An Interactive Program for Correlative Studies of Solar Energetic Particle Events

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Abstract. We have developed an interactive program which shows the solar energetic particle (SEP) intensity-time profile as observed by SOHO/ERNE, simultaneously with the associated coronal mass ejection in optical imaging movies taken by LASCO coronagraph, soft X-ray by YOHKOH, ultraviolet by EIT, DH radio emission by WAVE/Wind, and the Hα location for the solar flare and spectral radio emission from the journal of geophysical data. The whole set of data will provide increased scientific knowledge on the solar energetic particle events and the solar phenomena associated with them, because in this program one can see easily the temporal associations of each phenomenon during the evolution of the particle intensity. The (SEP) intensity-time profile will give a clear view to detect the velocity dispersion in the events, if it exists. The ERNE data are commented in order to follow of phenomena associated with changes of the intensity-time profiles. We introduce this set of data as an index for the ERNE/SOHO solar energetic particle events. The interactive program is applied for statistical, correlative study of SEP events observed on board SOHO.

1. Introduction

Solar energetic particle (SEP) events are one of the most interesting phenomena in solar physics, which has been widely observed near the Earth with energy ranges varying from some keV/nucl to some GeV and they might have different sources such as solar flare in the low corona, coronal shock and interplanetary shocks driven by CMEs. Mason et al. (1999) suggested that high energy and low-energy particles may result from different seed populations and acceleration mechanisms. The sources of the SEP events have been studied in the last two decades in details, but still there are lots of arguments about the the main accelerators for the energetic particles in different levels of energy. Different classes of events may produce or accelerate different ranges of energies and intensities. The intensity-time profile and the associated solar phenomenon and composition studies are probably the main sources for such studies.
In the 1980's the solar flares and coronal mass ejection CME have been considered the main source for the SEP events. On the basis of SEP events signature in soft X-ray Cane et al. (1986) found out two classes: 1) impulsive events, which have high electron-to-proton ratio, and are never associated with interplanetary shocks, but are associated to impulsive flares that occur low in the corona, and 2) gradual events, which can accelerate much higher proton energies and are well associated with coronal and interplanetary shocks, and occur high in the corona in extended regions.

To study the association of solar flares to the SEP events one has to follow all the data related to soft X-ray emission and Hα line absorption. The GOES series of satellites provide observations through the Solar Geophysical Data. On the other hand, the YOHKOH satellite provides continuous observation for the Sun in soft X-ray emission. Coronal Mass Ejections (CMEs) have been shown to be associated with Long Duration Events (LDEs) (Sheeley et al., 1975; Kahler, 1977; and Sheeley et al., 1983), and with interplanetary shocks (Sheeley et al., 1983, 1985).

The role of CMEs and solar flares in accelerating the SEP is not clear yet. Gosling (1993), in his solar flare myth paper has moved the central role of SEP from flares to CMEs. There are different ideas about the role of coronal and interplanetary shocks. On the one hand, Reames (1999) suggested that most intense SEP events, with particles of highest energies, are produced by acceleration at collisionless shock wave driven by CMEs. But on the other hand, Kallenrode (1996) suggested that 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 which were initially accelerated close to the Sun. Between the two arguments, some recent studies indicate that SEPs may be produced also on the global corona scale between the impulsive flare and the interplanetary shock (Kocharov et al., 1999; Laitinen et al., 2000; Klein & Trottet, 2001). The LASCO coronagraph on board of (SOHO) is a rather good tool for getting available scientific data concerning the CMEs. Thus, to study SEP events we have to follow carefully each changing in the intensity-time profile and find the link with the associated eruptions in the Sun.

Associations of radio emission with SEP events are very important to determine characteristics of eruptions and acceleration mechanisms. Kahler (1982) concludes that the occurrence of a type IV burst "appears to be a requirement for most proton flares" at energies >20 MeV. Type IV bursts are often, but not always, accompanied by type II bursts, which reveal the passage of a large scale shock wave through the corona (Klein & Trottet, 2001).

