Proceedings of ICRC 2001: 3454 © Copernicus Gesellschaft 2001

ICRC 2001

Energetic electron spectra in solar energetic particle events associated and non-associated to coronal mass ejections

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Abstract. We considered energetic electron spectra in solar energetic particle (SEP) events after flare/coronal mass ejection (CME) associations and after flares only using measurements onboard various spacecraft (s/c) at radial distances of 0.3-1 AU during the 21st solar activity cycle. Statistics included about a hundred events of both types. More than 50 events of each type were observed simultaneously at various points of the inner heliosphere. Energy spectra in the range 0.3 to 3 MeV were generated from the maximum flux at each energy. The relationship between the exponent of integral electron spectrum, γ and CME speed, V and angular width was considered and it was obtained that electron spectra become harder with increase of V. The best correlation between γ and V arrives when the observer's magnetic footpoints are in the limits of the CME angular width. In this case the best fit approximation of γ(V) looks as $\gamma \propto V^{-0.5}$ with γ and V in the range of 4.5-1.5 and 500-2000 km/s, correspondingly.

1 Introduction

Contrary to protons and ions relation of energetic (E>100 keV) electron components in SEP-events to CMEs and CME-driven shocks has not been investigated in detail yet. Up to now only two energetic electron enhancements without an active region flare association have been reported (Kahler et al, 1986; 1998). Under appropriate conditions in the outer heliosphere electron acceleration to relativistic energies in interplanetary shocks has been observed (Lopate, 1989). However, it`s well-known that energetic electrons are effectively produced in impulsive flares and injected into interplanetary (IP) space within ~1 minute of the onsets of the flare impulsive phase (Lin and Hudson, 1976; Lin, 1987; Kallenrode et al., 1992). Up to now many investigators (e.g. Droge, 1995, Miller and Roberts, 1997) believe that subrelativistic and relativistic electrons in SEP-events are accelerated exclusively in impulsive phase of flares.

However, large energetic electron enhancements occured also after gradual flares (e.g., Lin, 1987; Kallenrode et al., 1992) including that ones with weak impulsive phase (WIP) in microwave radio- and X-ray emission (Daibog et al., 1993) and the question arises how to produce electrons in the WIP case. Parent flares may be or not be in association with CMEs and possible approach to look for evidence of CME-shock accelerated electrons is to assume that flare-accelerated electrons are injected nearly instantaneously and that the extended duration of any shock acceleration will be reflected in the shape and time scales of electron intensity-time profiles. The influence of CMEs on the time behavior of energetic electrons in SEP events observed on the Helios, ISSE-3 and Phobos s/c was examined by Kahler et al. (1994), Stolpovskii et al. (1995, 1997), Daibog et al.(1996). It was obtained that the rise time, T_r, and the time to maximum, T_m, of the electron enhancement are statistically related and increase with V. Analysis of the onset times, t_{on} of electron enhancements gave some evidences that energetic electron injection at the observer's MFL is provided by CME-driven shock and the time of injection depends on CME speed (Stolpovskii et al., 1997, 2000).

A different approach to look for evidence of shock accelerated electrons is to compare energetic electron spectra in SEP events associated and nonassociated to CMEs. Moses et al. (1989) found two classes of electron events according to the difference in electron spectra in the range 0.1–100 MeV. Those with a single power law in rigidity spectra were related to long-duration flares (duration of X_t–burst >1 hour) and those with a double power law spectra (much steeper spectra occurred at low rigidities, extending down to ~ 0.4 MeV/c,) were generally related to impulsive flares (duration of X_t–burst

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<1 hour). Dröge (1995) showed that electron spectra constructed taking maximum differential fluxes, from solar flares observed simultaneously on ISEE-3 and Helios 1 and 2, were in very good agreement in spite the s/c were widely spaced .He made a supposition that the observed spectra are representative of the accelerated electron spectra in a source at or near the Sun. Neither Moses et al. (1989) nor Dröge (1996) have considered the relation between electron events and CMEs and confined themselves to an association of electron events with IP shocks. They obtained that the most part of a single power law spectra events were associated with IP shocks but some short-duration events were in association with shocks too. Thus the assumption that a flare coronal shock is responsible for events with a single power law electron spectra (Moses et al., 1989) was made accepting higher probability for long-duration flares to be associated with coronal shocks.

