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The Bulk of Solar Energetic Particles (SEP) Acceleration as Seen From the Intensity-Time Profile

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Abstract
In this work 27 events have been chosen for the period from (17 Feb 2000 to 10 Sep 2014) to analyze their intensity profile and find out what is the most effective reason behind the bulk of the accelerated SEPs as seen in the interval from the onset to the maximum intensity. It was found that the parameters of the associated eruptions (CME and solar flare) could play a major role in this acceleration. We considered some of these parameters such as: flare class related to soft X-ray flux, CME's speed and acceleration, site of the eruption (western, eastern) and particle transport in the IP medium. The shape of the profile showed a clear changing in ΔT1 (time from onset to maximum), as an inverse relation with the acceleration of coronal mass ejection (CME) and the class of the flare associated. While the value of the maximum intensity was found to have a direct proportional relation with the speed of CME and the class of the flare.

Keywords: SEP, CME, solar flare, particle acceleration, shockwave.

تعجيل الجسيمات الشمسية ذات الطاقة العالية اعتمادا على الرسم البياني للشدة مع الزمن

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الخلاصة
تم في هذا البحث اختيار 27 حدث شمسي SEPمن تاريخ 17 شباط 2000 الى 10 ايلول 2014 لدراسة وتحليل الرسم البياني للشدة للجسيمات ومراقبة العوامل المؤثرة عليه كقوة التوهجات الشمسية (solar flare) وسرعة وتعجيل المقذوفات الكتلية الاكليلية(CME) وموقع الانفجار على سطح الشمس (شرقي او غربي) ومناقشة الاسباب وراء هذه التغيرات في الرسم البياني. شكل الرسم البياني اظهر اعتماد كبير على هذه العوامل حيث لوحظ الوقت اللازم للوصول الى اعلى قيمة للشدة (ΔT1) انه يتناسب عكسيا مع تعجيل المقذوفات الاكليلية وقوة التوهج الشمسي بينما قيمة الشدة العظمى للجسيمات تتناسب طرديا مع سرعة المقذوفات الاكليلية و قوة التوهج الشمسي ايضاً.

Introduction:

Solar energetic particles (SEPs), which consist of electrons, protons and ions up to Fe are accelerated at Sun or in the interplanetary medium during flares and CMEs reaching energies up to several GeV. SEPs are called so, because of their high-energy solar origin and behavior as single particles [1]. The SEP events are one of the most effective phenomena in solar physics, which has

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been widely observed near Earth with energy ranges varying from some keV/nucl to some GeV/nucl. They might have different sources such as solar flare in the low corona, coronal shock and interplanetary shocks driven by CMEs, which had been first observed in the early 1940s [2]. Their intensity-time profile, energy spectra, elemental, isotopic and ionic charge composition carry fundamental information on the source region of their acceleration and propagation processes [3]. The sun contributes enormously to the energetic particle population in the heliosphere through various processes; flares, coronal mass ejection (CMEs) and Co-rotating Interaction Regions (CIRs). CIRs are regions of compressed plasma formed at the leading edges of co-rotating high-speed solar wind streams originating in coronal holes as they interact with the preceding slow solar wind [4]. SEP contains electrons and ions. Electrons are accelerated up to hundreds of MeV ; ions are accelerated up to many GeV [5]. Cane et al. [6] found two classes of SEP events based on the signature of SEP event in soft X-ray (the energy range~1-25 keV):

a. Impulsive events, which have high e/p ratio, and never associated with interplanetary shock, and occur low in the corona.

b. Gradual events, which can accelerate particles to much higher energies, are well associated with coronal and interplanetary shock, and occur high in the corona in extended regions.

