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Low Energy Solar Particles Observed During the Pre-Phase of Large Particle Events *

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Abstract. Solar proton and electron measurements ($E_p \geqq 80$ keV, $E_e \geqq 20$ keV) of the Helios 1 and 2 spacecraft are used together with additional information published in the Solar Geophysical Data to study the pre-phase particle emission occurring $\lesssim 5$ days before the large particle events in the same McMath region. Emphasis is laid on the question of whether both suggested particle acceleration steps in the pre-phase actually take place. It was found that about 60% of all pre-phase events are associated with Type II/IV radio-bursts, the general proton indicator. The remaining 40% of the pre-phase events were associated only with small flares and a group of Type III bursts. However the proton/electron ratio, which is $\gtrsim 10$ and $\gtrsim 100$, at ~ 0.1 MeV and ~ 1.0 MeV particle energy, respectively, as well as the maximum particle energies reached indicate that the second (Fermi-type) acceleration process has taken place also for these events. The first and second acceleration process were not separable and it must be concluded that the Type III associated events are independent and are not a precursor of the main event.

Key words: Solar particle events – Radiobursts – Acceleration process

Introduction

Large cosmic ray events are generated in highly active solar regions which release about 10^{32} erg in 10^3 s when one or more optical flares occur, together with microwave and X-ray emission. It has been suggested that the acceleration of solar particles up to relativistic energies takes place in two different acceleration steps (de Jager 1969; Svestka and Fritzova-Svetskova 1974; Lin 1974; Svestka 1976; Ramaty 1979; and others). The first step, with time scales of 10–100 s, also called the flash or impulsive phase, would primarily produce electrons in the energy range 10–100 keV; effects of these accelerated electrons include the accompanying bremsstrahlung photons.

The second stage then is thought to generate relativistic protons and electrons and is accompanied by Type II/IV radio bursts. Particle acceleration in the second stage has been explained in terms of second order Fermi mechanism (Ramaty 1979), second order transit time damping (Fisk 1976), and the first order Fermi mechanism of shock acceleration (Axford et al. 1977; Fisk et al. 1980). The former acceleration processes are related to the formation of the Alfvén (Fermi) and the magnetosonic (transit time) wave spectrum that scatters particles in momentum space. Shock acceleration occurs at the shock discontinuity when "seed" particles perform multiple crossings at the shock front.

Type II, IV radio bursts are produced by shock waves interacting with both the solar atmosphere and the interplanetary plasma and generally indicate the emission of protons from the sun (Warwick 1962; Croom 1971; Akin'yan 1977). The Type III radio emission is associated with nearly relativistic electron streams interacting with the corona and interplanetary plasmas (Fainberg and Stone 1974), the electrons possibly being accompanied by protons (Svestka 1976). Type III radio bursts often occur without visible manifestation of flares.

A different acceleration process may be responsible for Type III bursts and the steady (hours to days) production of low energy (< 1 MeV) ions (Rust and Emslie 1979).

The purpose of the present study is to examine the pre-phase of large particle events, whenever enhanced, and to investigate the physical configuration of the solar emission compared to the main event. We use low energy ($E_p > 80$ keV, $E_e > 20$ keV) ion and electron measurements on the Helios spacecrafts within

Table 1. Solar particle events

Main Event	Pre-emission	Pre-emission with Type II/IV	Pre-emission with Type III
28 March 76	1	1	0
5 Sept. 77	1	1	0
22 Nov. 77	3	1	2
27 Dec. 77	3	3	0
1 Jan. 78	1	1	0
13 Feb. 78	4	2	2
25 Feb. 78	2	2	0
6 March 78	1	0	1
8 April 78	2	1	1
11 April 78	–	–	–
7 May 78	3	2	1
11 May 78	1	1	0
10 Nov. 78	3	1	2
11 Dec. 78	1	1	0
24 Jan. 79	1	0	1
16 Feb. 79	0	0	0
1 March 79	–	–	–
9 March 79	–	–	–
3 April 79	2	0	2
13 April 79	–	–	–
Sum: 20	29 (100%)	17 (~60%)	12 (~40%)

