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MULTI-ERUPTION SOLAR ENERGETIC PARTICLE EVENTS OBSERVED BY SOHO/ERNE

by

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Abstract

In the last two decades of studying the Solar Energetic Particle (SEP) phenomenon, intensive emphasis has been put on how and when and where these SEPs are injected into interplanetary space. It is well known that SEPs are related to solar flares and CMEs. However, the role of each in the acceleration of SEPs has been under debate since the major role was taken from flares ascribed to CMEs step by step after the skylab mission, which started the era of CME spaceborn observations. Since then, the shock wave generated by powerful CMEs in between 2-5 solar radii is considered the major accelerator. The current paradigm interprets the prolonged proton intensity-time profile in gradual SEP events as a direct effect of accelerated SEPs by shock wave propagating in the interplanetary medium. Thus the powerful CME is thought of as a starter for the acceleration and its shock wave as a continuing accelerator to result in such an intensity-time profile. Generally it is believed that a single powerful CME which might or might not be associated with a flare is always the reason behind such gradual events.

In this work we use the Energetic and Relativistic Nucleus and Electrons ERNE instrument on board Solar and Heliospheric Observatory SOHO to present an empirical study to show the possibility of multiple accelerations in SEP events. In the beginning we found 18 double-peaked SEP events by examining 88 SEP events. The peaks in the intensity-time profile were separated by 3-24 hours. We divided the SEP events according to possible multiple acceleration into four groups and in one of these groups we find evidence for multiple acceleration in velocity dispersion and change in the abundance ratio associated at transition to the second peak. Then we explored the intensity-time profiles of all SEP events during solar cycle 23 and found that most of the SEP events are associated with multiple eruptions at the Sun and we call those events as Multi-Eruption Solar Energetic Particles (MESEP) events. We use the data available by Large Angle and Spectrometric Coronograph LASCO on board SOHO to determine the CME associated with such events and YOHKOH and GOES satellites data to determine the flare associated with such events. We found four types of MESEP according to the appearance of the peaks in the intensity-time profile in large variation of energy levels. We found that it is not possible to determine whether the peaks are related to an eruption at the Sun or not, only by examining the anisotropy flux, He/p ratio and velocity dispersion. Then we chose a rare event in which there is evidence of SEP acceleration from behind previous CME. This work resulted in a conclusion which is inconsistent with the current SEP paradigm. Then we discovered through examining another MESEP event, that energetic particles accelerated by a second CME can penetrate a previous CME-driven decelerating shock. Finally, we report the previous two MESEP events with new two events and find a common basis for second CME SEPs penetrating previous decelerating shocks. This phenomenon is reported for the first time and expected to have significant impact on modification of the current paradigm of the solar energetic particle events.

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Turku, October, 2009

Amjad Al-Sawad

Contents

List of refereed publications included in the Thesis

The thesis is comprised of three refereed research papers published in international scientific journals (papers I, III, IV), one research paper published in a refereed proceedings book of an international conference (paper II) and one research paper published in a proceedings book of an international conference (paper V). The papers are listed below:

Paper I: Amjad Al-Sawad, Jarmo Torsti, Leon Kocharov, and Kalle Huttunen-Heikinmaa. A search for two-component energetic proton events observed onboard SOHO. Journal of Geophysical Research, VOL. 111, A10S90, doi:10.1029/2005JA011362, 2006

Paper II: Amjad Al-Sawad
Multi Eruption Solar Energetic Particle events observed with SOHO/ERNE. YSC'14 Proceedings of Contributed Papers (eds. G. Ivashchenko, A. Golovin), pp. 5-14, 12/2007

Paper III: Amjad Al-Sawad, Oskari Saloniemi , Timo Laitinen and Leon Kocharov. Observation of solar energetic particle event behind previous coronal mass ejection. Astronomy and Astrophysics, 497, Issue 1, pp.L1-L4, 2009.

Paper IV: L. Kocharov, T. Laitinen, A. Al-Sawad, O. Saloniemi, E. Valtonen and M. J. Reiner. Gradual solar energetic particle event associated with a decelerating shock wave. Astrophysical Journal letters, 700, L51-L55, 2009.

Paper V: Amjad Al-Sawad, Oskari Saloniemi , Timo Laitinen , Leon Kocharov and Eino Valtonen. Probing successive coronal mass ejections using high-energy protons Proceedings of the 31st International Cosmic Ray Conference Lodz/Poland 5-15.07.2009.

Part I

Introduction

Chapter 1

Motivation

The Sun is a star of our Milky Way galaxy embedded about 33 000 light years from the center. The Sun is a typical main-sequence star of spectral class G. It is thought that the Sun was born by contraction of interstellar material in the Orion arm, about 4.5-5.0 10^9 years ago. The Sun is the star that provides Earth with life by sending energy in different forms. The interest of humankind in this star has been prominent since the beginning of history. During the development of human knowledge the Sun's secrets have been revealed slowly until the era of new technology when humans started to develop new ways of observing the Sun. In recent decades the observations of active Sun led to studying solar activity carefully and now we know that the secret of the active Sun lies in its ever changing magnetic field. Recently, research activity has been related to the observations of big solar eruptions, leading to different phenomena that can be observed on Earth. In big solar events, before the magnetic storms hit the Earth we might observe solar energetic particles (SEP) that bombard Earth earlier, and may be both (storms and particles) come from the eruption which is called Coronal Mass Ejection (CME). Eruptions at the Sun are not similar to each other. We sometimes observed eruptions associated with different composition and energy spectra and thus, we need to investigate their source and to hold the key to the secrets of the SEPs.

On the 2nd of December 1995 the spacecraft Solar and Heliospheric Observatory (SOHO) was successfully launched at Kennedy Space Center by Atlas-II AS through a co-operative program between ESA and NASA. The spacecraft was placed into the halo orbit close to Lagrangian point L 1, about 1.5 10^6 from the Earth towards the Sun. The goal was to study the structure, chemical composition, and dynamics of the solar interior, the structure and dynamics of the outer solar atmosphere, and the solar wind and its relation to the solar atmosphere. SOHO carries twelve scientific instruments, GOLF, VIRGO, MD/SOI, SUMER, CDS, EIT, UVCS, LASCO, SWAN, CELIAS, COSTEP, and ERNE (Energetic and Relativistic Nuclei and Electron experiment) from University of Turku (Torsti et al., 1995).

In the beginning of 1987 ESA and NASA announced an opportunity for proposing an energetic particle analyzer for the SOHO spacecraft. The energetic particle analyzer was given the following resources in the model payload: mass 8 kg, power 4 W, telemetry 200 bps and dimensions 20×20×20 cm^3 or 20×15×10 cm^3. In response to the announcement the staff of the space research laboratory in the University of Turku, Finland, under the direction of the head of the laboratory at that time Dr. J. Torsti, started to design the instrument. The work was done during the time period of 1987-1992 ending with an instrument of two energetic particle sensors, low energy detector (LED) and high energy detector (HED). These telescopes were designed by the space research laboratory of Turku University. The mechanical design of the telescope has been the responsibility of the VTT Instrument Laboratory.

The detectors in ERNE provide an opportunity to analyze protons and helium nuclei intensity-time profile with high resolution. The intensity-time profile can provide the first registration for the arriving of the SEP from the Sun. This can give us the opportunity to investigate the first injection time of the SEPs and thus know the starting time of acceleration. The ability of ERNE to detect SEPs in different energy channels will able us to study the possibility of the velocity dispersion of the detected particles, meaning the observation of high energy particles before the lower energetic ones. Velocity dispersion is the first tool to prove that the source of particles is from the Sun. The arrived particles carry information about their source. The most useful tool in this matter is the measurement of species ratio. ERNE can provide this information and thus, we used these measurements to indicate the release time of energetic particles and compare it to available sources for the coronal eruptions (see also detailed description in chapter 3). One of the problems regarding the injection measurements is the intensity background. In frequent occurrence of eruptions an event might began before the previous event decays to the cosmic-ray background and thus a delay in the injection time can be found regarding the associated eruption at Sun. The "background" problem seems unavoidable for dealing with events containing features such as double peaks or second component, since the first peak has not completely decayed when the second injection starts.

In this Thesis, I study the double peak phenomenon in SEP events. The peaks can be related to spatial effect, temporal effect, or to completely new eruption from the Sun. Five papers published in international journals and conference proceedings discuss and analyze this phenomenon from those points of view. Beside those papers the Thesis consist of an introduction related to the scientific foundation of the research, and discussion of the results. In Chapter 2, I review the Solar Energetic Particles (SEP) events, their characteristics, associated phenomena and particle acceleration. In Chapter 3, I introduce the instruments and method that I use for data analysis. In Chapter 4, I present the results and discuss them, and form conclusions in Chapter 5.

The refereed research papers are listed on page 9. Paper I introduces the double-peaked events with peaks separated by 3-24 hours, related mostly to a single event. The possibility of temporal and spatial effect is discussed, velocity dispersion and ^{4}He/p ratio is used. In paper II, I introduce for the first time the term Multi Eruption Solar Energetic Particle (MESEP) events. A definition of the MESEP events is established and classification according to energy level and intensity-time profile is founded. The paper also contains a list of all MESEP events found during most of solar cycle 23. In paper III, we selected one event from the list of MESEPs presented in the previous paper and we found the new phenomenon of observing energetic protons penetrating a previous interplanetary shock wave. This phenomenon has been presented for the first time and it is inconsistent with current paradigm of continual acceleration in interplanetary shock wave in gradual events. In paper IV, we introduce another MESEP event chosen also from the same list of MESEP events of paper II. We discover for the first time that the newly observed energetic protons penetrate a previous decelerating shock wave. An additional amplification in the SEP event was found due to mirroring by old CME. A model of type II dynamic spectrum and SEP transport was applied for the data interpretation. In paper V, we introduce comparison study for four MESEP events from the same previous list. A common feature of decelerating CME association was found.

Chapter 2

Solar Energetic Particles

The SEP events are one of the most interesting phenomena in solar physics. They have been observed near the Earth with energy ranges varying from some keV/nucl to the GeV/nucl. They might have different sources, for example, from solar flare in the low corona, coronal shock and interplanetary shocks driven by Coronal Mass Ejection (CMEs). In the last two decades more attention has been brought up to investigate the sources of the SEPs since magnetic clouds resulting from the same sources have clear impact on modern space technology. The SEPs are fast enough to reach Earth earlier and thus act as an alarm for upcoming magnetic storms. The need for further investigations of all the associated phenomena with the production of SEPs has resulted in building new spacecraft that can cover wide range of SEP energy. The Solar and Heliospherical Observatory SOHO has made a revolutionary work in developing our knowledge of CMEs and SEPs. The Energetic and Relativistic Nuclein and Electron experiment ERNE on board SOHO (Torsti et al., 1995) is capable of detecting SEPs in energy ranges 1-116 MeV. To cover the history of the production of SEPs we need to combine data from many instruments. That will allow us to have a clear scientific view of at least the major part of SEP production. In this work we concentrate on a specific area in the SEP events that has not been explored. The phenomenon of Multi Eruption Solar Energetic Particle (MESEP) events, a SEP intensity-time profile that may have resulted from multi eruptions on the Sun. In some events multiple acceleration from single event or spatial effect in interplanetary medium can be found. We need to consider all the results of previous investigations on the classification and sources of SEP events and associated phenomenon, from the starting of the eruption on the Sun and all the way through eruption propagation till Earth and beyond.