Here we consider energetic electron spectra in SEP events of various durations and their relationship with CMEs and CME-driven shocks. We used the data obtained in observations onboard the Helios-1, 2, ISEE-3, Venera-13, 14 s/c at distances of 0.3-1 AU from the Sun in 1977-1983.

2 Experimental data

S/c trajectories and methods of energetic particle measurements, as well as identification and selection of events, were described in detail in (e.g. Kallenrode et al., 1993; Moses et al., 1989). Here we used the results of measurements electron fluxes in energy range of 0.3-3.0 MeV and considered integral spectra of peak electron intensities in the power law representation $J(>E) \propto E^{-\gamma}$. In a case of the ISEE-3 s/c values of γ were obtained by recalculating electron momentum spectra from (Dröge, 1995; Moses et al, 1989). In the case of the Venera s/c exponents γ were taken from (Logachev et al., 1988). In a case of the Helios s/c we considered the hourly and 15 minutes averages of intensities of electrons in four nominal energy ranges of 0.3-0.8, 0,8-2.0, 2-3 and 3-4 MeV and protons also in four energy channels of 4-13, 13-27, 27-37 and 37-51 MeV. Using procedure elaborated by Bialk et al. (1991) the proton contamination in the electron channels of the Helios instruments was estimated and corrected electron fluxes were applied to construct the maximum electron spectra. According to Bialk et al. (1991) the actual electron ranges are slightly higher but we obtained that proton contributions to the counting rates in the E03 electron channel were unimportant practically in all SEP events considered. For most events the same conclusion holds for E08 electron channel. So we estimated γ using the nominal values of electron energy ranges.

Standard data on solar flares were taken from the “Solar Geophys. Data”. CMEs were observed by coronographs at the P78-1 and SMM s/c. We used such CME characteristics as a speed V, limb time (time of appearance of CME at the limb) t_{lb}, position angle ϑ and angular size ψ at the limb (Transient list, 1996; Burkepile and St.Cyr, 1993; Sheeley et al., 1985). Geometrical parameters of CMEs and their speeds are visible projections of the real values of corresponding parameters onto the sky plane. Under supposition that CME originates on the Sun nearby a flare site and moves radially from the Sun it was possible to estimate “real” values of V and ψ (Daibog et al, 1996). Solar wind and IMF parameters at the observation points, as well as data on SC, were taken from NSSDC website. Data on interplanetary shocks were taken from Volkmer and Neubauer (1985), Sheeley et al. (1985) and Cane (1985). Coordinates of the observer’s magnetic footpoint (MFT) were calculated using the V_{sw} solar wind velocity measured at the observation point and the angular distance, φ, between MFT and a flare site was calculated in usually adopted manner.

We considered SEP events with electron intensity enhancements more than one and a half orders of magnitude above background without considerable data gaps. The total statistics includes more than two hundred impulsive and gradual SEP events. We selected 72 events when parent CMEs and solar flares were located in the same hemispheres both longitudinally and latitudinally and t_{lb} differed from the flare onset time no more than 20 min. 22 events were observed simultaneously on two and 6 - on three s/c that allowed to compare the results of multispacecraft observations with the statistical regularities obtained. The most part of CMEs selected were accompanied by IP shocks.

