Coronal Mass Ejections (CMEs) Interaction and the Acceleration of Solar Energetic Particle (SEP)

H.N.AbedJasim, W.A.Taha, [*]AmjadAl-Sawad

Physics Dept., Science College, BasraUniversity, Basra, Iraq.
Physics Dept.,SpacePhysicsandAstronomy,TurkuUniversity,Finland.

Abstract

This paper presents the analysis of the 16 solar energetic particle (SEP) events have been observed during solar cycles 23 and 24 by using the Energetic and Relativistic Nuclei and Electron (ERNA) instruments on board the Solar and Heliospheric Observatory (SOHO). This observation was covered the period 1998–2012, with intensities of $>10^{-3}$ $cm^{-2}\cdot sr^{-1}\cdot s^{-1}\cdot MeV^{-1}$at energies of 1 MeV to 116 MeV.

The methods used in calculating the first injection of the SEPs associated with solar eruptions, such as CMEs and solar flare were successfully evaluated. In addition, the characteristics of the eruptions that are capable of producing such SEPs and when and where the acceleration of the SEPs starts, also studied.

On other hand, the interaction of coronal mass ejections associated with the events and the effectiveness of this interaction on events were examined. The analysis concluded that CME–CME interactions can be a key factor in particle acceleration and transport.It is found thatthere are two identified types of interactions that affect particle injection, distinguish the different interactions according to the intensity-time profile as follows:

1. In the CME–CME interactions happen at the beginning of the event.

2. There are distinct events of the interactions between (CME1) and new particles (SEP2) which result from (CME3).

Key words. Sun: coronal mass ejections (CMEs) – solar flares –corona –solar energetic particle(SEP) – acceleration of particles.

1. Introduction

Solar energetic particle (SEP) events are one of the most interesting phenomena in solar physics, which have been widely observed near the Earth with energy ranges varying from some keV/nucl to the GeV. They might have different sources, for example, from solar flare in the low corona, coronal shock and interplanetary shocks driven by CMEs.

Knowing when and where exactly the solar particles are produced and injected onto field lines is important in the study of the mechanisms of particle acceleration and transport. Extrapolating the particle release times by onset time analysis is a means to obtain such information. The onset time of particles should be proportional to the reciprocal of particle speed ***v***(Ismael Diaz *et al.* 2011).

Only observations can tell us which part is the major accelerator (coronal or interplanetary) and which one is minor. If the bulk of the acceleration is due to coronal shock, then the flare might be in charge of the major acceleration beside the CME, since coronal shock could be due to flare. But if the bulk of acceleration takes place in interplanetary medium, then the interplanetary shock driven ahead of the CME is the major accelerator and hence the flare part in acceleration will be a minor or even not at all an accelerator. However, the existence of separate flare blast wave and CME-driven shocks would have interesting implications for SEP acceleration (Cliver *et al.* 2004), and if we can deduce the SEP injection profiles at the Sun relative to the flare impulsive phase and to the appearance of the CME, we can begin to understand the roles of the impulsive phase and coronal shocks in producing the SEP events. The prompt emission could be attributed to acceleration by coronal shocks at early times in the eruption, whereas the delayedcomponent is accelerated by the CME bow shock at greater distances, >5R from the Sun (Kahler, 1994).

On the other hand, a CME-driven shock may not itself accelerate significant numbers of particles out of the ambient solar wind to high energies, but it can confine and re-accelerate particles initially accelerated close to the Sunoccurs even at 1 AU (Kallenrode, 2003).