2.1 Eruptions at the Sun and SEP events classification

The sources of SEPs from the Sun have been connected to two major phenomena, the solar flares and CMEs. The participation of each in the production of SEP has been debated for many decades. Earlier the solar flares have been thought to be the major reason for SEPs observed on Earth. With the development of space science and technology the

CMEs entered this field strongly. The SEPs due to those two parts of solar eruption are known as SEP events, and are studied widely from different aspects. The well-known classification of SEP events as gradual and impulsive (the current paradigm) depends on the production time of the SEPs, different compositions and associated phenomena such as radio emission (Lin (1974); Van Hollebeke (1975); Pallavicini, Serio & Vaiana (1977); Kocharov, Kovaltsov & Kocharov (1983); Cane, McGuire & von Rosenvinge, (1986); Reames (1990); Kallenrode, Cliver & Wibberenz (1992); Lin (1994); Reames (1995b); Cliver (1996)). Gradual SEP events last for days and impulsive SEP events last for hours. Impulsive events are high in the electron to proton ratio and gradual events are rich in protons. Many different aspects have been added to each class starting from studying the spectrum of the solar flares up to the characteristics of CMEs. Characteristics of solar flares and CMEs have been studied separately and simultaneously to adjust both in the gradual and impulsive classification.

2.1.1 Solar flares

Solar flares are the most energetic and interesting eruption phenomenon observed at the Sun and have further effect on Earth and in the heliosphere. The amount of energy released in those eruptions is up to 10^{32} ergs on short time scales of several tens of seconds to several tens of minutes. The flare is still considered as one of the main sources for SEPs. During the flare, annihilation of magnetic field will transfer the energy to kinetic energy of energetic particles, and this indicates the importance of the flare as a source of SEPs.

The first observation for a solar flare was in white light in the year 1859 (Carrington, 1860). However, only after a century the relation between solar flare and magnetic storm, energetic particles and shock wave has been established. The associations between flares and large, nonrecurrent geomagnetic storms have been noted by Hale (1931), and their ionospheric effect was first clearly recognized around 1936 (Richardson, 1951). Solar flares have been widely discussed and statistical association of large flares and storms appeared by Newton (1943). Later, cosmic ray intensity rising in association with large flares were detected by (e.g., Forbush (1946); Meyer, Parker & Simpson (1956)), suggesting the ability of such flares to accelerate charged particles to energies up to GeV. Then Parker (1961) suggested the possible association between a large solar flare and a shock wave reaching the Earth after 1-2 days.

The energy released in solar flares is in the form of suprathermal electrons and ions, which remain trapped at the Sun and produce a wide variety of radiation (e.g., Ramaty & Murphy (1987)) as well as escape into interplanetary space (e.g., (Reames, 1990)). The radiation from trapped particles consists in general of (1) continuum emission, which ranges from radio and microwave wavelengths to soft ($\sim$1-20 keV) X-rays, hard ($\sim$20-300 keV) X-rays, and finally gamma rays (above $\sim$300 keV), which may have energies in excess of 1 GeV; (2) narrow gamma-ray nuclear de-excitation lines between $\sim$ 4 and 8 MeV; and (3) high-energy neutrons observed in space or by ground-based neutron monitors (e.g., Miller (1998)).

The important part in solar flare spectrum associated with SEP events is the soft

X-ray time duration for the well known B, C, M and X classification. Based on the signature of the SEP events in soft X-rays,Kocharov, Kovaltsov & Kocharov (1983) and Cane, McGuire & von Rosenvinge, (1986) divided the solar events into two classes: 1) impulsive events, which have high e/p ratio, are never associated with interplanetary shocks, and occur low in the corona; and 2) gradual events, which can accelerate particles to much higher energies, are well associated with coronal and interplanetary shocks, and occur high in the corona in extended regions. Impulsive events are usually relatively low-intensity and short-duration events; they have ion abundances with strong enhancements of ^{3}He and heavy ions relative to coronal abundances and ion charge states exceeding coronal thermal values. Typical maximum particle energies in such impulsive events are 10 MeV per nucleon, and the events are usually observable only if the accompanying flare occurs close to the nominal root (at W60°) of the interplanetary magnetic field lines connected to the observer. The particles in these events are generally believed to be accelerated in impulsive solar flares (e.g., Reames (1999)).

Many studies consider the flares a minor accelerator and their contribution to SEP events is only in impulsive SEP events (e.g., Gosling (1993)). However, the role of flares is still thought to be the major in impulsive events, but also recently, their contribution in major SEP events seems reasonable (Cane et al., 2008). In general high class (M and X) solar flare with more than one hour soft X-ray emission is considered to be associated with gradual SEP events, while short soft X-ray emission flares (minutes) are considered to be associated with impulsive SEP events.

2.1.2 Coronal mass ejections

The term Coronal Mass Ejection was unknown to science until the era of Skylab 1973-1979. Observations of frequent coronal disturbances from the Sun by Skylab are reported in first summary study by Gosling et al. (1974), indicating that these disturbances are eruptions from the coronal material producing the high speed solar wind flows which are responsible for geomagnetic storms. Gosling et al. (1976) indicated that the speed of such flows is in the range o $<$100 km/s to $>$1200 km/s. An observation by Skylab of huge loops associated with expulsion from the Sun of an eruption bigger than the disk of the Sun was reported by Eddy (1974). Finally, Coronal Mass Ejection was the name chosen for these events after many different proposals.

For years it was thought that solar flares were responsible for major interplanetary (IP) particle events and geomagnetic storms. However, many studies (e.g., Gosling (1993) started the important paradigm shift that coronal mass ejections (CMEs), not flares, be considered the key causal link with solar activity. CMEs are vast structures of plasma and magnetic fields that are expelled from the Sun into the heliosphere. Fast CMEs produce transient IP shocks, and those shocks are thought to accelerate the solar energetic particles (SEPs). The evidence obtained in several studies (e.g., Reames (1990, 1995a, 1999) ; Cane (1995); Kahler (1992); Gosling (1993), and Dryer (1994)) suggested that energetic particles observed in large "gradual" SEP events are accelerated at shock waves driven out of the corona by CMEs. Many studies indicate that gradual SEP events are associated only with CMEs (Gosling (1993); Reames (1995a)). An earlier study by Cliver, Kahler & McIntosh (1981), suggested that even the largest SEP events were correlated with CMEs, not with flares. Large gradual SEP events showed a 96% association with CMEs (Kahler et al. (1984, 1987)). The apparent association between flares and large nonrecurrent storms is, however, far from one-to-one (Gosling, 1993).

Earlier CMEs have been shown to be associated with Long Duration Events of X-rays (LDEs) (Sheeley et al. (1975); Kahler (1977); and Sheeley et al. (1983a)). CMEs have been shown to be associated with interplanetary shocks (Sheeley et al., 1983b, 1985). Interplanetary proton events have been shown to be associated with LDEs (Nonnast, Armstrong & Kohl, 2000), with CMEs (Kahler, Hildner & van Hollebeke (1978); Kahler et al. (1984)), and with interplanetary shocks (Cane & Stone, 1984).

It is likely that all long-lasting (gradual) flares and some impulsive flares result from the reconnection of field lines pulled out by the CMEs (Cane et al., 2002). At that point the major role in acceleration of SEPs was attributed to the CMEs and their driven shocks. But not every CME is associated with gradual SEP events and capable of driving a shock. Gopalswamy et al. (2002) indicated that only a small fraction (1%–2%) of CMEs are associated with SEPs, and thus specific characteristics in CME can make a good candidate for gradual SEP events. For instance, the Earthward-directed CME on January 6, 1997, was studied widely and hence it was clear that this < 500 kms^{-1} halo did not produce a SEP event (e.g., Webb et al. (1997); Cane et al. (1998); Torsti et al. (1998); [Forbes, Peredo & Thompson (1998); Reiner et al. (1998); Webb et al. (1998); Sheeley et al. (1999)). Fast CMEs with velocity $>$500 km s^{-1} are expected to form bow shocks at $\sim$3–5 solar radii from the Sun (Reames, 1999) and no fast CMEs with widths less than 60° are associated with SEP events (Kahler & Reames, 2003). Sometimes a CME of higher transit speed produces much fewer protons than a slower CME originating from approximately the same solar longitude (Torsti et al., 1998), but generally the CME speed and the SEP intensity are well correlated (Kahler, 2001). Torsti et al. (1998) concluded that potentiality of CME to accelerate SEPs depends on the eruption evolution below $\sim$2 R$_\odot$.

However, the role of the solar flare is still thought to be important in gradual events. Klein & Trottet (2001) found that SEP events producing particle enhancements at energies $\geq$100 MeV are also accompanied by flares; those accompanied only by fast CMEs have no proton signatures above 50 MeV. There is no evidence that a fast CME alone is able to accelerate solar energetic particles up to energies exceeding, say, 1 MeV/nucleon (Klein, 2007). De Jager (1988) and De Jager & Sakai (1991) suggested that the MeV protons are accelerated nearly simultaneously with MeV electrons in solar flare. In statistical study of 253 events Kurt et al. (2004) have confirmed and given quantitative characteristics of the SEP relation to the flares.

The recent understanding of flare's association with CMEs is that the flares do not derive CMEs, but they both reflect the energy released in the corona from the same magnetic source. In the current paradigm of SEP classification the role of CME and solar flare is still under debate and the classification itself is still unclear. Many gradual events also exhibit the composition signatures of impulsive events at energies >10 MeV/nuc, including enhancements of Fe,^{22}Ne, and highly-ionized charge states characteristic of temperatures >5 MK (Mewaldt et al., 2004). This blurs the distinction between impulsive and gradual events. It is unlikely that there is a sharp division separating the SEP events into two classes and abundance variations no longer indicate a clear separation into two classes (Cane & Lario, 2006), while typical impulsive events and typical gradual events still exist.

2.2 Sources of Solar energetic particles

The solution to the origin of SEP production lies in observations: When does the acceleration start, related to the other manifestations of the solar eruption? The observational work on this issue is somewhat scattered.

In the recent view of SEP acceleration source, there is no doubt that both flare and shock wave result from CME generators of accelerated SEPs observed at Earth. But the controversial issues regarding SEP production is whether the bulk of the acceleration takes place in the solar corona, say below a few $R_\odot$, or whether it occurs in traveling interplanetary shocks associated with CME (Reames, Barbier & Ng, 1996). We are concerned with this issue because 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, according to some studies (e.g., Gosling (1993)). However, the existence of separate flare blast wave and CME-driven shocks would have interesting implications for SEP acceleration (Cliver, Kahler & Reames, 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 delayed component is accelerated by the CME bow shock at greater distances, $>5R_\odot$ from the Sun (Kahler, 1994).

The shock acceleration evidence has been available earlier (Ogilvie & Arens, 1971). Interplanetary shock is believed to be both accelerating protons and trapping them (Simnett, Sakai & Forsyth, 2005). Many studies indicate that interplanetary shocks are the main accelerator for the high energy SEP events. Reames (1990) suggested that interplanetary shocks are able to accelerate energetic particles up to a hundred MeV. He pointed out that if flare-associated shocks did exist, one might expect the energetic particles from them to have intensity/time profile like those from impulsive flare because of the short acceleration time. They point out that coronal shocks are short-lived blast-wave shocks induced by flare and confined to the solar corona while interplanetary shocks are driven by CMEs.

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 initially accelerated close to the Sun. In a statistical study Kallenrode (1997) concluded that either there is a strong contribution of flare-accelerated particles or, in the context of current knowledge (interplanetary shock wave as a main accelerator) more likely, the shock is a more efficient particle accelerator close to the Sun than in interplanetary space, and the relatively small amount of particles accelerated locally in interplanetary space do not require significant acceleration. It might even be re-accelerated material from a large population of particles accelerated close to the Sun. In the hecto keV/nucl range, efficient particle acceleration occurs even at 1 AU and beyond. In the deka MeV/nucl range, the acceleration at the shock preferentially occurs close to the Sun (Kallenrode, 2003).

Klein et al. (1999) suggested that the CME may play the role of a trigger or even contribute to the buildup of magnetic stresses in the corona, but its bow shock is not the main accelerator of the high-energy protons. Simnett (2002) analyzed energetic particles events from 20 April to 9 May 1998 and concluded that they were unlikely to have been accelerated in the interplanetary medium by CMEs, but were more likely to have been accelerated in the closed magnetic field region of the corona, whence they either propagate within the closed corona until they escaped onto the open field region of the corona, or they lost their energy.