3 Results

We constructed size distributions of amplitude and spectral characteristics of SEP events over flare and CME parameters. For flares without CMEs and CME- driven shocks a size of the SEP particle emission cone is about of 50W,E. The full wide of a half maximum (FWHM) of the size distribution of event number vs. φ is about 30W,E. However under simultaneous observations of the same impulsive events at two and more s/c (45 events, 98 observations) it was obtained that probability of non observing SEP events is about 20% and in some cases the cone of emission did not exceed 15-25 degs. Here selection criterion is very important. In our case only the events with the >0.3 MeV electron peak flux of about 10^4 part/m^2ssec and more were selected. Total width of the size distribution of SEP events after flare-CME associations vs. φ equals ~150 W,E and FWHM is about of 70W,E. For these events probability of “non observation” becomes valuable only in a case of angular distances, $\varphi > 90^{\circ}$. We have built size distributions of SEP events with and without CMEs vs peak fluxes of particles and obtained that for CME-flare associated events the median value of the >0.3 MeV electron peak intensities

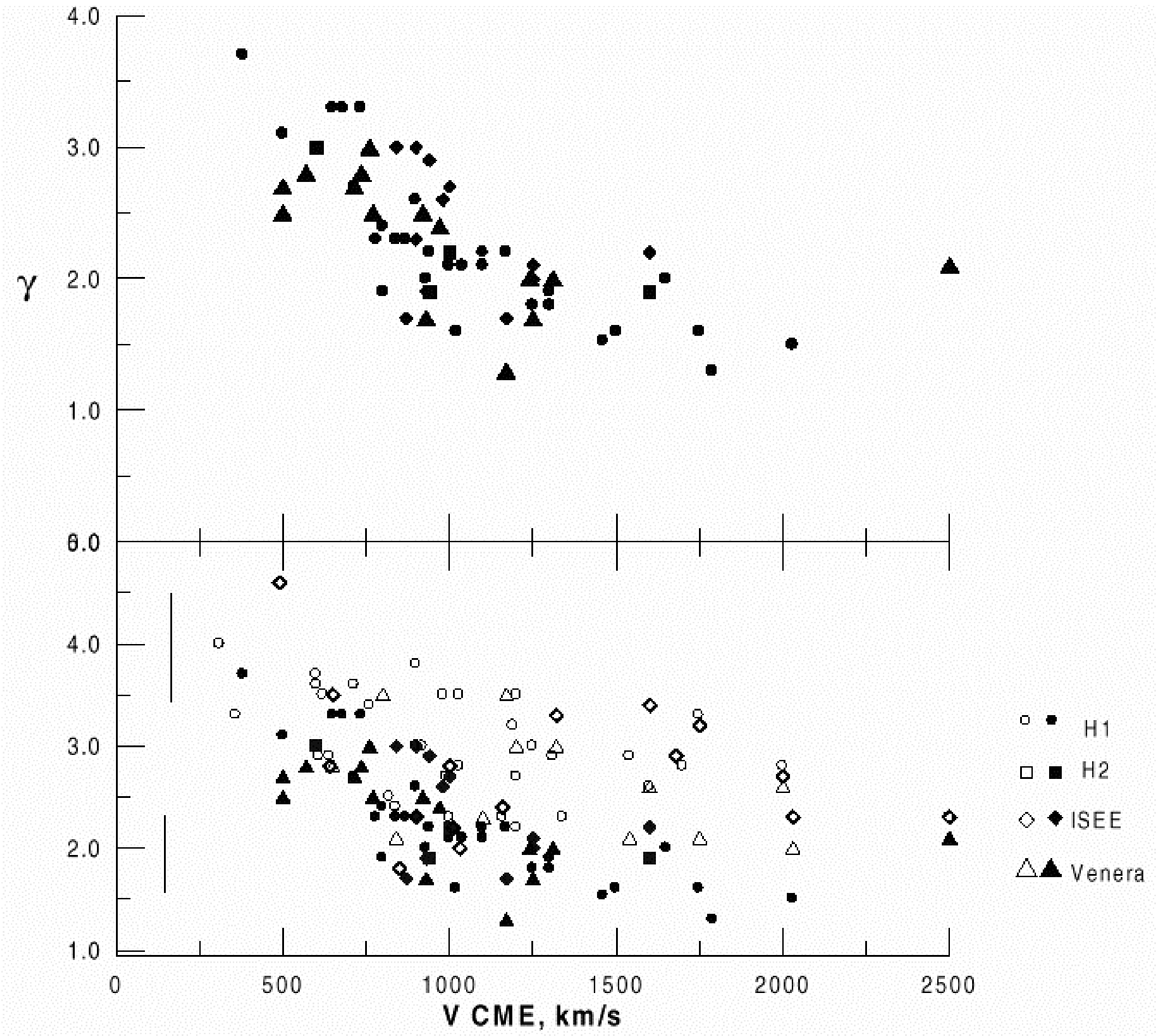

Fig. 1. The exponent of integral electron spectra γ over CME speed V. Bottom panel: all events. Vertical lines on the left side are typical values of errors. Top panel: separately φ <ψ/2 events.

exceeded that one obtained for "pure" flare associated events about 50 times.

We examined energetic spectra of electrons in the energy range 0.2-3.0 MeV in the maxima of events associated and non associated with CMEs. For non CME associated SEP events the values of exponent, γ varied from 2.8 to 5.0 (error ~ 15%) and FWHM of γ is ~3.0-3.8. Average value <γ > is about of 3.8 and the slope of the spectra does not depend on φ. In a case of events associated with CMEs the situation is more complicated. The values of γ ranged from 1.3 to 5.0 and FWHM of size distribution was ~2.2-3.4 at <γ> ~3.0. The slopes of the spectra increased with φ and in average γ was ~1 more at 80-90W,E than in the 0-50W,E interval. It was discovered that for events at the angular distances, φ less than a half of CME angular widths, ψ/2 size distribution is more narrow and <γ>~1.9.