Type II radio bursts are believed to be produced by shocks propagating through the solar corona and interplanetary medium (e.g., Rieger et al., 2000). It is generally accepted that metric type II (slow-drift) solar radio bursts are manifestations of coronal shock waves caused by disturbances moving outward through the solar atmosphere with speeds of several hundred kilometers per second (Nelson & Melrose, 1985). The existence of fast mode shocks in the corona is strongly supported by the observation of rapidly drifting radio bursts and their association with fast (≥400 km/s) CMEs (e.g., Kahler, 1992).

There has been a long-standing controversy about the relation between metric type II bursts, flares, CMEs and IP shocks (Chao, 1974, 1984; Wagner
& McQueen, 1983; Gosling, 1993; Gosling & Hundhausen, 1995; Svestka, 1995; Dryer, 1996; Gopalswamy et al., 1998; Cliver et al., 1999). Using the data from November 1994 to June 1998, Gopalswamy et al. (1998) reported that 93 metric type II bursts did not have interplanetary signatures. On the other hand, Cliver et al. (1999) insisted that metric type II, EIT wave, and decimetric-hectometric type II bursts are driven by fast CMEs. The recently observed EIT waves are found to be associated with metric type II bursts (Klassen et al., 1997; Gopalswamy et al., 2000) in their speeds and positions as well as with CMEs (Thompson et al., 2000).

A distinction is generally made between type II radio bursts observed at decimetric-metric wavelengths, referred to as coronal type II bursts, and hectometric-kilometric wavelengths, referred to as IP type II radio bursts. While IP type II bursts are usually ascribed to bow shock waves driven ahead of a CME piston (Kahler 1992), the proposed origins for coronal type II bursts are still debated. Some suggest that these are CME driven, like interplanetary shocks (Cliver, Webb & Howard, 1999). However, coronal type II bursts are known to have a close temporal association with solar flares (Swarup, Stone & Maxwell, 1960; Dodge, 1975; Cane & Reames, 1988).

Recently, Reiner et al. (2001) suggested that the harmonic component of metric type IIs can be possibly related with decimetric-hectometric type IIs. Also, Leblanc et al. (2001) argued from 10 type II bursts that the shock waves may be driven by the CMEs all the way from $\sim 1 R_\odot$ to 1 AU. In addition, they admitted for some events that the evidence available cannot exclude the hypothesis that the shock is a blast wave from the flare to 1 AU (Smart & Shea, 1985). Cho et al. (2003) reported that CMEs and flares are initiated nearly simultaneously, at least for type II associated events, based upon the temporal relationship obtained from data from May 1998 to December 2000. Recently, it has been suggested that CMEs and flares (metric type II) are initiated nearly simultaneously (e.g., Zhang et al., 2001; Neupert et al, 2001; Moon et al., 2002; Cho et al., 2003; Shanmugaraju et al., 2003).

We have provided all the above important data running simultaneously with the intensity-time profile provided by ERNE/SOHO to establish new view for studying the SEP events and to achieve the result for such studies much more easily.

2. The Data

We have used intensity-time profile for proton and Helium particles provided by the two ERNEs detectors, High Energy Detector (HED) and Low Energy Detector (LED) (Torsti et al., 1997). We used the linear intensity-time profile and compare the closest eruption on the Sun to the first arrived protons on the high energy channels. The SOHO/LASCO catalog at [http://cdaw.gsfc.nasa.gov/CME_list/UNIVERSAL/](http://cdaw.gsfc.nasa.gov/CME_list/UNIVERSAL/) has been used to determine the closest CMEs to those events. For each event we suggest one or more CMEs seen by Lasco and make the movies run simultaneously with the intensity-time profile. We also make all the features (speed, acceleration, central position angle and angular width of the associated CMEs), available in the comments. Then we repeat the same steps with the Yohkoh movies, to provide the information about the solar flare through the observa-
Figure 1. The interface of the interactive program

The EIT movies are also provided to detect the EIT wave onset and give more information about the associated solar flare. From the (Solar Geophysical Data) we use the data concerning the metric radio emission associated to the event. The decimetric-hectometric radio emission data are provided through WAVES/Wind.