A few case studies indicate that the proton acceleration at intermediate scales, between flare acceleration and interplanetary CME driven shock acceleration, significantly contributes to the production of $>$10 MeV protons. This acceleration seems to be caused by the CME lift-off processes, including coronal shocks (Kocharov et al., 1999). However, it seems that both sources (coronal and interplanetary shocks) contribute in producing energetic particles in gradual events. The prompt emission could be attributed to acceleration by coronal shocks at early times of the eruption, whereas the delayed component is accelerated by the CME bow shock at greater distances, $>5R_{\odot}$ from the Sun (Kahler, 1994). Kocharov & Torsti (2002) formulated a SEP classification scheme that considers the CME bow shock as a re-accelerator of particles accelerated by flare and CME liftoff/aftermath in solar corona.

2.3 Interplanetary Coronal Mass Ejection

The term Interplanetary Coronal Mass Ejection (ICME) has come after subsequent detection of the interplanetary manifestations of CMEs, and it is referred to the traveling plasma structure and some form of magnetic field pattern of CME. Observations of CME propagation further in interplanetary space continue to identify and study the characteristics of the ejected material-interplanetary coronal mass ejection. Many studies (e.g., Hirshberg et al. (1970, 1972); Borinni et al. (1982)) reported an enhancement in helium abundances in region of ejected plasma a few hours following some interplanetary shocks. The size of the region can be of a scale of $\sim$ 0.2 AU, since it extended for period of time as $\sim$ 1 day, suggesting that this plasma was the material ejected from the Sun that generated the shock. It was thought that the ejected material might be related to a component from solar flares that were accelerated through some explosion, or piston process. Observations of limb CMEs by spacecraft were conducted since the 80s of the last century (e.g., Schwenn (1983); Sheeley et al. (1985); Lindsay et al. (1999)) or near the Earth (e.g., Webb et al. (2000)) showing clear association with shocks and the related ejected material. ICME can be classified in two types: magnetic cloud and ejecta (Gopalswamy et al., 2001a). The magnetic cloud is an extension of magnetic flux ropes into IP space with a high magnetic field, while ejecta have no distinct magnetic flux rope.

An ICME brings several structures past a spacecraft, all with their own signatures. Fast ICMEs will tend to drive a shock, which is used as a signature associated with many ICMEs. The shock is considered the main particle accelerator. The turbulence in the sheath behind the shock modulates their propagation and is an important ingredient in the acceleration process.

2.4 SEP acceleration mechanisms

The observations of the characteristics of impulsive and gradual SEP events led to the general scenario that energetic particles are accelerated by different mechanisms. There is ongoing debate about the relative roles of CME-driven shocks and flares in producing high-energy solar heavy ions (e.g. Tylka et al. (2002), Cliver, Kahler & Reames (2004)). However, in some studies (e.g., Cliver (1996) and Mandzhavidze & Ramaty (1993)), there was an argument that the acceleration mechanism which is responsible for impulsive flares, is somehow involved in acceleration of particles in gradual events. Those particles are originally from the impulsive phase and have impulsive flare abundances, but they remain trapped at the Sun and have impulsive flare abundance in gradual events. This means, that the gradual events contains an impulsive flare part, which share in later acceleration mechanisms. Klein et al. (2000), in observation of a large 1989 September 28 event, suggested that coronal acceleration behind the bow shock of the CME leaves its fingerprints in the particle time profile at 1 AU.

The most widely accepted mechanism for the acceleration of particles in gradual SEP events is the diffusive shock acceleration at the CME-driven shock waves. The efficient particle acceleration in such shocks requires strong turbulence in the upstream of the shock, while the rapid release of the particles in to interplanetary space requires low levels of turbulence further away from the shock. Recently, Kocharov et al. (2005) studied particle acceleration in a scenario where the turbulence was strong in the corona but weaker further out and the CME-driven shock accelerated particles in that turbulent layer. More usually, however, the turbulence generated by the particles themselves is believed to enable fast and efficient acceleration of SEPs. The steady-state models for the self-generated waves by Bell (1978) and Lee (1982), have recently been extended into fully time-dependent models by Vainio & Laitinen (2007) and Ng & Reames (2008). In these studies, energies of $\sim$100 MeV were obtained within 10 minutes of the initiation of the acceleration, provided that the shock velocity and the injection strength were sufficiently strong, while the particle transport to 1 AU needs further consideration.

The self-generation of the turbulence leads to trapping of the particles into the vicinity of the shock, and, further, to streaming-limited intensities in strong events, and as a result, the particle intensities peak at shock passage, even at energies of $\sim$500 MeV in some events (Reames, 1999). However, based on solar observations, Kahler (1994) concluded that maximum acceleration occurs when the shock is above 5 $R_\odot$ and the peak of the injection profile occurs when the associated CME reaches heights of 5-15 $R_\odot$. Tylka et al. (2002) found that both flare-and shock-acceleration mechanisms operated in the April 15, 2001 event, with the flare becoming more important at high energies.

2.5 Double-Peaked SEP events

The double-peak structure in intensity-time profile of some SEP events is not a frequent occurring phenomenon. McCracken, Moraal & Stoker (2008) observed the Ground Level Event (GLE) of 20 January 2005 and found that the GLE comprised two distinctly different cosmic ray populations. A scatter-free initial impulsive phase and second phase with diffusive character. Shea & Smart (1997) noted that a dual structure of the intensity-time profiles was observed in some (GLEs) (for example, the events of November 15, 1960 and possibly of August 7, 1972). In events, like 29 September 1989, two injections during the development of the eruption was the reason behind the double-peaked structure seen in the intensity-time profile (Miroshnichenko, De Koning & Perez-Enriquez, 2000). Shea & Smart (1997) presented the implication of two acceleration sources for the 22 October 1989, event. A number of single cases have been studied that revealed double-peak structure with high resolution spaceborn instruments like SOHO/ERNE (e.g., Torsti et al. (1997), Kocharov et al. (1997)). As many other studies the main conclusion was about finding a second source or second acceleration from the same source in creating the double-peak structure. In additional to a second source or second acceleration, the interplanetary influence on the particles during their propagation in the interplanetary medium is a second choice for reflecting such structure in the intensity-time profile. A study taking into consideration this division has not been presented until we did the statistical study for double-peaked events showing common features in the intensity-time profile, but each might not be the result of the same effect.

For possible first peak source for the double peaked event, a recent model of shock acceleration of protons in a turbulent layer at the base of the solar wind by Kocharov et al. (2005) may explain the prompt proton injection which typically starts about 10 min after the flare and continues for 1–2 hours. On the other hand, a few events were reported with a strong ^{3}He enhancement in the high-energy range of few tens of MeV (Torsti et al., 2002, 2003). They can be explained with an interplanetary shock acceleration at $\sim$0.3 AU from the Sun (Kocharov & Torsti, 2003), which corresponds to time scales of $\sim$15 hours. It cannot be ruled out that both shock accelerations are met in a single event to give rise to a double-peaked event with the intensity peaks separated by about half a day.

2.6 Radio emission association

Associations of radio emission with SEP events are very important in determining characteristics of eruptions and acceleration mechanisms. Different types of radio emission might reflect different mechanism in production of different components of SEPs near the Sun and further in the interplanetary medium. For example, the type III radio burst is known to be generated by the low energy electron component of the flare particles which has escaped the closed loops to open field lines (Figure 2.1). Thus, from some observation of type III radio bursts we know that large SEP events also have associated flares and type III radio bursts (Cane et al., 2002), but the flares are much longer in duration.

On the other hand, type II radio bursts are believed to be produced by electrons accelerated at the shock front. It is generally accepted that metric type II bursts are caused by disturbances moving outward through the solar atmosphere with typical speeds of several hundred kilometers per second (Nelson & Melrose, 1985), and the rapidly drifting radio bursts have been associated with fast ($\geq$400 km/s) CMEs (e.g., Kahler (1992)).

Type IV radio bursts are a continuum radiation that persists smoothly over a broadband of frequencies. The type IV bursts are due to continuously accelerated or trapped electrons in large-scale coronal loops. 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 slowly-drifting continuum emission, usually attributed to rising plasmoids (see review on solar radio bursts in Dulk (1985)). Type IV bursts are often, but not always, accompanied by a type II burst, which reveals the passage of a large scale shock wave through the corona (Klein & Trottet, 2001).

A distinction is generally made between type II radio bursts observed at decimetric-metric wavelengths, referred to as coronal type II bursts, and decametric-kilometric wavelengths, referred to as IP type II radio bursts. While IP type II bursts are usually ascribed to 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 IP 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)).

There has been a long-standing controversy about the relationship among metric type II bursts, flares, CMEs and IP shocks (Chao (1974, 1984); Wagner & MacQueen (1983); Gosling (1993); Gosling & Hundhausen (1995); Svestka (1995); Dryer (1996); Gopalswamy et al. (1998); Cliver, Webb & Howard (1999)). Using the data from November 1994 to June 1998, Gopalswamy et al. (1998) reported that 93% of the 45 metric type II bursts did not have IP signatures. On the other hand, Cliver, Webb & Howard (1999) insisted that metric type II and D-H type II bursts are driven by fast CMEs.

Reiner et al. (2001) suggested that the harmonic component of metric type IIs can possibly be related to D-H type IIs. Also, Leblance 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 as suggested by Smart & Shea (1985). Reiner et al. (2000) indicated two distinct shocks in association of metric

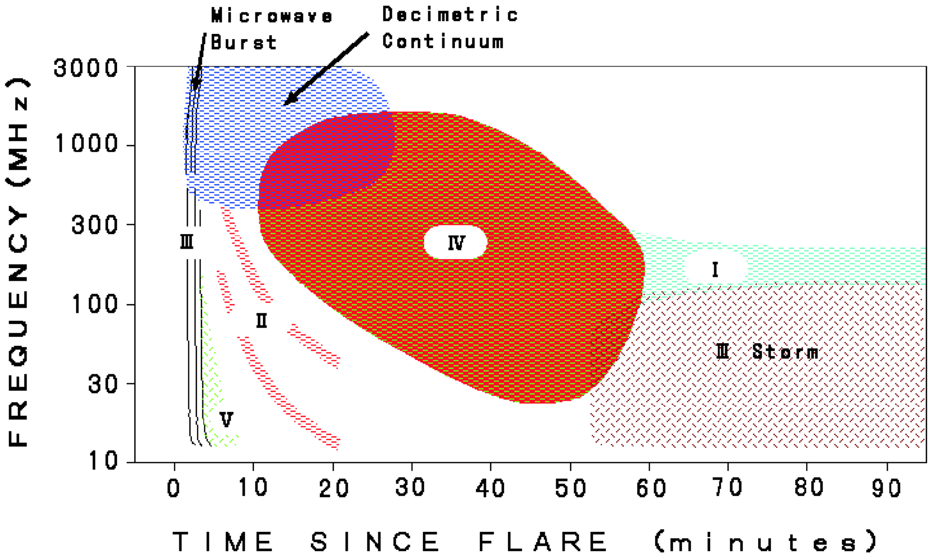

Figure 2.1: Schematic dynamic radio spectrum classification of radio bursts from centimetre to decametre wavelength taken by Hiraiso solar observatory. The characteristics of the types of bursts III, II and IV are described in the text.

and D-H type II radio emission. 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)).

Radio observation has also been a tool to distinguish acceleration mechanisms in SEP events. Li & Fleishman (2009) suggest that some of the narrowband microwave and decimeter continuum bursts may be a signature of the stochastic acceleration in solar flares. Gopalswamy et al. (2001b) found that between 3 and 4 $R_{\odot}$, the Alfvén speed attains maximum and hence acts as a filter that removes all weak shocks in the inner corona (below 1.5 $R_{\odot}$,), which produces metric type II bursts. On the other hand, observation of radio emission in association with CMEs can reveal information about CME's characteristics, propagation and the effect of associated flares on such CMEs. Lara et al. (2003) found that in general, the distribution of the width and speeds of the CMEs associated with metric type II bursts are shifted towards higher values compare to those of all CMEs observed by LASCO in the 1996–2001 period. The study indicates that there are at least two possibilities for the origin of metric type II bursts: (1) The CME-driven shock produces the metric type II when at low altitudes and then the decametric-hectometric type II, at a higher degree of association between the two phenomena at fast CMEs; (2) A shock driven by the blast wave produced by a flare can be an exciting agent that produces the metric type II bursts.