Reames [7] suggested that the impulsive events were related to flares and the gradual SEP events were related to coronal mass ejection (CME) driven coronal and interplanetary shocks. There were many controversial ideas about the role of flare and CMEs. CMEs have been shown to be accompanied with gradual events of X-ray [8] and with interplanetary shocks [9]. Interplanetary proton events were shown to be accompanied with gradual events [10] with CMEs [11] and with interplanetary shocks [12]. The present view for the gradual SEP events suggested that such events are created from the continual acceleration of particles at the CME-driven bow shocks [13-16]. Fast CMEs with velocity > 500 km/s are expected to form a bow shocks at~3-5 R_Θ (where 1 R_Θ=one solar radius = 6.96×10^5 km) from the sun. The CME-driven shocks in interplanetary space are thought to be a source of accelerated particles in the gradual SEP events [7]. At leading edge of the CME bow shock in its up-stream region, the accelerated protons may be activate magneto-hydrodynamic (MHD) waves to form a turbulent sheath, with its fluctuating magnetic field components, the mean free path, λ, of energetic particle scattering is small and the diffusive shock acceleration of the particles is rapid [17]. Behind the bow shock the shock down-stream region is also turbulent. There the up-stream turbulence is compressed and enhanced by the shock. At small values of the mean free path the particle diffusion through the sheath is slow and the shock can accelerate particles to high energies such a regime is typically assumed for the SEP- productive shocks. At large values of λ the shock turbulent sheath is transparent for SEPs and the diffusive shock acceleration is not significant [18]. Reames 1999 [7] mentioned that a high-energy particles from the sun were first observed by Forbush [19], as sudden increases in intensity in ground-level ion chambers during the large solar events of February and March 1942. Since this was long before the discovery of coronal mass ejections (CMEs), it was natural to assume that the energetic particles came from the solar flares that often accompany large CMEs. The flare myth has had a profoundly negative effect on nearly all aspects of SEP studies for many years. The change in this picture, illustrated by the scheme in Figure- 1(a,b), has provided an awakening in understanding the physical mechanisms of particle acceleration in SEP events. Until born the ‘flare myth’ Gosling [20] that dominated thought in the SEP community for over so many years.

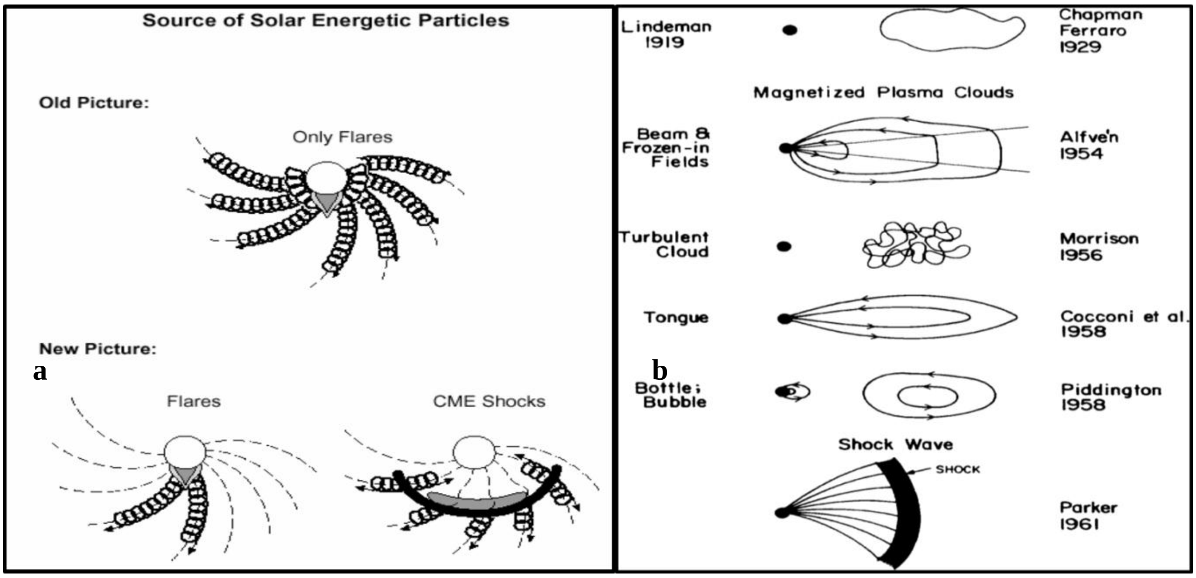

Figure 1- a: a scheme illustrating an awakening in understanding the physical mechanisms of particle acceleration in SEP events [7].b: History view of ICMEs structure [21].

