Solar Energetic Particle Events at the Rise Phase of the 23-rd Solar Activity Cycle Registered Aboard the Spacecraft "Interball-2"

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Abstract

The complicated increases of solar energetic particles (SEPs) from flares on the Sun on November 4 and 6, 1997, April 20, May 2 and 6, August 24, 1998 are analyzed. Characteristics of SEP propagation in interplanetary space in the energy interval from 7 to 300 MeV are discussed by using measurements aboard the spacecraft "Interball-2". The events are the first flare events in the new solar activity cycle, and their complex analysis is important in many aspects.

1 Brief Description of the Experiment:

The spacecraft "Interball-2" was launched in the elliptic orbit on August 29, 1996 with the inclination 62°, the rotation period 5 h 46 min, the perigee 770 km and the apogee 19184 km. A space-borne installation 10K-80 consists of electronic and detection units with the wide-angular scintillation detector of 100 mkm in thickness with an area of 1 cm^2. The geometric factor of a telescope is 4 cm$^2\cdot$ sr. The instrument registers the protons in five differential channels in the energy intervals of $27-41, 41-58, 58-88, 88-180, 180-300$ MeV and in the integral energy channel with $E_p > 7$ MeV.

2 Analysis of Data and Discussion:

The event on November 4, 1997 was observed only by the spacecraft. It was assotiated with the active region NOAA 8100 where there was the flare X2/2B (S14W33). The maximum of brightness was observed at 0558 UT. Thereby, the spacecraft SOHO registered an ejection of coronal mass between 0552 and 0608 UT (Lario et al., 1998). At 0640 UT, ~ 40 min after the flare, the 10K-80 detected the beginning of SEP intensity increase in all channels. Fig.1a presents times when the solar flare observed. Unfortunately, there were no possibility to determine more exactly the beginning of arrival of first particles and their dependence on the energy, since "Interball-2" was located in the radiation belts of the Earth. Nevertheless, if we know the coordinates of SEP flare the acceleration of which in most cases takes place immediately in the region of the optical flare (Reinhard and Wibberenz, 1994) and the injection place of SEP into interplanetary space (the field line base connecting the Sun with the Earth) which was obtained, taking into account the solar wind speed ~ 350 km/s (Solar and Geophysical Data, 1998) and the Sun's rotation $\Delta L = 37^\circ$, then one can suppose that there was the rapid coronal transport of the SEP from the generation place to the injection point. The temporal change of SEP intensity increase in the undisturbed interplanetary magnetic field (Krimigis,1965) is satisfactorily approximated by of the diffusion equation solution assuming the impulse particle injection provided that a dependence of the diffusion coefficient k on the heliodistance r is given by an exponential function $k = k_0 r^\beta$ (Mason et al., 1999), where β asymptotically approaches to 1 as the energy increases. The path length λ increases from $5.6 \cdot 10^{11}$ cm up to $9 \cdot 10^{11}$ cm as the energy increases. The event is characterized by enough hard differential energy spectrum, $\gamma = 1.89$ (Fig. 2a).

The event on November 6, 1997 is the most large observed for the last seven years in the soft X-rays by many spacecrafts and which was detected with neutron monitors as GLE. The flare X9/2B was in the same active region NOAA 8100. Its coordinates were (S18W63) with a maximum intensity in H_α at 1155 UT on November 6. In that time the movement of the coronal mass ejection from the west limb of the Sun (Lario et al., 1998) has been observed. About 30 min after, the the sharp increase was about 3 times for the protons with energies from 27 to 300 MeV (Fig. 1a). In the integral channel, in which the particles with energy more than 7 MeV, the amplitude of the increase on November 6 was smaller than for the event on November 4. It is probably associated with the more long diffusion process for the low-energy particles. The differential energy spectrum of this event was the most hard ($\gamma = 1.58$, Fig. 2a). By observations of the "Interball-2" the intensity decrease phase is more prolonged than in the previous case. It is indicative of the influence of the complex inhomogeneous interplanetary magnetic field caused by an ejection of the coronal mass on November 4, 1997, from which the shock wave passed near the Earth at 2248 UT on November 6, i.e., ~ 64 hours later. The strong anisotropy and also the contribution of particles from the preceding event into the observed flux pose major problems for the use the diffusion model to define the parameters of charged particle propagation in interplanetary space for this event.