There was an argument that the acceleration mechanism which is responsible for impulsive flares, is somehow involved in acceleration of particles in gradual events.The gradual events contains an impulsive flare part, which share in later acceleration mechanisms.The coronal acceleration behind the bow shock of the CME leaves its fingerprints in the particle time profile at 1 AU (Klein *et al.*, 2000). Since CMEs are magnetic structures carrying ionizedplasma, the physics of the interaction would therefore be very complex. The nature of the interaction depends on whether the CME magnetic structures interact,but in all cases the result is an equalization of the speed ofthe two CMEs.In the absence of magnetic interaction, the forward shock of the faster CME interacts with the slow leading CME, and accelerates it.When the two CMEs have magnetic fields with the same sense of rotation, magnetic reconnection occurs between the two CMEs, leading to the formation of a single magnetic structure: in the most extreme cases, one CME "eats" the other. When the senses of rotation are opposite, reconnection does not occur, but the CMEs collide in a highly non-elastic manner, again forming a single structure. The possibility of enhanced particle acceleration in such processes is assessed. The presence of strong magnetic reconnection provides excellent opportunities for the acceleration of particles, which then form a seed population for further acceleration at the CME shocks (Schmidt and Cargill 2004).

Observational and numerical studies have shown that a CME's shape, velocity, and direction may change significantly through collisions and interactions.

Questions arise as to what dominates SEP injectionand what thecause of particle acceleration is.The primarily aims fromthis study is to addressthese questions throughselected events.

2. Data Analysis

In Table (1)analysis of 16 solar energetic particle (SEP) events have been studied during solar cycles 23 and 24.

This study adopted the energetic proton observations from the SOHO/ERNE (Torsti et al 1997) particle instrument, which consists of two particle detectors, namely, low-energy detector (LED) with an energy range of 1.3 MeV to 13 MeV and high-energy detector (HED) with an energy range of 13 MeV to 140 MeV**.**

For the proton events, we determined the onset times for up to 20 energy channels (10 LED channels and 10 HED channels)(Huttunen–Heikinmaa *et al.* 2005)assumed that particles with different energies are released simultaneously at or close to the Sun.

We performed VelocityDespertion Analysis(VDA) and fixed-path length methods (1.2 AU) for all events using data with a 1 min time resolution. The flighttime of the non-scattered protons along the Archimedean field line with a nominal length of 1.2 AU and subtracted the result from the observed time on ERNE wascalculated. All data calculated by both methods at proton injection times.

The injection time of the first protons to the lift-off time on the SOHO/LASCO catalog at http://cdaw.gsfc.nasa.gov/CME_list/ was compared to determine the closest CMEs to the events.

We searched for associated eruptions at the Sun for each event. The soft X-ray and Hα flare characteristics were obtained from solar geophysical data listings (NGDC). The characteristics of the associated CMEs were derived from the LASCO CME catalog.

The approximate value for the height–time of the CME wascalculated.

The speed is normally determined from a linear fit to the height-time (h-t) plots but CMEs often have finite acceleration, so that the linear fit speed should be understood as the average value within the coronagraphic field of view. Quadratic fit to the (h-t) plot gives the constant acceleration, which is again an approximation because the acceleration may change with time (Gopalswamy 2006).

Linear and quadratic fit wereemployedto determinewhere and when the located interaction between the primary (CME1) and the preceding CME (CME2) occurs. The effect ofthis locationon acceleratingparticles was also analyzed.

3. Resultsand Discussion

One of the main tasks in space physicsisto understand where and how solar particles are accelerated to high energies in large solar energetic particle (SEP) events.

Large SEP events are always associated with flares and coronal mass ejections (CMEs), both of which are different manifestations of the same process of magnetic energy release**.** Theoretically, flares and CME-driven shocks can accelerate charged particles to high energies. Evidence also shows that direct particle acceleration in flare sites cannot be ruled out(Li *et al.* 2013).Figure (1) shows the flareassociated with theevent(9-11 May 1998).Also there is a clear role for the interaction of two successive coronal mass ejections (CMEs) to particle acceleration.

An estimated CME height was provided for each method obtained injection time of SEPs (1.2 AU and VDA).The CME locations obtained with average injection times.The CME heliocentric heights measured by the two determination methods are fairly close. Among the CMEs, proportion of them are located between 5 and 10 Rs; other ratio are located below 5 Rs, and the proportion of are located above 10 Rs,theseare shown in the attached table (1).