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* A preliminary version has been presented at the 7th European Cosmic Ray Symposium, Leningrad, Sept. 1980

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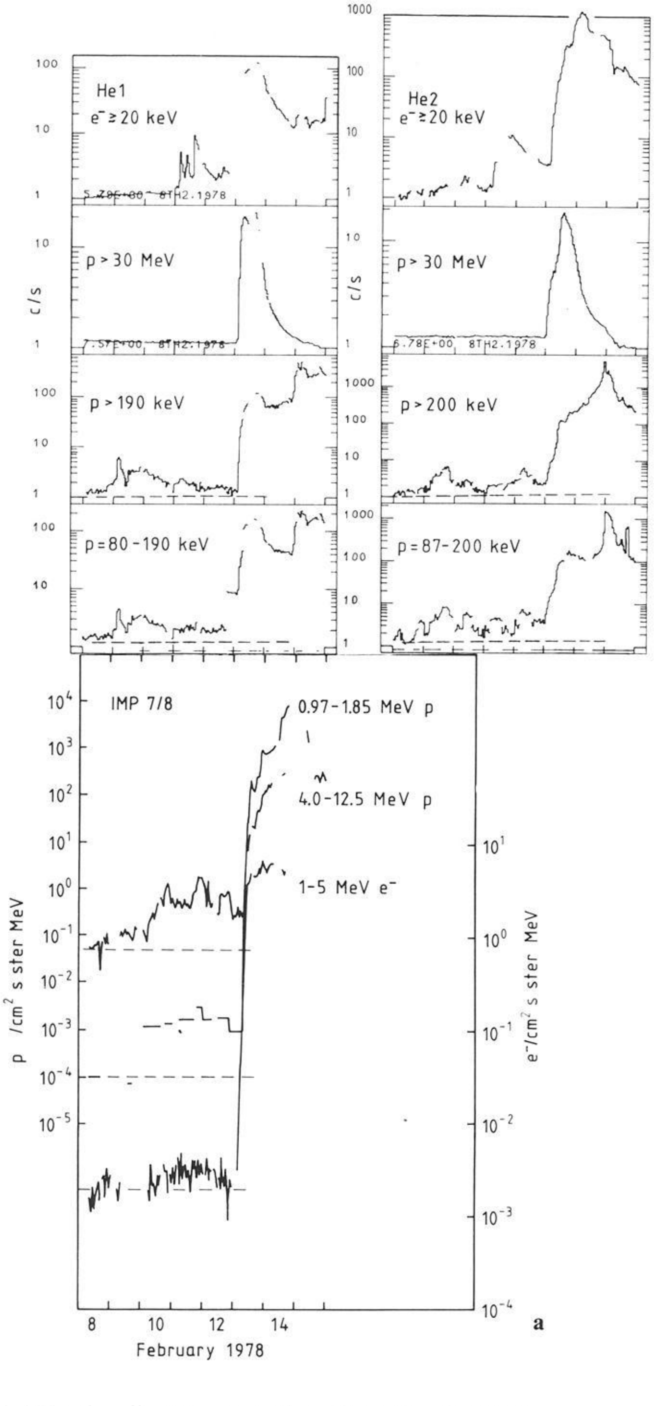