Instruments and data

The data used in this work obtained from different sources. SOHO (Solar and Heliospheric Observatory) satellite devices has been used for collecting the information. Speed and acceleration of the CME and the time of sequence are taken from LASCO (Large Angle and Spectrometric Coronagraph). The association of the CME and the first injected SEPs and the error percentage are measured using a MATLAB code from the data by the CDAW (Coordinated Data Analysis Workshop) from the website [http://cdaw.gsfc.nasa.gov/CME_list]. UV and soft X-ray images by EIT (extreme ultraviolet imaging telescope) and YOHKOH spacecrafts are used to track the CME. Solar flare data were obtained from GOES (Geostationary Operational Environmental Satellite). The SEPs intensity-time profile was obtained from ERNE (energetic and relativistic and nuclei and electron) detector on board of SOHO from the website [https://srl.utu.fi/erne_data/datafinder/df.shtml]. The 1-10 min time resolution were used for energy channels 1-116 MeV, chosen according to the most clear background in the profile to extract the injection time clearly.

Data analysis

A logarithmic scale for the intensity-time profile, provided from website [https://srl.utu.fi/erne_data/datafinder/df.shtml], was used. We selected the energy channels from 18 MeV to 90 MeV with 10 min resolution to avoid the fluctuations and the unclear background. In some events when the intensity-time profile is not clear enough (for instant in the high energy channels 90 MeV), we took the lower energy channels instead, as in Figure-2.

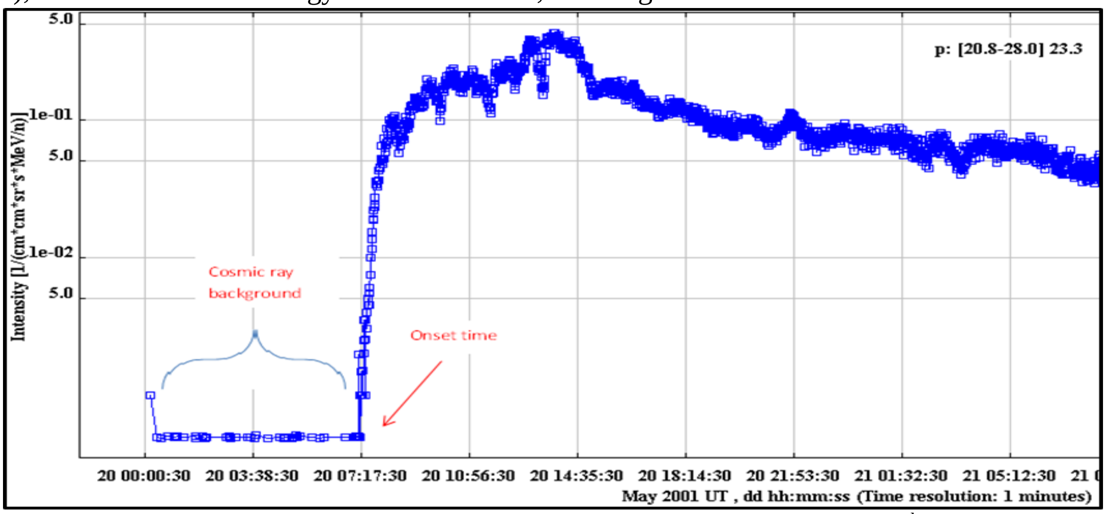

Figure 2- the intensity-time profile of protons for event of May 20th 2001.

The acceleration of SEPs started by the injection due to the eruption which can be connected very well by analyzing the intensity-time profile of protons events and connecting it with solar events such as (CMEs, flares). We calculated the onset-time of the protons from the first rise of the intensity over the cosmic-ray background and as we mentioned earlier we calculate the liftoff time for the CME and the starting of the soft X-ray emission for the solar flare. The association of CMEs was found with most of the events and those CMEs were associated with solar flare. The effect of the parameters of those CMEs and flare were studied during the time of the bulk of the acceleration for the protons which means, the time of the rising phase in the intensity-time profile ΔT1. During the liftoff of the CME a coronal shock will be formed which propagate perpendicular to the solar magnetic field and thus the energy of the interaction will turned to the particles which result for prompt acceleration. This will be continued and grow until it reach the maximum acceleration which can be seen as a maximum intensity. A decay normally will be seen after that in the intensity time profile reflecting a decay in proton acceleration.