The first injection time associated with solar flare and thepossible CME interaction in these events are discussed.The bulk of the proton events are associated with CMEs with a speed above 460 km/s and a width above 80°.Most of the CMEs are halo CMEs.

High-energy protons are mostly caused by powerful eruptions. In the associated CMEs, this event usually means high speed, large AW, western side, and a huge SEP flux. For solar flares, such an event mostly indicates high intensity and long duration of X-ray flares. The proton events are all associated with CMEs.

In this study, we utilized quadratic fits on the height–time plots of the interaction between CME1 and CME2. The heights of each interaction and the injection time using 1.2 AU and VDA methods for all selected events.

Also we obtained twotypesofinteractionaffect particleinjection:

1. CME–CMEinteraction. This interaction type occursat the beginning ofan event (Figure (2)).

2. Interaction typeoccurs witha change in theintensity–time profile of SEP. Duringexamination, we found anewinjectionof SEPsas a result of new SEPs (SEP2) from CME3that cameafterCME1.

4. Conclusions

In this study, we analyzed the SEP events' intensity–time profiles during solar cycles 23 and 24 by using the ERNE data finder application.A set of 16 energetic proton events selected from May 1998 to July 2012, was chosen by taking the most extensive possible energy range starting from 1 MeV up to 116 MeV to estimate the associated CME's height at the obtained SEP first injection time and at thepoint of CMEinteractions.

The principal results from these studies may be summarized as follows:

1. All of the studied events were associated with CMEs, and most of the first injected protons in those events were associated with CMEs,Proportion of the CMEs were associated with solar flares.
2. The measured CME heights, which were obtained by comparing the results from the VDA and 1.2 AU methods, are fairly close to one another.
3. Our results confirm the hypothesis that an earlier injection close to the sun in the flare site accompanies the liftoff of CMEs, and SEP acceleration continues because of the different mechanisms in each phase of the propagation of CMEs near the Sun and in the interplanetary medium.
4. CME–CME interactions can be a key factor in particle acceleration and transport. The efficiency in particle acceleration is expected to change because of modifications in shock strength and structure of the preceding ejection.
5. Based on the analysis of the studied events, we identified twotypesofinteractionsthataffectparticleinjection, as follows:
    a. CME–CME interactions happenat the beginning ofthe event.
    b. There are distinct events of the interactions between (CME1) and a new particles (SEP2) which result from (CME3)that cameafterCME1.

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تفاعل الكتل الاكليلية المنبعثة وتعجيل الجسيمات الشمسية النشطة

هديل نجم عبد جاسم، واثق ايوب طه، *امجد عبد النبي السواد

***قسم الفيزياء، كلية العلوم، جامعة البصرة، البصرة، العراق**
***قسم الفيزياء، مختبر ابحاث الفضاء، جامعة تركو، فلندا**

الملخص:

يقدم البحث تحليل16 حدث للجسيمات الشمسية النشطة (SEPs) رُصدت خلال الدورات الشمسية 23 و24 باستخدام جهاز (ERNE) المحمول على متن المركبة الفضائية (SOHO) خلال الفترة 1998–2012، حيث كانت الشدة لهذه الجسيمات اكبر من ($10^{-3}\ \mathrm{cm^{-2}\cdot sr^{-1}\cdot s^{-1}\cdot MeV^{-1}}$)للطاقات من(1–116) ميكا إلكترون فولت.تم تقييم الأساليب الحسابية المستخدمة في عمليات الحقن الاولي لهذه الجسيمات المرتبطة بالانفجارات الشمسية، مثل الكتل الاكليلية المنقذفة (CMEs) والتوهج الشمسي. درسنا خصائص الانفجارات القادرة على انتاج مثل هذه الجسيمات وتحديد متى وأين يبدأ تعجيل هذه الجسيمات الشمسية .

قمنا بدراسة تفاعل الكتل الاكليلية المرافقة للأحداث ومدى فعالية هذا التفاعل واستنتجنا أن التفاعلات CME–CME يمكن أن تكون عاملا رئيسا" في تعجيل الجسيمات الشمسية وعملية النقل فيها. حددنا نوعين من الاصطدامات التي تؤثر في حقن الجسيمات، وقد ميزت باختلافها على النحو التالي:

1– يكون التفاعل بين كتلتين اكليليتينCME–CME عند بداية الحدث.