Chapter 3

Measurements and Instruments

In all of the papers in this thesis, we use the energetic proton observations from the SOHO/ERNE (Torsti et al., 1995, 1997), particle instrument, which consists of two particle telescopes, Low Energy Detector (LED) and High Energy Detector (HED). The identification of protons is based on an on-board algorithm, which provides intensities in the energy ranges 1.3–14 MeV (LED), and 13–140 MeV (HED), with one minute time resolution. The particle data is accessible through the Erne Datafinder application, which can be found at `http://www.srl.utu.fi/erne_data/`. Figure 3.1 illustrates the intensity-time profile provided through ERNE datafinder.

We depend on three measurements from ERNE instrument in our study. The first injection time analysis, the anisotropy analysis and the ^{4}He/p analysis.

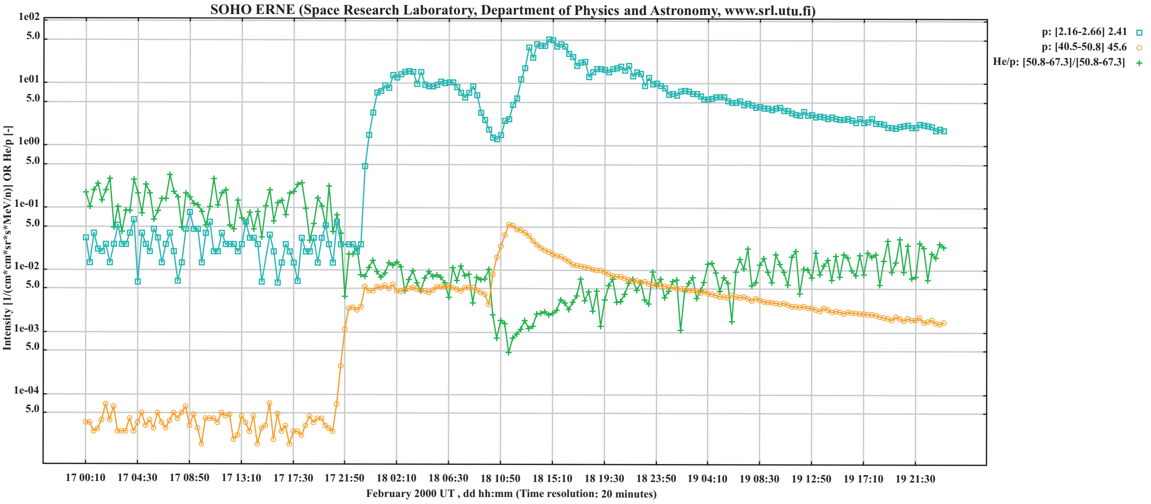

Figure 3.1: The double peak intensity-time profile of the Multi-Eruption event of February 17-19 2000, from the datafinder. The ERNE intensity-time profile shows a clear velocity dispersion in both peaks. The figure also shows the clear changing in ^{4}He/p ratio in both periods.

3.1 Injection time analysis

First, for the proton events, we determine the onset times for up to 20 energy channels (ten LED channels and ten HED channels), by using the same method as Huttunen-Heikinmaa et al. (2005). Assuming that particles with different energies are released simultaneously at or close to the Sun, the onset of the event at 1 AU should be observed earlier at higher energies than at lower ones. Assuming further that the energies of the particles remain unchanged through the passage in interplanetary space and that the path length does not depend on energy, it is possible to fit the release time of particles at the Sun and the path length travelled. This kind of analysis is called Velocity Dispersion Analysis (VDA), and it has been widely used (e.g., Debrunner, Flückiger & Lockwood (1990); Debrunner et al. (1997)).

Clear velocity dispersion was required for the proton events, although it was necessary to choose the appropriate energy channels for the velocity dispersion fit. On one hand, the onsets of the highest energy channels are often delayed when compared to the velocity dispersion of the lower energy channels. This "velocity dispersion turnover" is caused by the turnover in the background spectrum (galactic spectrum starts to dominate) (Huttunen-Heikinmaa et al., 2006). Therefore, the higher backgrounds of the highest energy channels can mask the onsets when compared to the lower energy channels. On the other hand, the lower sensitivity of LED (0.9 Vs. 24–36 cm^2 sr) can cause delayed onsets for the LED channels when compared to the velocity dispersion of the HED channels. Two energy channels from energy ranges, used for the velocity dispersion fits, are shown in figure 3.1. The VDA fit for May 12, 1997, event is shown in figure 3.2.

We also employ the fixed path length method, where we use the same Archimedean spiral length for all events. For this method, we determined the injection time from the highest energy channel that was still consistent with the expected velocity dispersion. For the path length we used value of 1.2 AU, which is often used in the event onset studies (e.g., Haggerty & Roelof (2002), Cane (2003a)). The value presumably originates from the path lengths of 1.1–1.3 AU, obtained by Krucker & Lin (2000) for protons in the majority of their proton events, and for electrons in all their events. It should be noted that the Parker spiral length for a solar wind of velocity 400 km/s is below that value, at 1.14 AU. However, the three-dimensional structure of the magnetic field, and fluctuations along the magnetic field, may be expected to increase the path length, thus we find this difference explainable. In addition, the first observed particles have most likely already experienced some scattering, as the pre-event background prevents the distinction between the background and first event particles.

In paper I, table 1 show the injection time obtained by both methods. In paper II, it was pointed that the velocity dispersion analysis in essential to determine the real effect from any second eruption. In paper III, the injection time of protons associated with first CME was calculated in both methods. In paper IV, the injection time of protons associated with first CME was calculated in both methods. In paper V, the onset time for two events was given.

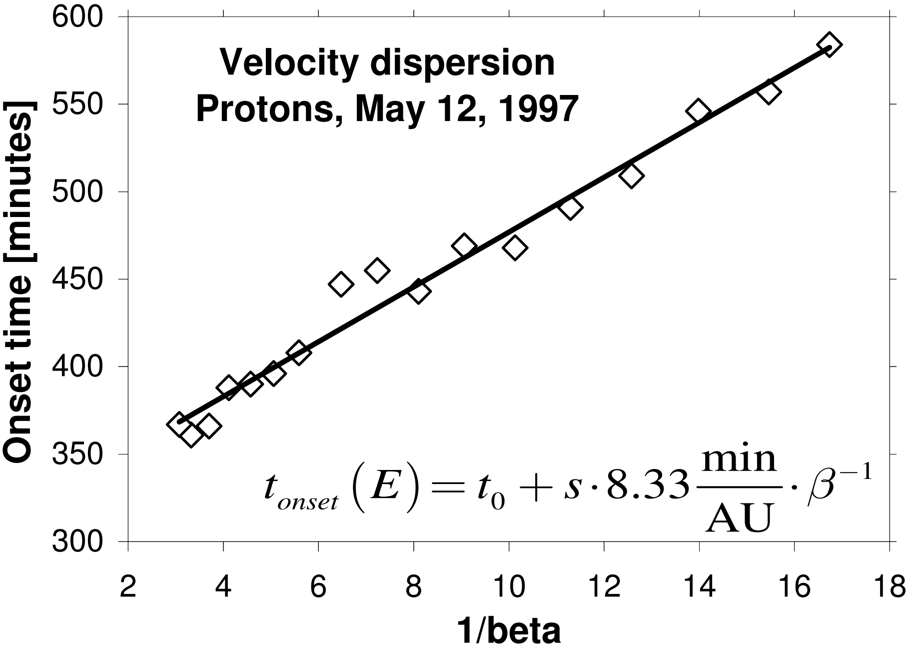

Figure 3.2: Proton velocity dispersion for the event of May 12, 1997. Open diamonds represent the observed onset times in minutes from the beginning of the day at different energy channels. The equation for the velocity dispersion is given in the figure, where t_0 is the release time of the protons, s is the apparent path length travelled, and $\beta^{-1} = c/v(E)$. Black line is the least squares fit which yields t_0 = 5:28 UT ± 6 min, and $s = (1.88 \pm 0.08)$ AU.

3.2 ^{4}He/p analysis

Generally, it is believed that a different ratio of ^{4}He/p during specific period of SEP events indicates that we observe new injected SEPs from different source of seed population, or that we are entering new magnetic field tube that contains different ratio of species. The ratio of ^{4}He/p has been used to identify different classes of SEP events (e.g Reames (1990, 1993, 1995b, 1997); Kahler (1992, 1994); Gosling (1993); Cliver (1996)). Usually gradual events have ^{4}He/p ratio of less than 10^{-2}. We used the ^{4}He/p measurements to identify the different period of injected SEPs, whether it has resulted from single eruption or multi-eruption. The tool of ^{4}He/p measurements can identify those cases if we join the results with other measurements such as velocity dispersion and anisotropy flux. Figure 2.1 shows the changing in ^{4}He/p ratio, measured with high energy channels by HED in association with clear velocity dispersion in both periods.

In paper I, the measurements of ^{4}He/p ratio were calculated and plotted for each event in figure 1. In paper II, the ^{4}He/p ratio was measured and plotted for the event of November 11, 2000, and plotted in figure 2. In paper III, the ^{4}He/p ratio was measured for the event of October 19, 2001, and plotted in figure 1. In paper IV, ^{4}He/p ratio was measured for the event of April 4, 2000, and plotted in figure 1. In paper V, previous measurements for ^{4}He/p ratio from the last two papers were given.

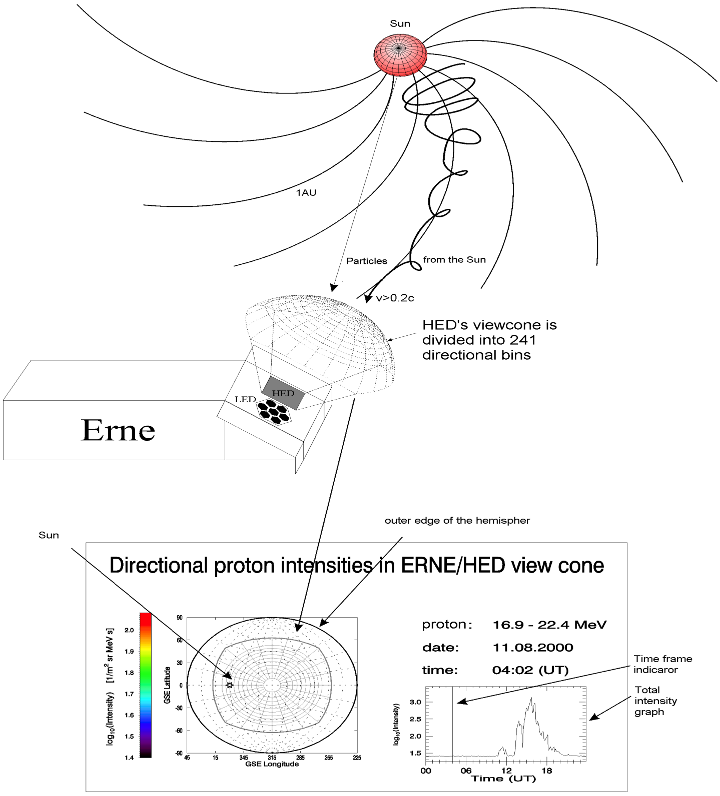

Figure 3.3: Cartoon scenarios for anisotropy measurements by ERNE .