Our results showed that when the flare associated with the CME causing the energetic proton event, has a higher class (X, M) a shorter ΔT1 will be found, which it means that faster reaching to maximum acceleration and this means that the bulk of the acceleration occurred when the CME is still close to the solar disc, as shown in fig. 3 right. On the other hand, the class of the flare has a clear effect on the value of the maximum intensity, which means higher value for higher class, as shown in fig. 4 right. As for the CME parameters, few events showed that the acceleration of the CME has an effect on the ΔT1, Figure- 3, left. While we didn't find any influence for the speed of the CME on the ΔT1, but it has a clear influence on the value of the maximum intensity, as shown in Figure- 4, left.

Theoretically, the particles produced by eruption from the western side of the sun arrive earlier than the particles accelerated from the eastern side. The reason behind that is because the eastern particles undergo a long distance from the east due to the poor magnetic connection. This is reflected very clearly in the intensity time profile as a prolonged climbing time. Figure-5 demonstrate an essential difference between typical western and eastern event, the average climbing time ΔT1 in the eastern events reaches up to 7 hours while in western events we found that is about 2 hours.

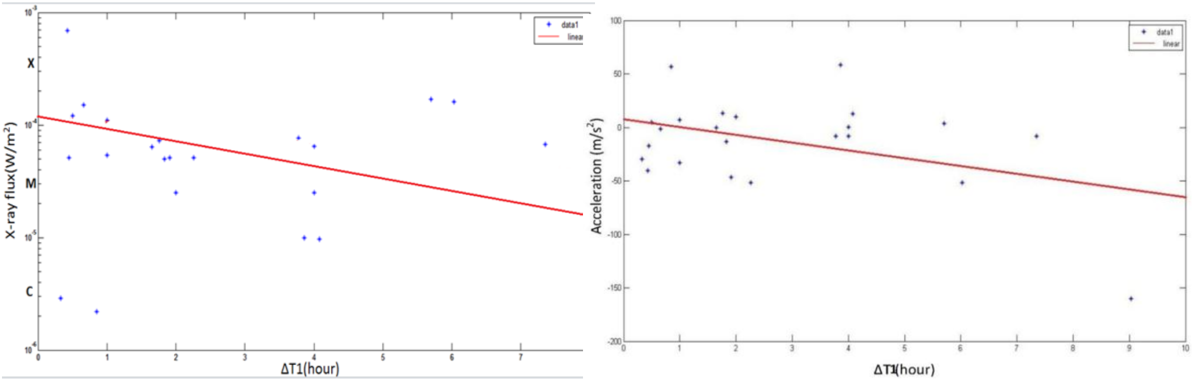

Figure 3- represent a linear fit of inversely proportion relation between flare class and acceleration of CME with ΔT1.

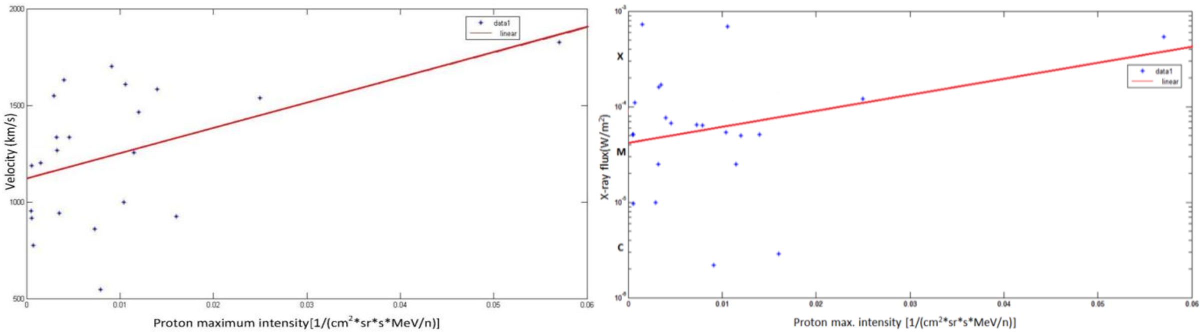

Figure 4- represent a linear fit of directly proportion relation between the speed of CME and class of the flare with the value of maximum intensity.