3. The Program

First step in studying the SEP events through the interactive program is to start with the catalogue interface 1. Fig. 1 shows the interface of the program. The time starts with the year that SOHO started to operate and continues as long as it stays operating. For an exact event in mind, one can just select the month in the year that this event has occur. Look through that list for chosen event and then click on it. Another interface will open Fig. 2. The chosen energy channels for that event will appear on the upper left side of the page. The selection is based on the fluctuation of the intensity-time profile. We normally choose the

1The Interactive program is temporarily located at http://www.it.savonia-amk.fi/hhoffren/soho/index.php
Figure 2. Demonstration for one of the analyzed events, the event of 9th of May 1998

less fluctuating energy channels with 10 minutes resolution. One can choose the energy channel that he likes to study and run it, or he can choose as many as he like and run them simultaneously. Each energy channel has different color. In Fig. 2 we have chosen six energy channels, three from protons and three from helium. The vertical line, which moves with the mouse in the interface shows the time at the position. On the same time the reading for the intensity will appear in the channel list in the top left.

On the upper right side of the interface there is a button. Which hides movies of Lasco, EIT and Yohkoh. Below the movies another button, which shows the comments, metric and D-H radio emission.

Normally we add our own comments to each event. The comments include the suggested eruption at the Sun, which is thought to be the source of the event. In some events there might be multiple eruptions. Those events we denote as Multi-Eruption Solar Energetic Particle Events (MESEP). An attempt to a statistical study for such events are being worked out. Work is underway to mark each event as a high energy or low energy event, depending on the highest energies produced by that event. The information about the associated metric and D-H radio emission were written according to the timing from the start of the event.
4. Measurements

The program is using the linear plotting for the intensity-time profile. This makes it easy to recognize the onset times of the events which shows clear velocity dispersion, that is, a higher energy channel starts to rise earlier than a lower energy one (see Fig. 2). When you have such event with velocity dispersion it means that it is mostly related to an eruption at the Sun. Thus we need to calculate the injection time of the event and compare it to the eruptions suggested by Lasco, EIT and Yohkoh.

The calculation for the injection time of the particles at the Sun can be achieved through two ways. The first way, similar to Torsti et al. (1999), is to consider that the non-scattered particles of the chosen energies are propagating along the Archimedean field line of nominal length 1.2 AU and calculate the flight time of those particles by using the particle energy. Then subtract the flight time from the observed time on ERNE and add 500 sec to get the observed time fit with the optical, radio and soft X-ray data. In the near feature you can get the result automatically by just clicking on the estimated onset time that you chose. The second way is to take into consideration the possibility that particles in different events might take different path lengths rather than the nominal 1.2 AU, assuming that particles of different energies were released simultaneously at the Sun, that the energy of the particle remains unchanged through the passage from the Sun to \( \sim 1 \) AU, and that the path length does not depend on the energy. This method employs the \( \frac{1}{\beta} \) technique discussed in detail by Debrunner, Flückiger and Lockwood (1990), Debrunner et al., (1997) and recently by Huttunen-Heikinmaa et al. (2005). We have added this calculation in some events that have been analyzed lately. On the other hand, multi-eruption events can be followed through the program since we provide the movies related to the time interval for the intensity-time profile of ERNE.

The well known problem which faces the calculation of the injection time is the background of the intensity-time profile. In some channels the background are not reliable to included in the measurements in both ways. In the interactive program it is easy to recognize the corrupted background in some energy channels. In Fig. 2 the background of highest channel of the protons intensity seems not to be in line with the others.

5. Conclusion

We have created a program for correlative studies of solar energetic particles events and we think that this program will be an effective tool for those kinds of studies according to the following facts:

1- The program provides a set of data, concerning the associated phenomenon with each SEP event in one body of work, which can not be found where else.

2- The intensity-time profile provided by ERNE instrument is running simultaneously with the associated phenomenon, so that the recognition of the association with each change in the intensity-time profile is easy.

3- The tools for calculating time and intensity are very easy to use.
The calculation for injection time is available for each event and for any energy, which will save time and work for researchers.

The previous studies for the events provided by statistical studies are available on the comments and provide help in studying the SEP events.

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