3.3 Anisotropy analysis

The HED detector is used for anisotropy measurement, but current methods are used after two years from the launch of SOHO by installing new analysis software in the ERNE on-board computer for directional intensity measurements. The HED view cone is divided into 240 small fixed solid angles 10 concentric rings in the project direction and 24 in azimuthal. This division allows HED to have approximately equal count rates in all bins during isotropic flux conditions, see Torsti, Riihonen & Kocharov (2004) and details of anisotropy measurements in paper III. Figure 3.3 shows the cartoon-like structure for the HED view cone.

The anisotropy flux measurement was used in papers, II, III and IV in the figures 2, 1 and 1 respectively. In paper V, the same measurements from paper III and IV were shown in figures 1 and 2.

3.4 Energetic and Relativistic Nuclei and Electrons (ERNE)

3.4.1 Low Energy Detector (LED)

Low-energy particles from protons up to iron in the energy range of 1.3-13 MeV and isotopes up to neon are measured by the Low Energy Detector (LED). LED consists of detector layers D1, D2 and AC with pulse amplification and digitization electronics (Fig 3.4). The D1 layer is very thin compared to the D2 layer and composed of seven circular detectors D11-D17, in order to enabled the larger geometric factor without highly inclined particle orbits, which complicate particle analysis Figure 3.4. Each detector is protected from the Sun light by a gold-coated mylar foil. The particles penetrate through the D1 layer and stop at the D2 layer. Below the D2 there is an anticoincidence detector AC which is used to reject particles not stopping in D2.

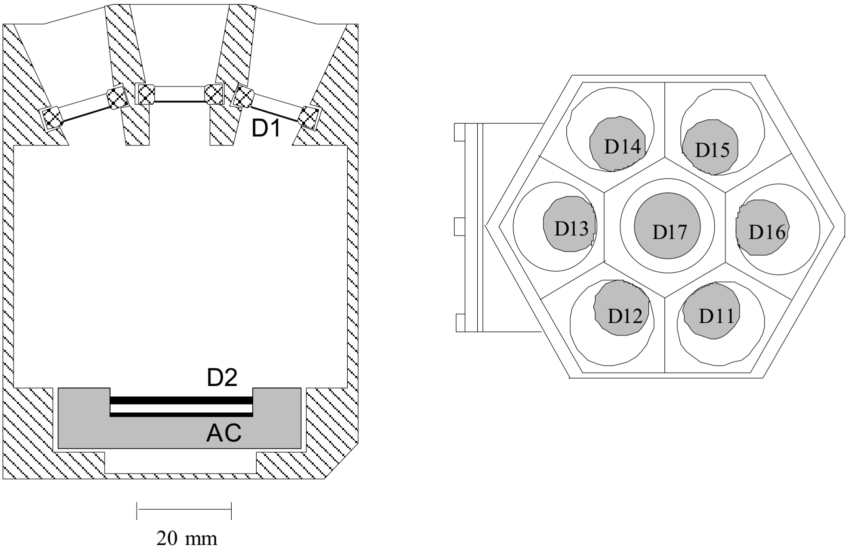

Figure 3.4: On the left simple schematics for vertical cross section of the LED detector. On the right the D1 layers, up pointing to the north, bottom to the south and left the direction to the Sun.

3.4.2 High Energy Detector (HED)

The HED consist of seven parallel detector layers, S1x, S1y, S2x, S2y, D1, D2, D3 and AC. The upper detectors S1, S2 and D1 are silicon detectors, and the bottom detectors D2 and D3 are scintillators (Fig 3.5). The detectors are cased in plastic scintillator anticoincidence shield AC in order to reject particles which do not stop in the detector layers. On the top of the detectors there are two thermal foils in order to block solar electromagnetic radiation and the solar wind. The HED can detect protons and helium particles of energies 11-120 MeV/n, other nuclei 11-540 MeV/n. The S1 and S2 detectors can determine the energy and direction of charge particles. The trajectory path length of the particles in the telescope is necessary to be known, to identify the elements and distinguish their isotopes. It is also important to carry out the anisotropy measurements.The HED electronics also contains a set of hardware counters which records particle hits that meet the pre-defined conditions. The counters are used to correct the intensities during high particle flux.

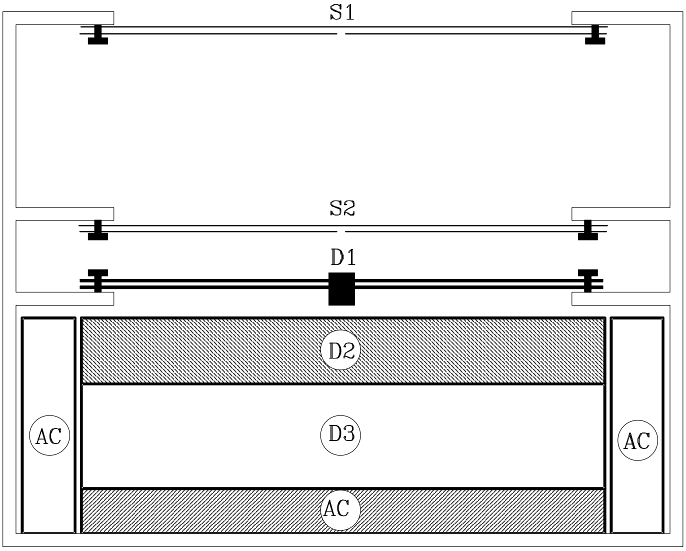

Figure 3.5: simple schematics for vertical cross section of the HED detector

3.5 Solar flare observations

During a solar flare a wide range of electromagnetic radiation from gamma ray to the radio frequencies are emitted (see Fig 3.6). This results in a rich source of knowledge of flare phenomena and especially for the observation of the occurrence and properties and associated events. We used Hα and X-ray observations in this study. After indicating the first injected particles we look for the associated eruptions at the Sun for each event. The soft X-ray and Hα flare characteristics were obtained from the Solar Geophysical Data listings (NGDC) `http://sgd.ngdc.noaa.gov/sgd/jsp/solarindex.jsp`.

3.5.1 Hα emission

The Hα emission is caused by an energy release in hydrogen atoms when an electron makes a transition from an n=3 to n=2 orbit corresponding to the wavelength of 656.3 nm, from the Balmer series. The solar atmosphere is best seen in Hα because it occurs in the middle of the big dark Hα absorption line (Fig 3.6). This absorption line falls in the red part of the visible spectrum. Observing in Hα permits us to understand the relation of the flare to the contact of the local magnetic field, filaments, and sunspot. Also it is universally used for patrol observation of solar flares, and most flare images are obtained in Hα. The intensity of Hα radiation in general rises rapidly in the early phase of the flare. The detection of the flare in Hα line can be extended to all flare phases. In the flash-phase the flare develops into a brilliant mound of Hα emission. The ribbons are also very bright in Hα and finally in the eruptive phase the sprays can be seen from the fragments of Hα emitting material. So the flare practically can be detected, especially in the location in Hα since the filament can be seen in the coronal surface by Hα emission. A simple scheme for classifying Hα flares importance is used by NOAA and elsewhere.

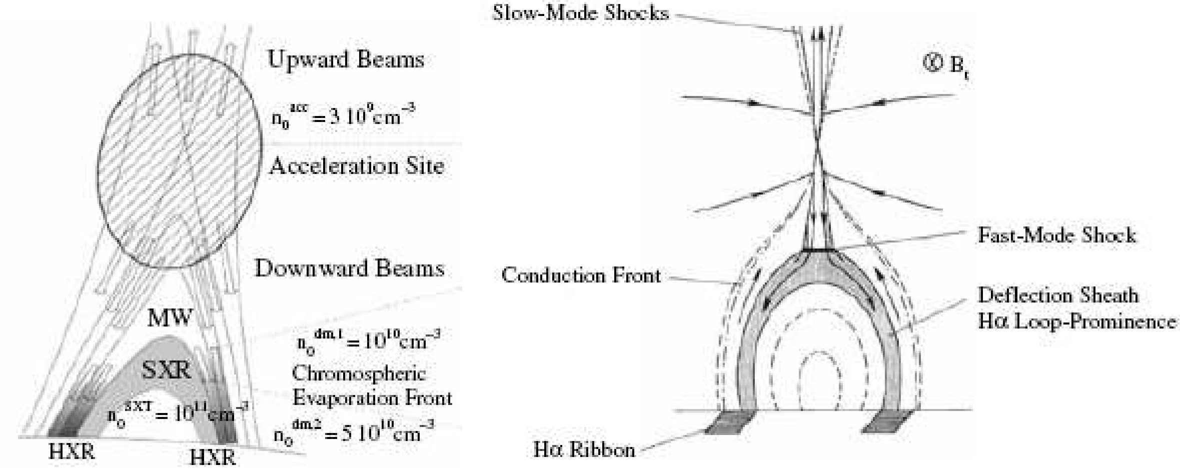

Figure 3.6: Cartoon scenarios from Hudson & Vilmer (1970)for magnetic reconnection in solar flares (left, from Aschwanden (2002); right, from Forbes & Malherbe (1986). The two views show essentially the same geometry, but the righthand shows various shock waves that may form and be important for particle acceleration

3.5.2 Soft X-ray emission

The soft X-ray emission in the solar flare seems to arise from very hot plasma with temperatures of up to about 20×10^6 K. Kundu et al. (1994) indicate that soft X-rays are produced by electrons with energies typically below 10 KeV. The profile of the soft X-ray varies gradually. Normally soft X-ray emission is observed in the impulsive stage but a longer soft X-ray rise is sometimes observed before the impulsive stage, especially the large flares (Fig 3.6). The soft X-ray emission consists of both continuum and lines. The quiet corona and active region soft X-ray continuum are barely emitted by plasma at the temperature of a few million degrees kelvin by Bremstrahlung or free-free emission. Part of the continuum emission is by free-bound emission which arises from re-combination of electrons on highly stripped ions of elements such as carbon.

Soft X-ray observation produced a very important distinction for the solar energetic particle events and classifies it in two classes as impulsive and long duration and even more than two classes. A universal scheme has been adopted by GOES in the form of lists of X-ray flare including their time and peak emission. These are made available by NOAA in solar geophysical data `http://sgd.ngdc.noaa.gov/sgd/jsp/solarindex.jsp`.

3.6 Instruments used in flare observations

In all of our papers we have used the Geostationary Operational Environmental Satellite GOES for indication of the solar flare through the Solar-Geophysical Data `http://sgd.ngdc.noaa.gov/sgd/jsp/solarindex.jsp`. In paper I, figure 1, there is indicated an associated solar flare or possible behind the limb flare as taken from previous studies. On paper II, we included the flares and their classes that have been observed by GOES and possibly associated with 268 MESEP events. Figure 1 in paper II shows the associated flares with each type of MESEP events. In paper III the two X-class flares where observed by GOES and Yohkoh. Figure 1 in paper III shows the X-ray profile taken by GOES 8. In paper V, table 1, we introduce the GOES observation for each associated solar flare with the MESEP events. The starting time of soft X-ray emission, class of the flare, Hα location and Active Region are all included.

3.6.1 The Geostationary Operational Environmental Satellite GOES

GOES is a joint effort of NASA and the National Oceanic and Atmospheric Administration (NOAA). The Soft X-ray Imager SXI is the main instrument on board GOES, which provides regular monitoring of solar active regions, coronal holes, and solar flares. The first SXI was in orbit in late 1992 (Wagner et al., 1987). Previous grazing-incidence Walter type I X-ray telescope used on board Skylab was used as technical model for the first SXI. The sensors of the SXI provide whole-disc images of the Sun in two soft X-ray (8-20 Å, 20-60 Å) and one EUV band (255-300Å). GOES-8/9/10/11/ X-ray sensors provide only average numerical data flux values. Thus a modification was done on the SXI on GOES 12 so that a full disc soft X-ray images was taken from geostationary orbit (Zimmermann, Zwirn & Davis, 2004). Figure 3.7 shows the flare of the event of September 12, 2000, taken by GOES SXI.