We had ~120 energetic spectra in the range of φ ~ 150° E,W and CME speeds ~ 300-2000 km/s. We considered separately dependences γ(φ) for events with V<700km/s and >700 km/s and obtained that for the former case γ ~3-4 while for the latter γ ~1.5-3. For fixed values of V average γ in the angular range φ> 60° E, W is about 1 more than for smaller φs. Thus an exponent γ is connected not only with φ but also with V. It can be seen from the bottom panel of Fig. 1 where the γ(V) dependencies are presented for the cases when φ >ψ/2 (open symbols) and $\varphi < \psi/2$ (filled symbols).

To reduce influence of φ the dependence of γ on V was built only for events with $\varphi<\psi/2$. This is shown in the top panel of Fig. 1 and one can see that spectra become harder (γ decreases from about 4.5 to 1.5) when V increases from 300 to 2000 km/s. This is right for both impulsive and gradual SEP events. It seems that for the case of flare-CME associations slopes of electron spectra in considered energy range are stronger correlated with V than with flare duration as was proclaimed by Dröge (1995) and Moses et al. (1989). γ(V) dependence can be approximated as $\gamma \sim V^{-a}$. For subset of events with $\varphi<\psi/2$ correlation between V and γ is strong (R~0.8) and the best square approximation becomes $\gamma \propto V^{-0.5}$.

Such dependence can be understood as diminishing of shock acceleration efficiency along with decreasing of CME speed. Particle acceleration begins when CME speed exceeds Alfvénic one. In the average model of solar atmosphere maximal Alfvénic speed V_a~350 km/s takes place at heights of 1-2 solar radii and it's necessary for acceleration CME having a speed V>350km/s. The more the CME speed, the more the Alfvén-Mach number and to the higher energies particles could be accelerated thus making a harder spectrum. At far shock flanks, i.e. at large angular distances, its speed decreases (Cane, 1996) that causes decrease of efficiency of acceleration and corresponding softening of electron spectrum.

4 Conclusions

Analysis of the spectra of energetic electrons in SEP-events show that CMEs and CME-driven shocks can be a sufficient factor for electron injection and acceleration.

Acknowledgements. The Russian authors thank Dr. B.Yushkov and O. Morozov for their help in data processing and useful discussions. Their work was supported by ISTC and EOARD (project 2063p). G. E. acknowledges support from Hungarian grant T030078.

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