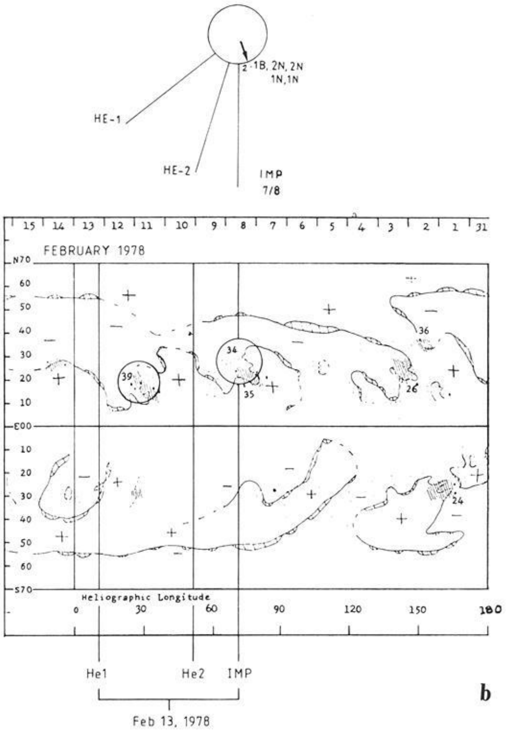


Fig. 1a–c. Data for February 1978. **a** Proton-electron measurements of Helios 1/2 (*upper part*) and of IMP 7/8 (*lower part*) from Feb. 8–15; **b** Positions of Helios 1/2 and of IMP 7/8 with respect to the Sun for Feb. 13 (*upper part*) and the H_α synoptic chart (*lower part*). The *vertical lines* indicate the foot points of the field lines which are connected to the three spacecrafts. **c** SMS-GOES X-ray measurements from February 8–13. The *horizontal bars* in the *upper part* represent Type III, II, IV – radio bursts and the flares in the McMath regions 15139, 15134

1 AU solar distance, as well as the IMP 7/8 satellites ($E_{p,e} \gtrsim$ 1 MeV) particle data, X-ray and radio observations as published in the Solar Geophysical Data.

The preflare enhancements before solar cosmic ray events have been studied earlier by Kuzhevskiy and Chupova (1977) and Block and Kuzhevskiy (1979, 1980).

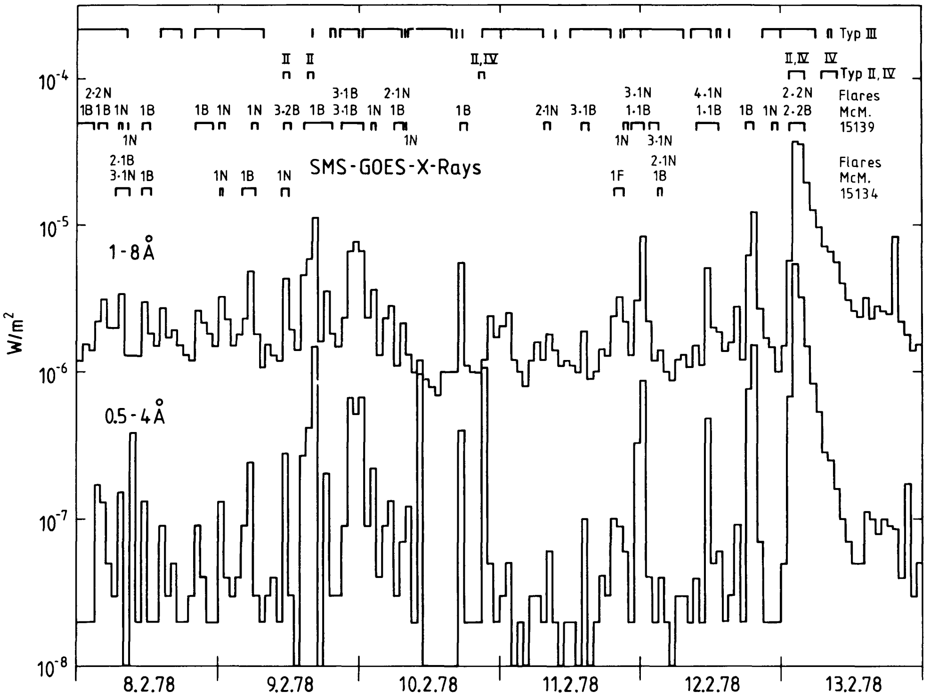
The physical quantities of interest are: association with Type II, III and IV radio bursts, X-ray emission, the proton to electron number ratio, energy spectrum, and the maximum energy of the accelerated particles. The criteria used to select the pre-emission events are as follows:

a) Identification of the flare in the same McMath plage region as the main event.