2– هناك احداث تميزت بتفاعلات بين (CME1) وجسيمات شمسية منشطةجديدة (SEP2)الناتجة من (CME3).

الكلمات المفتاحية:

الكتل الاكليلية المنبعثة، التوهجات، الاكليل، الجسيمات الشمسية النشطة، تعجيل الجسيمات الشمسية.

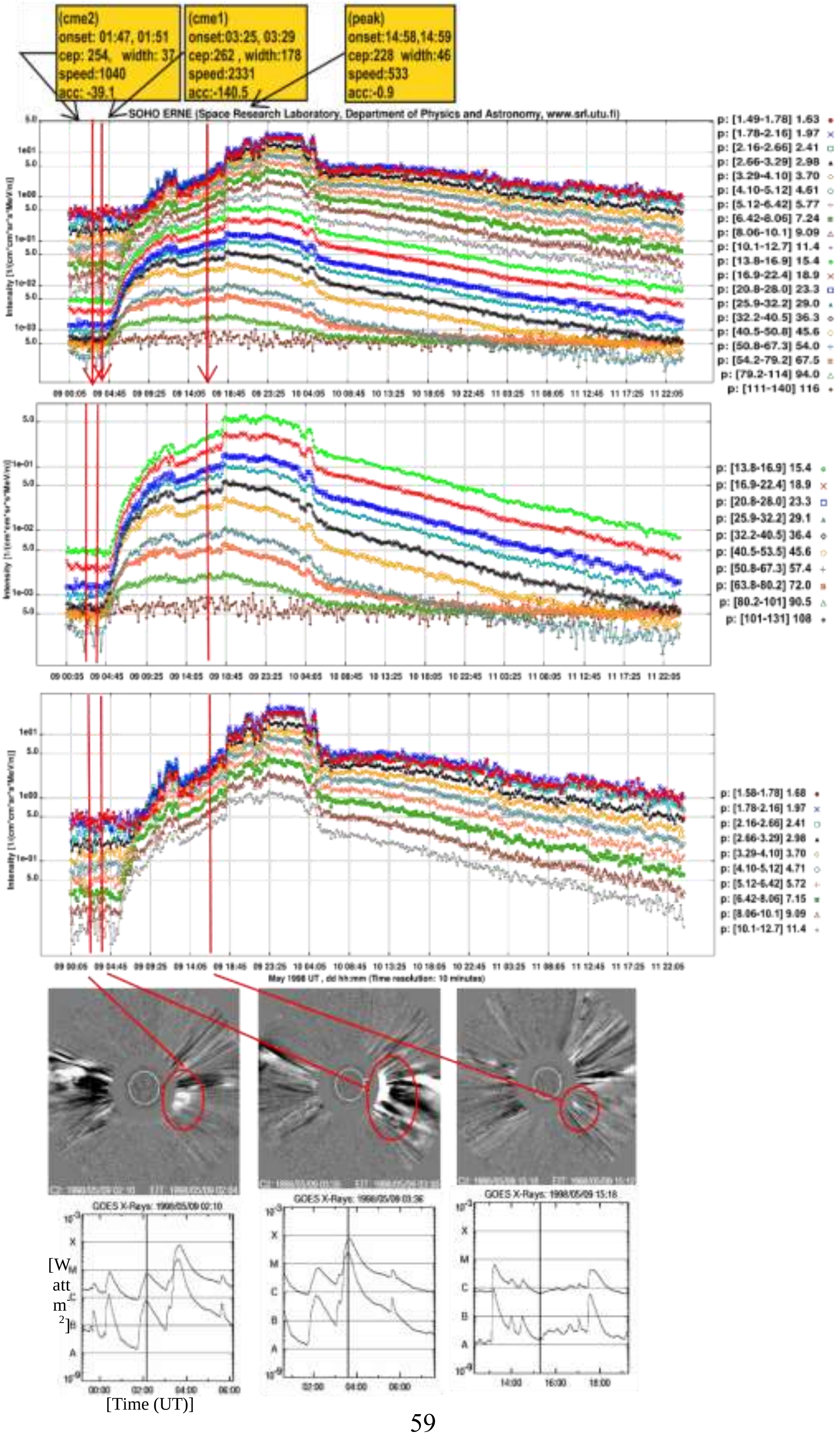
(cme2)
onset: 01:47, 01:51
cep: 254, width: 37
speed:1040
acc: -39.1
(cme1)
onset:03:25, 03:29
cep:262 , width:178
speed:2331
acc:-140.5
(peak)
onset:14:58,14:59
cep:228 width:46
speed:533
acc:-0.9
SOHO ERNE (Space Research Laboratory, Department of Physics and Astronomy, www.srl.utu.fi)
Intensity [1/(cm^2*sr*s*MeV/n)]
09 00:05
09 04:45
09 09:25
09 14:05
09 18:45
09 23:25
10 04:05
10 08:45
10 13:25
10 18:05
10 22:45
11 03:25
11 08:05
11 12:45
11 17:25
11 22:05
p: [1.49-1.78] 1.63
p: [1.78-2.16] 1.97
p: [2.16-2.66] 2.41
p: [2.66-3.29] 2.98
p: [3.29-4.10] 3.70
p: [4.10-5.12] 4.61