3.6.2 YOHKOH

A project of the Japanese Institute of Space and Astronautical Science (ISAS)-launched into space from the Kagoshima Space Center (KSC) in Southern Japan a satellite, known as Yohkoh ("Sunbeam") (Ogawara et al., 1999). The scientific objective was to observe the energetic phenomena taking place on the Sun, specifically solar flares in X-ray and gamma-ray emissions. There were four instruments on the satellite that detected energetic emissions from the Sun: I) The Bragg Crystal Spectrometer (BCS). II) The Wide Band Spectrometer (WBS) (Sato et al., 2006). III) The Soft X-Ray Telescope (SXT). IV) The Hard X-Ray Telescope (HXT). In this study, we use the SXT telescope onboard Yohkoh. The SXT imaged X-rays in the 0.25 - 4.0 keV range is one of three detectors

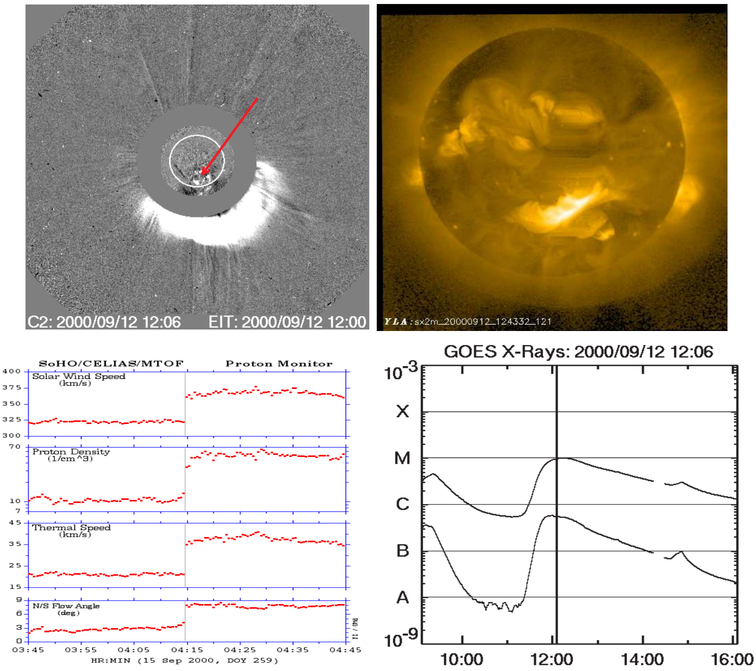

Figure 3.7: Data set for the observation of September 12 2000, event. Top right is the LASCO CME and EIT observation of the flare with arrow pointing. Left top is the Yohkok SXT image for the same active region. Right bottom the CELEIAS observation of the shock passage which resulted from the same CME. Right bottom the GOES plotting for the associated flare.

consists the WBS (Sato et al., 2006). Figure 3.7 shows the active region of the event of September 12, 2000, taken by SXT.

3.6.3 The Extreme-ultraviolet Imaging Telescope (EIT)

The EIT (Delaboudinière et al. (1989a,b), Clette et al. (1995)) is designed to provide full-disk images of the solar transition region and the inner solar corona to 1.5R$_{\odot}$. Its normal incidence multilayer-coated optics selects spectral emission lines from Fe IX (171 Å), Fe XII (195 Å), Fe XV (284 Å), and He II (304 Å) to provide sensitive temperature diagnostics in the range from 6×10^4 K to 3×10^6 K (Delaboudinière et al., 1996). We use the EIT in combination with sets of data from LASCO and GOES to track the origin of the solar flares associated with the CMEs. Figure 3.7 shows the EIT spotting the associated flares.

3.7 CME observations

The locations of the CMEs near the estimated first proton injection time (after adding 8 minutes for the light travel time) have been determined using the lists of *SOHO*/LASCO

CMEs. We consider CMEs taken from the *SOHO*/LASCO catalogue at `http://cdaw.gsfc.nasa.gov/CME_list/UNIVERSAL/`. The liftoff time of the CME is taken from the same catalogue produced by the LASCO team with two possible onset times (corresponding to linear and quadratic fits of the CME height-time profiles). We employ the quadratic fits of that catalogue to estimate the heliocentric location of the CME at the first proton injection time and some cases at the maximum intensity times of first and second peaks of high-energy protons.

As the error limit has not been calculated for the Lasco CME height-time, we calculated the error limit for the quadratic fit. Note that tracking the CME's height below $2R_{\odot}$ is not a trivial task. The C1 coronagraph is not available after 1998, thus we depend on fitting the height-time for the CME on C2 and C3. In case we are missing an observational data below $2R_{\odot}$, we calculate the approximate value for the height-time of the CME.

In paper I, the observations of LASCO for the associated CMEs with the double-peaked events was listed on figure 1. In table 1, it can be seen that we have calculated the heliocentric location for the associated CMEs. In paper II, the associated CMEs with the 268 MESEP observed by LASCO are listed in the index of the paper, also the associated CME with each type of MESEP is shown in figure 1 and in figure 2 for the November 11, 2000, event. In paper III, the associated two halos were taken from LASCO, and the location of the first CME during the launch of the second one was calculated. In paper IV, the associated two CMEs and the propagation scenario of the first one were considered including the estimation of the location of the first CME during the launch of the second CME. In paper V, the associated CMEs, including their characteristics, were listed in table 1. A set of observational data for the event of September 12, 2000, is showing the flare and CME observations in Figure 3.7.

3.7.1 The Large Angle Spectrometric Coronagraph (LASCO)

LASCO is a wide-field white light and spectrometric coronagraph consisting of three optical systems having nested fields of view that together observe the solar corona from just above the limb at 1.1 $R_{\odot}$, out to very great elongations (Howard et al., 1992). The three telescopes comprising LASCO are designated the C1, with coverage from 1.1 to 3.0 $R_{\odot}$, the C2, with coverage deliberately overlapping parts of both C1 and C3, and extending from 2.0 to 6.0 $R_{\odot}$, and the C3, which spans the outer corona from about 3.7 to 32 $R_{\odot}$. The C1 is fitted with an imaging Fabry-Perot interferometer, making possible spatially resolved high-resolution coronal spectroscopy in selected spectral emission and absorption lines, between 1.1 and 3.0 $R_{\odot}$. Figure 3.8 shows the propagation of the double CMEs, which helped us to conclude that the energetic particles from second CME were accelerated through magnetic field lines connected to the first CME.

3.8 Radio and magnetic field observations

The radio observations in this work are compressed under two types of observations; I) The spectral metric type II and IV radio bursts are taken from the earth-base radio tele-

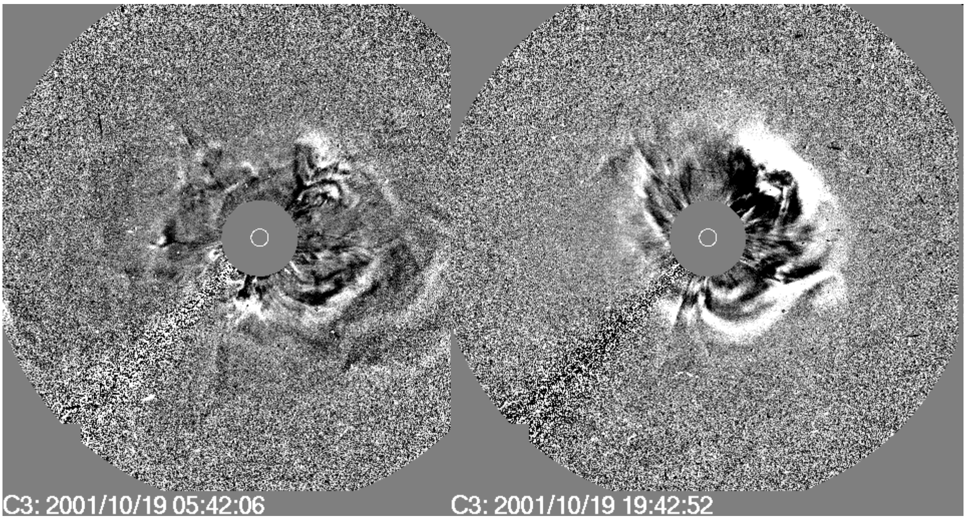

Figure 3.8: The multi CMEs of 2001 October 19-21, event. From the left to the right the CME1 and CME2. The propagation of both CMEs is clearly on the same direction proving that the second SEPs injection is toward the first CME

scope and their data are available from the Solar-Geophysical Data `http://sgd.ngdc.noaa.gov/sgd/jsp/solarindex.jsp`. II). The D-H type II and IV radio emission, and they were taken from Wind/WAVES. In paper I, metric type II and IV were observed in association with the eruptions associated with the chosen events and listed in figure 1. In paper II no radio observations were included. In paper III, the observations of metric type II and IV were taken as indication for shock wave formation. In paper IV, the metric and D-H radio emissions were taken in addition to model fitting of the type II dynamic spectrum. In paper V, both metric and D-H type II were observed as indicators for shock wave formation and listed in table 1. Beside the Solar-Geophysical Data we use the the WAVES for D-H radio observation.

The WAVES investigation on the WIND spacecraft provides comprehensive coverage of radio and plasma wave phenomena in the frequency range from a fraction of a Hertz up to about 14 MHz for the electric field and 3 kHz for the magnetic field (Bougeret et al., 1995). In situ measurements of different modes of plasma waves give information on local processes and couplings in different regions and boundaries of the Geospace leading to plasma instabilities: magneto-acoustic waves, ion cyclotron waves, whistler waves, electron plasma oscillations, electron burst noise and other types of electrostatic or electromagnetic waves. We used mostly the data of the D-H type II radio emission provided by WAVES.

3.9 Solar wind observations

The magnetic field data were taken from Wind and ACE. In paper I, the abrupt changing in the magnetic fields was considered in association with each double-peaked event especially in the time interval between the two peaks, and listed in table 1. In paper II the ACE magnetic field measurements was considered in the anisotropy flux measurements since SOHO does not have a magnetometer. In paper III, the same thing has been done concerning the anisotropy flux measurements, as well as the possible local effect of magnetic field in the time interval between the two CMEs, and the shock passage observation by CELIAS/SOHO, ACE and Wind. In paper IV, again we used ACE for anisotropy flux measurements and CELIAS, ACE, and Wind for shock passage observation. In paper V, the observation of shock passage by CELIAS, ACE and Wind was taken and listed in table 1. Figure 3.7 shows the CELIAS/MTOF observation for a shock passage for the September 12 2000, event.

3.9.1 The Charge, Element, and Isotope Analysis System CELIAS

The CELIAS instrument is designed to study the composition of the solar wind (SW) and of solar and interplanetary energetic particles on SOHO (Hovestadt et al., 1995). The CELIAS instrument consists of three different sensors with associated electronics, which are optimized each for a particular aspect of ion composition. These aspects are the elemental, isotopic, and ionic charge composition of SW or energetic ions emanating from the Sun. The CELIAS instrument consists of three different sensor units (CTOF, MTOF, and STOF) coupled to a Digital Processing Unit (DPU). We use the MTOF data available on `http://umtof.umd.edu/pm/FIGS.HTML` to determine the shock passage associated with the studied events. Figure 3.7 shows the CELIAC/MTOF plot for the shock passage of the associated CME of the September 12, 2000, event.

3.9.2 The Wind spacecraft

WIND was launched on November 1, 1994 and is the first of two NASA spacecraft in the Global Geospace Science initiative. WIND was positioned in a sunward, orbit with a maximum apogee of 250 Re during the first two years of operation. This was followed by a halo orbit at the Earth-Sun L1 point. Wind contains 9 instruments onboard; WAVES, EPACT, SWE, SMS,MFI,3-D PLASMA,TGRS KONUS, SWIM. In this study we use data from two of the instruments, WAVES and MFI.

The MFI instrument consists of dual triaxial fluxgate magnetometers mounted on a 12-meter radial boom, and a data processing and control unit within the body of the spacecraft (Lepping et al., 1995). The magnetometer sensors each produce analog signals proportional to the strength of the magnetic field component aligned with the sensor. MFI has a very wide field measurement capability, from $\pm$ 0.004 nT to $\pm$ 65,536 nT, with both automatic and commandable range-change capability.