b) The thresholds used for the pre-enhancements are: (p for protons, e^- for electrons) Helios 1/2: $\geqq 10$ p/cm² s sr ($E_p \geqq$ 80 keV), $\geqq 5$ p/cm² s sr ($E_p > 190$ keV), $\geqq 5$ e^-/cm² s sr ($E_e \geqq$ 20 keV) IMP 7/8: $\geqq 5 \cdot 10^{-3}$ p/cm² s sr MeV (E_p=0.97–1.85 MeV), $\geqq 1{,}0 \cdot 10^{-3}$ e^-/cm² s sr MeV (E_e=1–5 MeV) or generally ~20% above the background.

c) The reported pre-events are "impulsive", i.e. the particle data exhibit a sudden increase, a maximum and decay phase. ('Non impulsive' events not associated with flares have been discussed by Zwickl and Roelof, in press 1981). Both the main event and these impulsive ones take place in the same active region. The east-west solar scans (Solar Geophysical Data) at 3 and 10.7 cm wave lengths help to identify the heliographic longitude of the source region, discriminating from other solar active regions.

d) The particle injections take place under negligible coronal propagation. The foot points of the magnetic field lines are



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connected to the 'fast propagation region' (Reinhard and Wibberenz 1974).

e) The pre-phase period should not be disturbed by shocks in the interplanetary space produced by other flares.

f) For the interplanetary transport process of the low energy protons and electrons we assume the classical models: diffusion parallel to the smooth interplanetary magnetic field with fewer scattering processes taking place between onset and maximum phase of the particle events and isotropisation in the late phase of the events (compare Fisk and Axford 1968; Völk 1975; Earl 1976; Gombosi and Owens 1980 and others).

Experiment Description

The charged particle spectrometer flown on Helios 1 and 2 uses an inhomogeneous magnetic field to separate ions and electrons, three single semiconductor surface barrier detectors for electron detection and a telescope consisting of two similar detectors for ions. The latter have a geometric factor of $1.5 \cdot 10^{-2}$ cm^2 sr for ions and the former $<5 \cdot 10^{-2}$ cm^2 sr for the electrons. The experiment measures ions and electrons in 16 energy channels and 16 sectors in the ecliptic plane. The energy range covered is 20 keV–2 MeV for electrons and 80 keV–>750 keV for ions if they are interpreted as protons. For a detailed description of the instrument see Keppler et al. (1977).

The earth orbiting satellites IMP 7/8 are able to measure particles with $E > 0.2$ MeV using solid state detector telescopes as described in Solar Geophysical Data.