p: [5.12-6.42] 5.77
p: [6.42-8.06] 7.24
p: [8.06-10.1] 9.09
p: [10.1-12.7] 11.4
p: [13.8-16.9] 15.4
p: [16.9-22.4] 18.9
p: [20.8-28.0] 23.3
p: [25.9-32.2] 29.0
p: [32.2-40.5] 36.3
p: [40.5-50.8] 45.6
p: [50.8-67.3] 54.0
p: [54.2-79.2] 67.5
p: [79.2-114] 94.0
p: [111-140] 116
p: [13.8-16.9] 15.4
p: [16.9-22.4] 18.9
p: [20.8-28.0] 23.3
p: [25.9-32.2] 29.1
p: [32.2-40.5] 36.4
p: [40.5-53.5] 45.6
p: [50.8-67.3] 57.4
p: [63.8-80.2] 72.0
p: [80.2-101] 90.5
p: [101-131] 108
p: [1.58-1.78] 1.68
p: [1.78-2.16] 1.97
p: [2.16-2.66] 2.41
p: [2.66-3.29] 2.98
p: [3.29-4.10] 3.70
p: [4.10-5.12] 4.71
p: [5.12-6.42] 5.72
p: [6.42-8.06] 7.15
p: [8.06-10.1] 9.09
p: [10.1-12.7] 11.4
May 1998 UT , dd hh:mm (Time resolution: 10 minutes)
GOES X-Rays: 1998/05/09 02:10
GOES X-Rays: 1998/05/09 03:36
GOES X-Rays: 1998/05/09 15:18
X
M
C
B
A
[Watt m-2]
[Time (UT)]