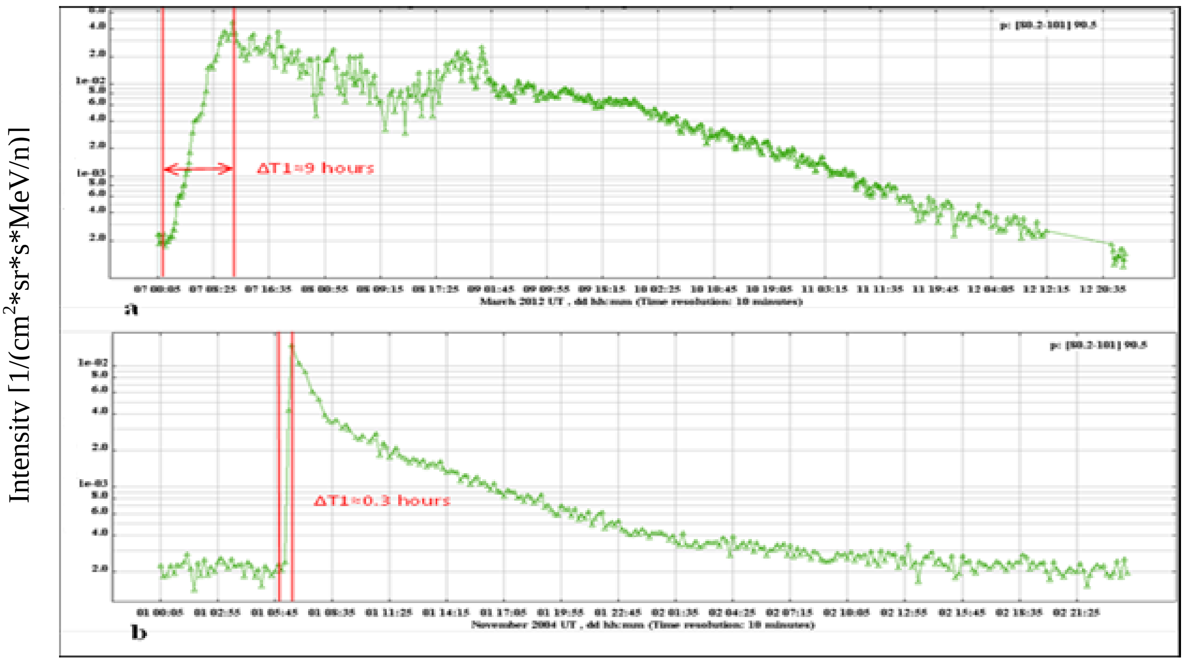

Figure 5- represent a comparison between typical intensity-time profiles for protons of (a)an eastern event and(b)a western event.

Conclusions

We observed 27 energetic proton events during the time interval from the 17th of Feb 2000, to the 10th of Sep 2014, and analyzed their intensity time profile and the associated solar flare and CME, and we found that:

1. The bulk of the acceleration of the energetic protons occurred near the sun because the CME at that position has the greater energy through its course.
2. The bulk of the acceleration has a shorter time (ΔT1) for the western events with an average of about 2 hours, than for the eastern events, which was about 7 hours because of the poor connection of magnetic lines reaches from sun to earth.
3. The climbing time was clearly depending on the power of the associated flare and the acceleration of the associated CME with an inverse relationship. While no effect on the climbing time was seen to depend on the linear speed of the CME. As for the influence of the SEP's energy, ΔT1 decreased with increase of energy of the protons and vice versa.
4. The maximum value of the intensity was strongly depended on the power of the associated flare and the linear speed of the CME. While no influence was found for the acceleration of the CME on the maximum intensity value.

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