Observations

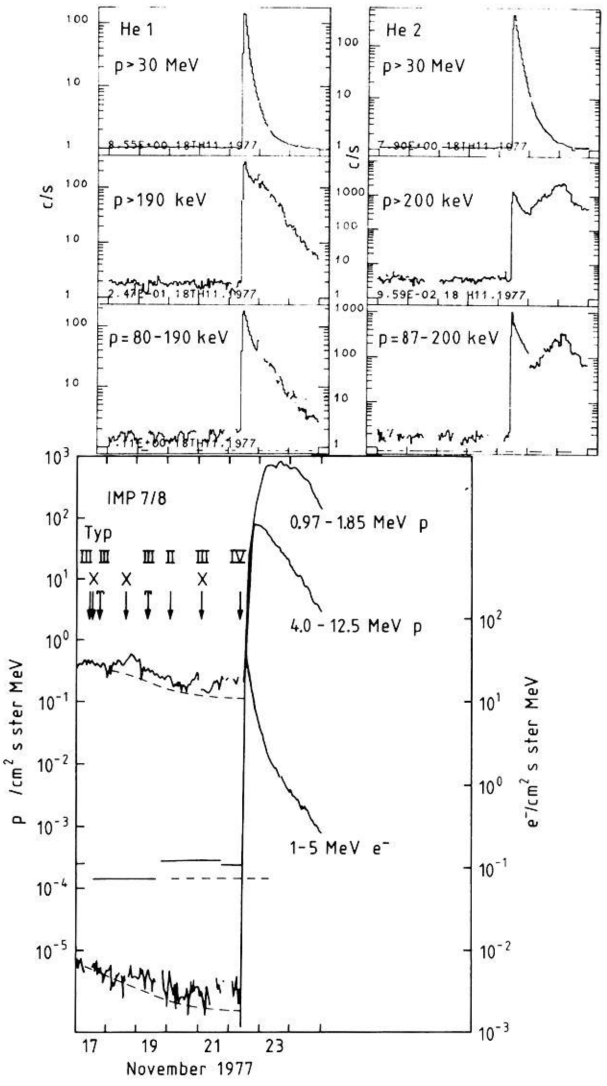
In Table I are listed 20 solar particle events from 1976–1979. They are characterized by the presence of >30 MeV protons. The period of our observations correspond to the quiet period up to the maximum of the solar activity of the cycle 21 as measured by the sunspot numbers. About 75% of these events were associated with pre-enhancements, observed by at least one of the three spacecraft described above. This fraction is consistent with the value obtained by Block and Kuzhevskiy (1979) during other periods and events. The 16 proton events exhibit 29 individual pre-emission cases; of which 17, or ~60%, are associated with Type II/IV radio bursts. The rest, i.e. ~40%, are associated with the Type III bursts.

We concentrate on the 40% of cases of enhancements associated with Type III radio bursts, that generally accompany small flares. The other events, i.e. 60% of the pre-phase enhancements associated with Type II/IV radio bursts, are being considered as the classical two-step acceleration mechanism and likely analog to the main particle event. We point out that Type II/IV associated events show often Type III radio bursts in addition.

Particle measurements from Helios and IMP probes during 8–15 February 1978 are presented in Fig. 1a. The main event starts on 13 February. In this illustration the time resolution is taken equal to 1 h. The proton-electron injections during the pre-phase of the main event can be seen above the (dashed line) background fluxes. No shocks are observed with the plasma experiment of the Helios 1, 2 during these pre-phase events (Dr. R. Schwenn, private communication). During the same interval no sudden commencements are reported (Solar Geophysical Data).

The maximum energy of the pre-emission events reach up to 20 MeV for protons and up to >1 MeV for electrons. In Fig. 1b (the upper panel) are sketched the locations of the three spacecraft at the onset of the main event and the flares of the sun. The IMP satellites are located at 1 AU helioradial distance, the Helios spacecraft within 1 AU. The lower part of Fig. 1b illustrates the H_α-Synoptic chart with the coronal connecting longitudes of the three probes, calculated according to the mapping technique (Nolte and Roelof 1973), for 13 February. Also shown are the two McMath regions 14139 and 15134; their activity was triggered between 8 February and 13 February. The east-west solar scan reveals that it is quite probable that the main particle event as well as the pre-emission originated in McMath region 15139.

Figure 1c shows the X-ray measurements of the SMS-GOES satellite (0.5–4 and 1–8 Å) during 8–13 February. The upper