Figure (1): event 1 (9-11 May 1998), the top panel intensity time profile for protons from SOHO/ERNE contains energies (1-116 MeV) displays CME1&CME2, second panel contains high energies only, third panel contains only low energies and the bottom panel is GOES/soft X-ray associated with first eruption.

Table (1): Onset time, , energy level, injection time in the 1.2 AU method, VDA method , height of CMEs from LASCO with the heliocentric heights for theinjectiontime using 1.2 AU and VDA methods, , interaction time with the height of theinteractions, lift-off CMEs, and duration and location time of solar flare for every event.

Event No.	DD.MM.YY	Onset Time (UT)	Energy (MEV)	(1.2AU) Injection Time (UT)	Height of (1.2AU) Injection Time (Rs)	(VDA) Injection Time (UT)	Height of(VDA) Injection Time (Rs)	Interaction Time (UT)	Height of Interaction. (Rs)	CME1 Lift Off	CME2 Lift Off	Solar Flare (S. X-ray)				Hα	A.R.
												Class	Start	Max	End		
1	09.05.98	04:34	94.0	04:18	12.78	03:58 ± 11.4	8.18	04:28	14.93	03:27 ± 2	01:49±2	M 7.7	03:04	03:40	03:55	SW100*	---
2	17.02.00	21:45	18.9	21:03	3.64±0.2248	21:01 ± 2.0	3.48±0.2248	21:49	7.26	20:19 ± 11	18:52±7	M1.3	20:17	20:33	21:07	S29E07	8872
3	23.04.00	14:05	45.6	13:40	10.46±0.2143	13:33 ± 25.5	9.63±0.2143	13:31	9.40	12:16 ± 8	08:55±19	---	---	---	---	NW110*	--
4	06.06.00	19:35	4.71	18:02	16.40±0.2698	17:56 ± 14.5	15.82±0.2698	----	----	15:22 ± 1	14:58±5	X2.3	14:58	15:25	15:40	N20E18	9026
5	12.09.00	13:05	45.6	12:40	7.92±0.300	12:39 ± 7.5	7.81±0.300	----	----	11:42 ± 4	10:06±19	M1.0	11:31	12:13	13:13	S17W09	---
6	02.04.01	12:25	57.4	12:03	6.44±0.214	12:10 ± 15.6	7.03±0.214	11:35	4.15	10:58 ± 1	8.35	X1.1	10:58	11:36	12:05	N16W62	9393
7	10.04.01	07:25	57.4	07:03	23.41±0.310	06:20 ± 3.3	12.79±0.310	05:37	4.32	0.5:19 ± 2	02:06±3	X2.3	05:06	05:26	05:42	---	9415
8	01.10.01	09:30	45.6	09:05	29.49±0.226	09:04 ± 8.2	29.3±0.226	07:44	16.55	05:19 ± 10	01:08 ± 9	----	----	----	----	----	----
9	22.10.01	15:52	36.4	15:24	5.08±0.610	15:20 ± 13.5	4.60±0.610	16:51	15.31	14:49 ± 1	08:30±11	M6.7	14:27	15:08	15:31	S21E18	9672
10	07.07.02	12:15	57.4	11:53	6.93	11:45 ± 7.6	6.01	11:43	5.89	11:02 ± 2	10:15	M1.0	11:15	11:43	13:17	----	-----
11	09.11.02	14:38	57.4	14:16	10.91±0.272	14:14 ± 20.2	10.60±0.272	14:08	9.74	13:11 ± 1	10:45±6	M4.6	13:08	13:23	13:36	S12W29	10180
12	18.08.10	06:45	57.4	06:23	7.83±0.176	06:18±9.0	7.17±0.176	05:49	3.28	05:30±2	23:22±64	C4.5	04:45	05:48	06:51	N17W97	1099
13	07.03.11	21:10	57.4	20:48	11.72±0.207	20:46±8.4	11.43±0.207	20:04	2.97	19:52±2	06:37±15	M1.4	19:46	20:16	21:19	S20W68	1165
14	26.11.11	08:27	45.6	08:02	6.63±0.285	07:51±18.6	5.79±0.285	10:23	17.90	06:49±3	23:08±58	---	---	---	---	N18E06	1356
15	26.05.12	21:48	45.6	21:23	9.98±0.309	21:25±9.6	10.38±0.309	21:55	16.02	20:35±6	16:32±12	---	---	---	---	S12E38	1492
16	17.07.12	15:58	11.4	15:02	5.48±0.343	15:00±9.3	5.36±0.343	14:58	5.23	13:36±33	12:07±2	M1.7	12:03	17:15	19:04	----	1520

Data with (*) incolumn**Hα** are obtained from [Cane *et al.* 2002].

