CMEs have higher sky-plane mean speed, projection corrected speed, and sky-plane peak speed than those of non-SEP- associated CMEs respectively by 30%, 39%, and 25%, even though the two sets of CMEs achieved their sky-plane peak speeds at nearly similar heights within LASCO FOV. We found Pearson?s correlation coefficients between the speeds of CMEs (sky-plane speed and corrected speed) and logarithmic peak intensity of SEP events are $cc = 0.62$ and $cc = 0.58$, respectively. We also found that the SEP-associated CMEs are on average of three times more decelerated (– 21.52 m s^{-2}) than the non-SEP-associated CMEs (– 5.63 m s^{-2}). The SEP-associated flares have a mean peak flux (1.85×10^{-4} W m^{-2}) three times larger than that of non-SEP-associated flares, even though the flare duration (rise time) of both sets of events is similar. The average formation heights of m and DH type II radio bursts for SEP-associated events (1.31 $R_\odot$ and 3.54 $R_\odot$, respectively) are lower than for non-SEP-associated events (1.61 $R_\odot$ and 3.91 $R_\odot$, respectively). 93% of SEP-associated events originate from the western hemisphere and 65% of SEP- associated events are associated with interacting CMEs. The obtained results indicate that, at least for the set of CMEs associated with m-to-DH type II bursts, SEP-associated CMEs are more energetic than those not associated with SEPs, thus suggesting that they are effective particle accelerators.

For purpose of second paper is to address the following questions: *i)* whether CME-CME interaction plays a vital role on the enhancement of the peak intensity of SEP events or not? *ii)* Is the flare material or coronal material can dominant seed particles for non-interacting CMEs and interacting CMEs associated hybrid SEP events? and *iii)* Is there any significant DH type II shock properties can differ for the single CME and twin-CMEs scenario?. In addition, we also compiled a set of data, in which the key ingredients of hybrid SEPs, CMEs, solar flares, m-to-DH type II radio bursts and their accompanying DH type III radio bursts for non-interacting CMEs and interacting CMEs associated SEP events are listed. Some of the results are summarized as follows: We have compiled a 58 m-to-DH type II bursts type II bursts, DH type III bursts associated major hybrid SEP (Ip > 10 MeV) events and their parent solar eruptions observed from 1997 – 2014. Our 58 sample of events are divided into two sets of events: 35 events are considered as non-interacting CME (single CMEs) events; and the remaining 23 events identified as interacting CMEs (twin-CMEs) events. We find that the twin-CMEs associated SEP events are relatively larger in duration, peak intensity, and integrated intensity than the single-CMEs events (single CME-SEPs: 3.29 days, 2.03 pfu and 4.20 pfu; twin-CME-SEPs: 3.55 days, 2.26 pfu and 4.46 pfu). On average CMEs speed is almost similar for both sets of events. Interestingly, The single CMEs (–16.38 m s^{-2}) are relatively more decelerated than the twin-CMEs (– 0.4 m s^{-2}). The mean peak flux (integrated flux) of solar flares for single-CMEs associated events is slightly lower than and twin-CMEs events (1.85 × 10^{-4} W m^{-2} (0.22 J m^{-2}) and 2.30 10^{-4} W m^{-2} (0.30 J m^{-2}), respectively). On the area of the active region (AR) of single-CMEs events is smaller than twin-CME events (459.57 msh and 660.87 msh, respectively). We find that the good correlation between the peak intensity of SEPs and the properties of CMEs (space speed: cc = 0.58, SEcc = 0.14), and solar flares (peak flux: cc = 0.40, SE_{cc} = 0.15; log integrated flux: cc = 0.52, SE_{cc} = 0.15) for single-CME events. Interestingly, there is no clear correlation among the peak intensity of SEPs and properties of both CMEs and flares for twin-CMEs events. We also find that there is no distinct difference in the Fe/O ratio (normalized to the reference coronal value of 0.134) for single-CME and twin-CME events (1.84 and 2.16, respectively). The peak intensity integrated intensity of DH type II bursts for single CMEs (3.64 sfu and 7.28 sfu, respectively) is lower that twin-CMEs associated DH type II bursts (3.71 sfu and 7.38 sfu, respectively). But shock speed of single-CMEs associated events is larger than twin-CMEs associated events (0.76 MHz hh^{-1} and 0.69 MHz hh^{-1}, respectively). However, the properties of DH type III bursts is almost same in magnitude for both set of events except the slope, that is the slope of DH type III bursts for single-CMEs associated events (19.04 MHz hh^{-1}) is relatively larger than the twin-CMEs events (16.83 MHz hh^{-1}). Almost 63% and 57% of single-CMEs and twin-CMEs associated events are originated from the western region. Even though speeds of CMEs for both sets of events are almost similar, but peak intensity of SEPs for twin-CMEs associated events (1654.46 pfu) are three times larger than single-CMEs associated events (491.82 pfu). From this results we implies that CME-CME interactions may play a significant role for enhancement of peak intensity for a set of SEP events.

The future work

In near future, we are going to perform a multiwavelength case study to address the same question whether the CMEs interacting really play vital role in the particle acceleration. In our previous study showed that interacting CMEs are further accelerated within the LASCO FOV. It implies that CME-CME interactions may be the super elastics in nature. We already choose the events for this case study. For a single CMEs event on 2011 March 7, the M3.7 class flare was observed at 19:43 UT at the western side W53°. The associated CME was the first observed above the occulting disk at 20:00 UT (speed of 2125 km s^{-1}), was highly decelerated with a magnitude of 63.1 m s^{-2}. But for twin-CMEs, the partial halo pre-CME was observed at 03:12 UT followed by the full halo primary CME with a speed of 2175 km s^{-1}. The CME interaction is clearly seen from the LASCO movie in the lower corona ($\sim 6\ R_{\odot}$). Both pre-CME and primary CME has the positive acceleration with the LASCO. However, why we choose these two events for our case study because these two hybrids SEPs associated CMEs are magnetically well connected with an Earth, moreover both CMEs speed is almost similar. In this work, we are going to extensively analyze these two events from the multiwavelength observation from SOHO/LASCO, STEREO, Wind/WAVES, ACE/Wind.

Scientific outcomes

- Prakash, O.; Feng, Li; Michalek, G.; Gan, Weiqun; Lu, Lei; Shanmugaraju, A.; Umapathy, S.: 2017, Characteristics of events with metric-to-decahectometric type II radio bursts associated with CMEs and flares in relation to SEP events, *Astrophys. Space Sci.*, 362, 50.
- Prakash, O.; Feng, Li; Liu-Guan Ding; Gan, Weiqun; Lu, Lei.: 2017, The meter-to-decahectometer type II busts associated major SEP events for single and twin-CMEs [in preparation]

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