3.9.3 Advanced Composition Explorer (ACE)

ACE is an Explorer mission of NASA which orbits the L1 libration point; it can provides coverage of solar wind parameters(Stone et al., 1998). There are nine scientific instruments performing on ACE. The most used instrument in this work is MAG, an instrument which measures the local interplanetary magneticfield (IMF) direction and magnitude and establishes the large scale structure and fluctuation characteristics of the IMF at 1 AU. The anisotropy flux measurements use the ACE/MAG since there is no magnetometer in SOHO.

Part II

Results

Chapter 4

Results and Discussion

According to the current paradigm, a gradual SEP event is completely due to the particle acceleration at CME bow shock in solar wind, while there is increasing evidence that coronal processes could also contribute to SEP production in the major events.

In this study, I have tried to prove the possibility of existence of more than one population of accelerated SEPs in prolonged intensity-time profiles of strong event. The start of such study has been done with bringing to attention the phenomenon of double-peaked intensity time profile. We introduce common features for the double-peaked events in statistical study of paper I since no statistical study of spaceborne measured double-peaked events had until that time been reported. However, individual double-peaked events had appeared in some previous studies, like the famous double-peaked event of 29 September 1989, which has been described in detail by Miroshnichenko et al. (1990) and Miroshnichenko, De Koning & Perez-Enriquez (2000) with neutron monitor data, and by Torsti & Schultz (1992) with data of GOES 6 and 7 and neutron monitor data, the 22 October 1989 ground level enhancement (GLE) by Shea & Smart (1997), the May 24, 1990 event, by Torsti et al. (1995) with data of GOES 6 and 7 and a number of events with double-peaked structures in GLEs detected during 1989–1990 by Vashenyuk et al. (1993). However, the neutron monitor counting rates are integrated in energy and may be strongly affected by the variable parameters of the Earth's magnetosphere, whereas the GOES data are contaminated by so-called secondary channels. Later on, in the era of *SOHO*, new results have been obtained, especially with opportunity of getting data from instruments like the ERNE. Intensive, multiwavelength investigation has been performed on the double-peaked proton events detected by ERNE on 9 July 1996 (Torsti et al. (1997), Kocharov et al. (1997, 1999), Laitinen et al. (2000), Kocharov & Torsti (2002)) and 9 May 1999 (Torsti et al., 2001). However, previous studies were limited with SEP production at time scales of <3 hours after the flare.

The event of 29 September 1989 was a result of a large flare behind the solar limb. Soft X-ray detected by GOES 7 of X9.8, 4 hours duration and it was the first GLE observed with underground muon detectors (Krymsky et al. (1990); Swinson & Shea (1990); Filippov et al. (1990)). The SEPs were observed, in particular, by the SEC/NOAA energetic particle detectors on the GOES-6 satellite in geostationary orbit. The event was associated with a CME (Burkepile & St. Cyr, 1993) of a very high speed of 1828 kms^{-1} (Cliver, Kahler & Vestrand (1993); Bhatnagar et al. (1996)), suggesting an association with a strong fast shock. Bhatnagar et al. (1996) emphasize that during the late stage of the event, simultaneously with a long duration soft X-ray burst, an outstanding and slowly rising post-flare Hα loop system developed and was visible for at least 10-12 h. Evidences for the hypothesis about double (two-fold, or dual) ejection of SCRs from two different coronal sources, with dynamic scenario, show that the first impulsive increase (spike), could be caused by acceleration in the upper corona due to fast reconnection of magnetic fields. During this period the footpoint of the IMF line connecting the Earth with the Sun was projected on the visible disk, the projection point being linked with an open structure stretched along the equator. Such a configuration could favour the rapid escape of the particles from the high coronal source . Such a configuration could favour the rapid escape of the particles from the high coronal source (Miroshnichenko, De Koning & Perez-Enriquez, 2000). Radio data associated with the event revealed at least two distinct phases of energy release (Bhatnagar et al., 1996).

Shea & Smart (1997) presented evidence on the 22 October 1989 GLE event that there were two distinct injections of relativistic protons into the interplanetary medium. The first injection resulted in an extremely anisotropic flux at earth. The second injection was approximately 15-20 minutes later. They did a comparison of timing of associated solar phenomena, such as coronal mass ejections (CMEs), X-ray and radio emission, with the particle observation and it showed that the first injection of solar particles occurred close to the flare time when the inner edge of the CME was at between 2-2.5 $R_{\odot}$.

Moreover, more than one phase in single SEP event has been studied widely from different aspects. In CME-flare associated SEP events which are mostly gradual (Reames, 1999), several studies suggest a paradigm of two accelerations, one in the flare site and another in the interplanetary medium by shock (e.g., Cane et al. (2003b)). Two acceleration processes for relativistic protons were observed in the Bastille Day solar event, one by shock and one by stochastic processes initiated by MHD turbulence (Bombardieri et al., 2006). Evidence of multiple acceleration was found also in a solar flare on the 20th of January 2000 (Struminsky, 2006).

Considering both events of September 29 and October 22 1989, we can include the possibility of the separate injections from single eruption in our double-peaked events. Unlike our study, previous studies considered observations of short time interval that separated the two peaks $\sim$1-3 hr, and high energy range. Also, previous studies did not measure the possible velocity dispersion and abundance ratio in the peaks. According to our study we can include the type T2 events from paper I (events with temporal onset of the second peak and change in the He/p abundance ratio) as candidate to be due to separated injections from a single eruption, at least for the July 25, 1997 event and May 9, 1999, since no nearby eruption is registered in association with the second peak. In such events the two peaks might relate to different acceleration mechanisms. The prompt acceleration is due to low coronal process, as can be seen from table 1 of paper I, that the first particles are injected while the CME was between 1.2-1.8 $R_{\odot}$ and 2.3 $R_{\odot}$ and the intensity peaked at $\sim$ 10-12 $R_{\odot}$ and 4.4-5.5 $R_{\odot}$ respectively, while the delayed component peaked beyond $30R_{\odot}$ in both events. A number of hybrid SEP events have been observed, with both low and high coronal sources involved, and the double-peaked events seem to fall into this category (Kocharov & Torsti, 2002). If such a scenario is behind the double-peaked events, resulting from different acceleration in single event, we have to expect higher peak in prompt component at high energies and higher peak in second component at lower energies, since many studies indicate that the shock wave near the corona can accelerate particles to higher energies than the shock in the interplanetary medium does (e.g., Kallenrode (2003), Kocharov et al. (2005)), which is consistent with our observation of the double-peaked events. A possible scenario for such a mechanism is that the prompt component of proton injection is related to a near-Sun shock and a large-scale reconfiguration of solar corona after the CME liftoff (Laitinen et al., 2000), while the delayed component starts once its source, the CME shock reaches a distance where Alfvén speed decreases, i.e., at $R \sim 3\ R_{\odot}$ (Vainio, 2003).

The isolation of the effects that cause the second peaks depends on the tools and measurements that we use in the observations. We separated the peaks that are due to spatial effect from those that are due to temporal effect in paper I by measurements of velocity dispersion and He/P abundance ratio. Still we have the S2 type, which reveals changing in He/P ratio without velocity dispersion in the second peak. This needs further investigations, although such types of events might be due to change in the geometry of propagating single shock (Tylka et al., 2005). Three S2 type events among 4 events from paper I, the events of November 28, 1996, February 07, 1997 and September 19, 1999, were associated with more than one eruption and thus are listed as MESEP events (events No. 4, 5, and 62 in paper II index, respectively). For the T2 type events, only the July 16 1999 event is listed as a MESEP event (event No.53 in paper II index). Note that all those events are listed under type 1 in paper II, since we found in their intensity-time profile that the second peaks get faded down as we go higher in the energy.

It is clear that we needed further investigation for the events studied in paper I and II as we can see from the result obtained after new analysis in later papers. The events of April 4, 2000 and September 12, 2000 are listed as MESEP events of type 1 (event No.79 and 98 in paper II index). Careful analysis of the intensity-time profile has been obtained in paper IV. It can be seen from figure 1 of paper IV, the second panel from the upper part, the second peak gets faded after the 67 MeV channel, but unlike the double-peaked events of paper I, the second peak here was due to a second CME. Thus similar types of intensity-time profile might be due to different kinds of acceleration mechanism.

The further analysis for intensity-time profile of the MESEP events in the list of paper II index shows that some MESEP events with certain period of time can be divided into many periods of time which shows different intensity-time profile types. The type 1 events in paper II, figure 1, show that some peaks get faded down in high energy channels and some do not. In the event of February 17, 2001, No. 78 from the index of paper II, the event in the period February 17-23 looks like type 1, see upper panel of figure 4.1. In the further analysis in paper V for MESEP for the period February 17-19, the event looks more like type 2, second panel of figure 4.1, moreover, the second peak in this event is even much higher than the first peak at the energy channel over 90 MeV, third panel of figure 4.1. Thus this event in the period February 17-19 looks more to belong to type 2 events rather than 1. Also in this event we notice the first difference between the MESEP events and the double-peaked events of type T2 in paper I, since the first peak gets below the second peak in higher intensities. The same story can be applied to the event of October 19, 2001. In paper II it is listed under type 4 since the general intensity-time profile especially in low energy channels does not show much identical peaks, but further analysis in paper III suggests that this events can be of type 1. However, we have seen that in some double-peaked events the second peak can be higher than the first one even in high energy channels. Higher SEP intensity was observed in events where a CME is preceded by another wide CME from the same source region, even with long time difference between them (Gopalswamy et al., 2004). It is clear in those cases that the effect of the acceleration in the interplanetary shock needs further investigation.

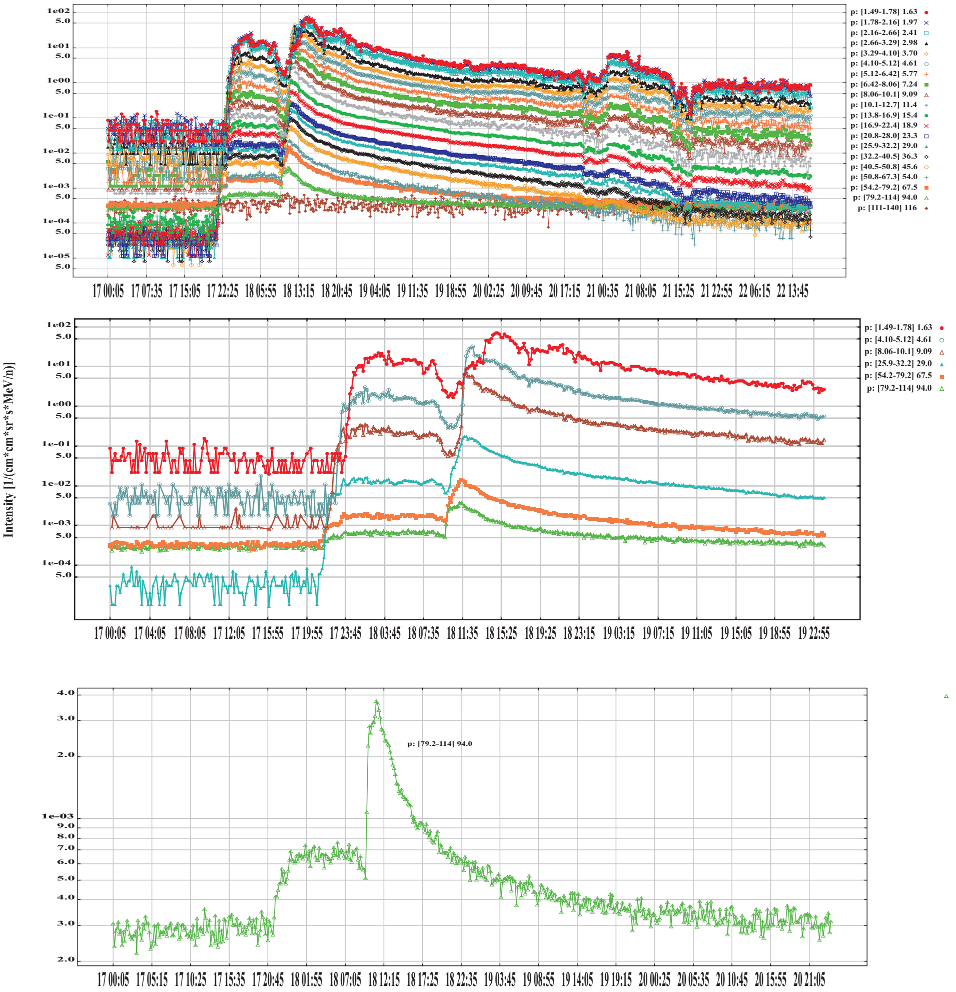

Figure 4.1: The February 17 2000, event. Top, the intensity-time profile for the period 17-23. Middle, the intensity-time profile for the period 17-19. Bottom, the intensity-time profile for over 90 MeV channel.