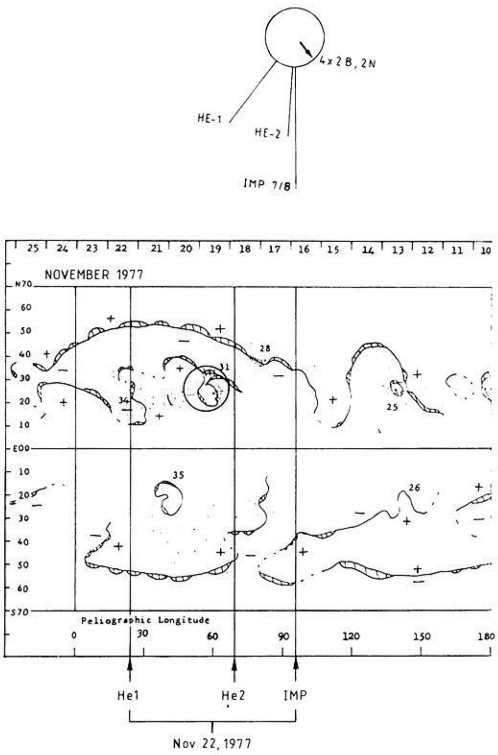


Fig. 2a, b. Data for November 1977. **a** Proton measurements of Helios 1/2 (*upper part*) and proton-electron measurements of IMP 7/8 (*lower part*) from Nov. 17–24; **b** As Fig. 1b but for Nov. 22, 1977

part, indicated by horizontal bars, exhibits the observed Type III, II and IV radio bursts and the type of the flares that have taken place in the active regions 15139 and 15134. It can be seen that not all Type III bursts are associated with distinct X-ray bursts. Only those particle increases in Fig. 1a which are associated with Type III bursts will be considered further. We note that the electron flux increases on 11–12 February shown in Fig. 1a are associated with Type III bursts. The IMP satellites detected small fluxes of >1 MeV electrons. Also, a proton to electron ratio at ~ 1 MeV energy of 500–1,000, for the pre-phase of these events could be determined. The Helios 1, 2 observations show that the proton to electron ratio at ~ 100 keV is already >10, described by different energy channels of the experiment. The maximum energies of the accelerated protons and electrons during this pre-phase are ~ 20 MeV and >1 MeV respectively, seen by the IMP measurements. The fitted differential power law spectrum obtained from the Helios output is of the order of $\gamma \sim -3$ for the exponent, with small fluctuations during the interval we discuss (compare Block and Kuzhevskiy 1979; Fisk and Lee 1980, who expect exponential spectra from the transit time acceleration as well as from the shock acceleration mechanisms).

A second illustration is shown in Fig. 2a where the 22 November 1977 event is the main reference. The pre-emission of low energy protons and electrons is small (electrons are not shown in the Figure) as measured by Helios 1, 2. The IMP satellites however reveal particle enhancements. The same event has been studied by Block and Kuzhevskiy (1979, 1980). They found proton and electron pre-emission as well as an indication of a hardening of the spectrum. The 22 November event occurred at the beginning of the present solar sunspot cycle.

The arrows in Fig. 2a (lower part) show the detected bursts of the X-, Type II, III and IV radiation. During the pre-phase of this event the X-ray emission was mostly below the level of detection. With the exception of 20 November, when a Type II radio burst occurred, most of the pre-emission events were associated with Type III bursts. Figure 2b illustrates the positions of the spacecraft, the flares at the Sun on 22 November and the H_α-synoptic chart with the calculated foot points of the field lines at the corona which are connected to the satellites. It can be seen that only one McMath active region could produce the pre-phase and the main particle emission. A special feature during 22 November is the hard X- and γ-ray emission which indicate that nuclear reactions have taken place in the solar photosphere (Chambon et al. 1978). Composition measurements for the main event (on 22 November 1977, as well as on 13 February 1978) have been published by McGuire et al. (1979). No evidence was found of low energy ^{3}He enrichment or of ^{2}H, or ^{3}H.

The maximum energies reached by protons and electrons during the pre-phase of 22 November event amount to < 13 MeV and ~1 MeV, respectively. The proton-to-electron ratio at ~ 1 MeV particle energy is ~100 as obtained from the IMP measurements.

We summarise our observations noting that the illustrative examples given above can be seen as typical of the so-called pre-phase events.

1) About 60% of the particle enhancements preceding large solar particle events are associated with small flares occurring in the same McMath activity region as the main event and Type II, IV radio bursts. The remaining 40% of the pre-phase events, examined in the present study, are associated with small flares and a group of Type III radio bursts.