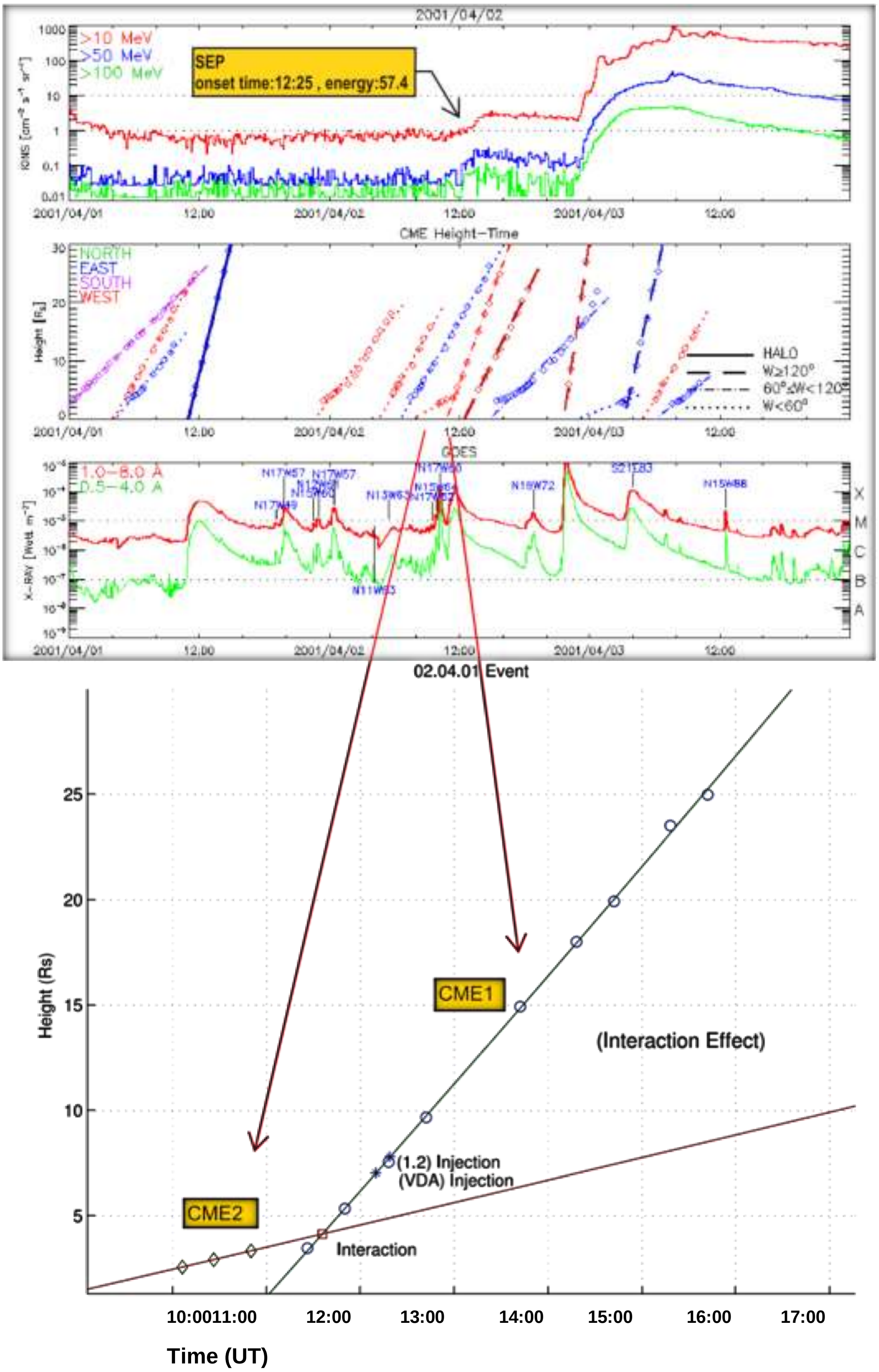

Figure (2): Intensity – time profile from GOES exhibit event 6 (2-4 April 2001) with CME1&CME2 height time compared with our calculations for the (height-time) fitting for two CMEs.