Interplanetary coronal mass ejections are expected to decelerate with increasing distance from the Sun, while the relationship between the ICME dynamics and production of SEPs was not investigated. A study of the propagation of CMEs from near the Sun to 1 AU by González-Esparza et al. (2003b) was comparing a 1-D, hydrodynamic, single-fluid, numerical model (González-Esparza et al., 2003a) and an analytical model to study the dynamical evolution of supersonic velocity's fluctuations at the base of the solar wind applied to the propagation of CMEs (Cantó et al., 2005). Both models predict that a fast CME moves initially in the inner heliosphere with a quasi-constant velocity (which has an intermediate value between the initial CME velocity and the ambient solar wind velocity ahead) until a "critical distance" at which the CME velocity begins to decelerate approaching the ambient solar wind velocity. This critical distance depends on the characteristics of the CME (initial velocity, density and temperature) as well as of the ambient solar wind. Given typical parameters based on observations, this critical distance can vary from 0.3 to beyond 1 AU from the Sun. These results explain the radial evolution of the velocity of fast CMEs in the inner heliosphere inferred from interplanetary scintillation (IPS) observations (Manoharan et al. (2001, 2003), Tokumaru et al. (2003)). On the other hand, the numerical results show that a fast CME and its associated interplanetary (IP) shock follow different heliocentric evolutions: the IP shock always propagates faster than its CME driver and the latter begins to decelerate well before the shock.

There are two factors that lead to decreasing energetic particles acceleration by the interplanetary shock wave. First, there is continuous leak of particles from the ejected material through the diffusive acceleration of the energetic particles during the propagation in the interplanetary medium. Second, there is continuing expansion in the volume of the ejecta. Both facts probably contribute to thinning of the turbulent sheath of the shock wave and thus lead to decrease ability in acceleration of more energetic particles. Kallenrode (1997) found according to fitting 44 SEP events associated with interplanetary shocks to black box model by Kallenrode & Wibberenz (1997) that in most events the shock acceleration efficiency decreases with increasing radial distance. Thus most of the shocks are very efficient accelerator close to the Sun, but with rather strong decreases in acceleration efficiency at few tenths of an AU.

The turbulence level in the sheath region ahead of ICMEs is found to be higher than the ambient turbulence, allowing these regions to be tracked as they propagate through the interplanetary medium (e.g., Gapper et al. (1982)). Interaction of SEPs with ICMEs can reveal more about the structure of the ICME. The double-peaked MESEP events are rather a combination of two separated accelerations from two separated eruptions each of which has two components, coronal and interplanetary. An interferance occurs in the interplanetary medium is between the interplanetary shock of the first CME and the coronal injected particles from the second CME. In paper III and IV, the observation of the intensity-time profile was accompanied with careful anisotropy flux measurements. The effect of magnetic field is also included and thus the set of data is enabling us to hold the keys of the second SEPs acceleration associated with the second peak and second CME.

Our interpretations were based on the assumption that topology of interplanetary magnetic field is identical to the topology of the standard Archimedean field, but geometry may differ from the standard one. The assumed topology is that magnetic field lines are connected to the Sun at one end and open to beyond the Earth's orbit at the other end. We did not find in the local solar wind measurements indications of a closed topology (magnetic cloud), and for this reason the open topology has been assumed. At open topology, the magnetic field geometry, however, may differ from the standard one, and the local magnetic field data indeed indicate strong deviations of the local magnetic field from the standard Archimedean spiral. Thus, in paper IV, when we found different features in the anisotropy flux measurements of the event of April 04, 2000, beside the other data collected, we introduce a model of the events with compressed interplanetary magnetic field with bottleneck.

The scattering of the SEPs in the interplanetary medium reduces anisotropy of the energetic particles, as a function of time. However, prolonged acceleration results in prolonged anisotropy. As injection of new particles from the Sun naturally is manifested as streaming of the particles in interplanetary space. Our work refers to, e.g., the work of Kallenrode & Wibberenz (1997), where various effects during the SEP injection to the observed particle intensities and anisotropies were considered. The temporal evolution of the observed intensities and anisotropies has been fitted with the use of simulations for SEP events in many separate studies. Scattering can make the particle distribution isotropic only after the particle source ceases. Thus, since no dropouts were observed in the SEP intensity in either events, October 19 2001 and April 04 2000, we assume the onset of the second peaks in the intensity is due to SEPs propagation at the same magnetic connection to the shock driven by the first CME. Also, in those events it is noted that the rapid onset, compared to the first event onset, suggests that the path length is not very long (with regard to draped field lines), and transport isn't slow (with regard to the turbulent sheath). On the other hand, from the remarkable similarity of the two X-ray flare profiles for the event of October 19, 2001, as shown in figure 1 of paper III, we deduce that the acceleration scenario is most likely similar in the two events. The similarity and the relatively early observation of the second-event particles does, however, strongly suggest that the second-event particles are not significantly delayed on their propagation from the Sun to the Earth. Thus the previous ICME was transparent for new SEPs.

In paper IV, we indicate the reason that might be behind the deficiency in shock acceleration of over 10 MeV at > 0.4 AU. As it can be seen from table 1 of paper V, the first CME associated with April 04, 2000, has acceleration of 12.8 $m \cdot s^{-2}$ according to LASCO data, but the CME was seen by with C3 only and in four points starting from height of 12.44 $R_{\odot}$, which means that LASCO missed tracking the CME closer to the corona. Reiner et al. (2007) suggested that there are large uncertainties in the actual values of the apparent deceleration derived from the height-time measurements, especially for the faster CMEs. The LASCO measurements for CME acceleration depend on the near-Sun, plane-of-sky LASCO CME speeds, the mean 1 AU transit times, and in situ ejecta speeds and it has somehow indicating that the CMEs observed by LASCO generally accelerate but the acceleration was relatively small and increased linearly with the plane-of-sky CME speed measured in the LASCO coronagraphs (Gopalswamy et al., 2000). The LASCO measurements would assume constant acceleration from Sun to Earth which contradicts to the observed transit speeds and in situ shock speed measurements. A correction for these measurements introduced an acceleration-cessation distance, as well as corrections for projection effects and 1 AU shock speeds (Gopalswamy et al. (2001a, 2005); Michalek et al. (2004)). Thus in such kinds of measurements it is not possible to determine the precise heliocentric distance at which the acceleration ceased (Reiner et al., 2007), so they used fitting of low-frequency radio emission generated by shocks of the CMEs (see table 1 in that study). It has been found that the shock of the first CME in April 04, 2000, is decelerating by -99.5 $m \cdot s^{-2}$. Such fitting with the CME of April 4, 2000 is shown in paper IV, figure 2. Thus it is more likely that the CME became deficient to accelerate energetic protons at $\sim$0.4 AU.

The acceleration measurements according to LASCO are given in table 1 of paper V. We compare the results, in the event considered by Reiner et al. (2007), to LASCO measurements in order to reach the most accurate value of shock acceleration. Two events were not reported by Reiner et al. (2007), the event of October 19, 2001, and the event of February 17, 2000. However, in those events the CMEs were reported by the LASCO team as decelerating by -25.6 $m \cdot s^{-2}$ and -22.8 $m \cdot s^{-2}$ respectively, (see table 1 of paper V). As for the other two events, the event of April 04, 2000, and the event of September 12, 2000, were reported by both, Reiner et al. (2007) and LASCO team. The LASCO team reported both CMEs in the events as accelerating by 12.8 $m \cdot s^{-2}$ and 58.2 $m \cdot s^{-2}$ respectively, (see table 1 of paper V), while Reiner et al. (2007) reported same CMEs as decelerating by -99.5 $m \cdot s^{-2}$ and -38.5 $m \cdot s^{-2}$. Generally, this might give us a starting point that the decelerating shock of the first CME is the reason behind possible penetration, of energetic protons injected by second CME in each of those event.

Chapter 5

Conclusion

In this work I have used the ERNE instrument on board SOHO as an essential tool for the investigation of a phenomenon known as double-peak SEP events. The finding of a group of such events, analyzing their intensity-time profile, abundance ratio and possible velocity dispersion, was possible because of the high sensitivity of ERNE. The intensity-time profile was the initial point for the study through finding similarities of such profiles in the SEP events during the 23rd solar cycle. The first principle was consideration of wide range of proton energies provided by the instrument through both detectors LED and HED. The second principle, is to use different time resolutions in each case for different analysis, such as using high resolution for calculating the first injection time and a lower resolution for clarifying the component ratio or the shifting in the peak intensity-time.

In paper I, we surveyed 88 events during the solar cycle and chose 18 events of such similarity in having double-peak components. The intensity mostly reflects the acceleration of SEPs in eruption at the Sun and during the propagation of CME as far as Earth. Thus the start, variation and decay of the intensity reflect changes in the acceleration mechanism with time. The changing in the intensity during a time interval can form the double-peak structure. We set a criteria for such interval as 3-24 hours and variety for energies as ERNE provides and followed the eruption at Sun associated with the double-peaked events from the start through the decay. This enable us to separate the second peaks due to temporal effect from those of spatial effect. The combination of ERNE measurements with other spacecraft measurements such as magnetic field and radio emission, has lead to confirm such separation.

In paper II, we used again the intensity-time profile as a starting point to survey 333 SEP events. This time we compare the double-peak structure to possible multi eruptions at the Sun. We introduce the term Multi-Eruption Solar Energetic Particle (MESEP) events for such events and classified them in four types according to the appearing of the peaks with the energy level in the intensity-time profile. We deduce that a new tool such as anisotropy flux measurements provided by ERNE is essential with the previous measurements used before in analyzing the double-peaked events, to determine the possible association of the peaks with an eruption at the Sun.

In paper III, we chose a large SEP event from the previous study and show the association of > 10 MeV protons from eruption at the Sun with the second peak and that the energetic protons found their way to the instrument through the previous shock wave of the first CME. In paper IV, in the case of another solar event we strengthen this finding and model the transport of the accelerated protons, and find that the protons of the second peak penetrated through the previous shock because most probably the shock was decelerating. In paper V, we made a comparative study of four MESEP events and obtained the same results as in paper III and IV.

In this study we found that if the double-peaked events reveal a change in the compositions ratio and velocity dispersion of the second peak then in such events the second peak may be related to a different acceleration process at the Sun. If SEP flux and pitch angle distribution change simultaneously with the He/P ratio and velocity dispersion is observed, and there was an eruption at the Sun in association with the second peak, then the second peak is due to the new eruption at Sun. These findings provide fresh knowledge for new modeling of the shock wave propagation in the interplanetary medium and the ability of this shock for accelerating particles.

We have found that a significant fraction of double-peak events is caused by consecutive events of particle acceleration at/near the Sun and an earlier ICME does not shield the new SEP source behind it. This implies that the role of CME bow shock acceleration in production of major SEP events was overestimated and coronal acceleration and interplanetary transport processes also strongly affect the SEP profiles near the Earth's orbit. This finding is useful for both understanding of SEP origin and for the SEP forecasting.

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