2) Such pre-phase proton events are associated with X-rays and quasi relativistic electrons (sometimes up to > 1 MeV).

3) The proton-to-electron number ratio for ~0.1 MeV particles amounts to ~10, reaching > 100 at ~1 MeV energies.

4) The maximum energies of accelerated protons and electrons are < 20 MeV and > 1 MeV, respectively.

5) The shock waves possibly associated with such pre-phase events are below the level of detection. Sometimes the equatorial Dst-value of the geomagnetic field shows small disturbances which could result from flares producing the Type III bursts.

Discussion

The presented study has shown that small flares occurring in the pre-phase (< 5 days) of large particle events can obviously accelerate electrons and protons up to energies > 1 MeV and < 20 MeV, respectively in association with Type III bursts and X-rays without, however, detectable Type II, IV bursts and also without shocks. It has been suggested that solar particles are accelerated in two stages to high energies, the first one leads to ~1 MeV energy, the second one up to relativistic energies (de Jager 1969; Lin 1974; Svestka 1976; Lin and Hudson 1976; Bai and Ramaty 1976, compare also Emslie and Rust 1980). The time resolution (1 h) of the X-ray and particle data (the higher time resolution of the Helios experiment could not be used due to the small particle fluxes) give no direct evidence for the second acceleration stage. However, the maximum particle energies reached and the proton-to-electron ratio in particular indicate that the second acceleration process has taken place. In a recent paper Ramaty (1979) has treated analytically the second order Fermi-type acceleration process and found that more protons than electrons are accelerated by the second acceleration stage. Because a Type II/IV radio burst and a direct shock wave in the solar wind was not detectable during the events presented here, the role of an accompanying shock wave is still unclear. Since individual small flares in the pre-phase of larger particle events can accelerate protons and electrons to moderate energies we consider all pre-phase events as independent events and not as the precursor of the main event. The fact that the particle energy increases the nearer the main event comes in time (Block and Kuzhevskiy 1979, 1980) could be explained by larger and more efficient flares occurring in the same McMath region.

Kahler (1979) studied the pre-flare characteristic < 20 min before small flares in soft X-rays and concluded that coronal pre-flare heating lasts not longer than 2 min indicating again that all flares are independent events. The pre-flare events seem to have no influence on the composition of the main events as can be seen from the measurements published by McGuire et al. (1979).

Since Type III bursts are more common than proton events and not always related to observable flares it can be concluded that electrons are temporarily stored in closed coronal field configurations (corresponding to a height of 4–6 solar radii) and are released by a still unknown mechanism. McGuire et al. (1975) concluded that a rest matter of 5–10 μg/cm^2 allows a storage of electrons for > 5 days in the corona, a value which should also be valid for the pre-phase events. Stored protons seem to lose their energy rapidly due to their stronger ionisation effects with the rest matter in the acceleration region. Krimigis (1972) calculated storage times of < 1 day for low energy protons ($E=$ 0.1–0.3 MeV) and coronal densities of $4 \cdot 10^5/\mathrm{cm}^3$–$3 \cdot 10^4/\mathrm{cm}^3$ (3–6 solar radii). It is noted here that McGuire et al. (1975) have suggested the continual acceleration of low energy protons and electrons in "active solar regions" which may be different from the acceleration process operating in the pre-phase of large particle events. Considering the energy spectrum, the maximum energies reached and the association with Type III bursts, we find that the pre-emission events can best be compared with the so-called micro events studied by McDonald and van Hollebeke (1972). They found that ~20% of the micro events are associated with Type II and IV radio bursts and ~80% with a group of Type III bursts only.

As a side result we note that the empirical formulas relating duration and intensity of the micro-wave burst and the expected proton flux near the Earth derived by Croom (1971) and Akin'yan et al. (1977) cannot be applied to the pre-phase events because they predict too high fluxes. The relation between X-ray intensity and ~1 MeV protons (Gold and Roelof 1977) also predicts too high fluxes.

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