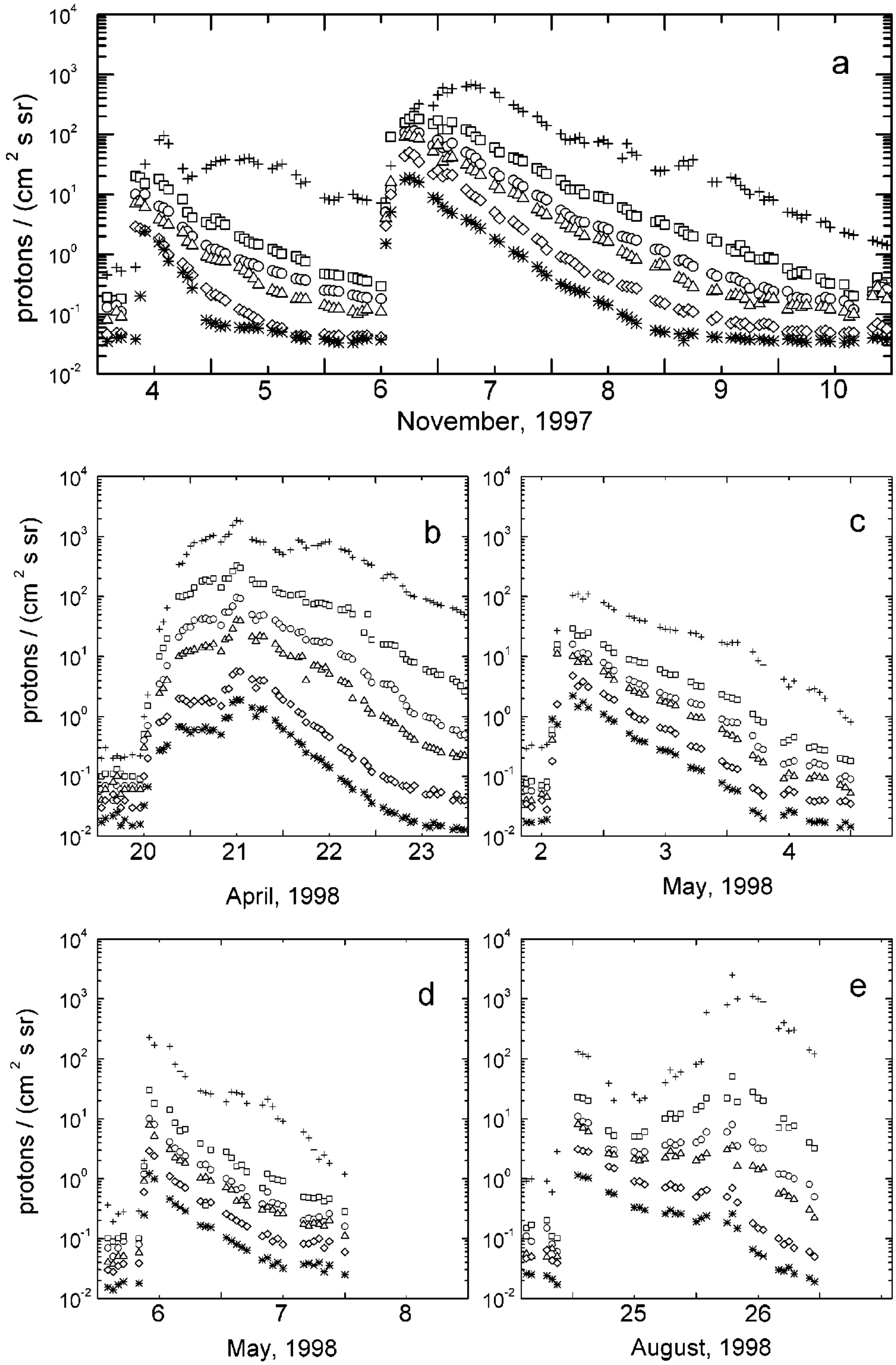

Figure 1: Temporal profiles of SEP increases from the solar flares November 4 and 6, 1997, April 20, May 2 and 6, August 24, 1998, registered with the installation 10k-80.

The event on April 20, 1998 is associated with the active region NOAA 8194 where the flare M1/EPL (S43W90) with a maximum in H_α at 1021 UT following by the coronal mass ejection with a velocity $V \sim 1000$ km/s took place (McIntosh, 1998). The propagation time (without a scattering) of SEP from the generation place on the Sun to the observation point

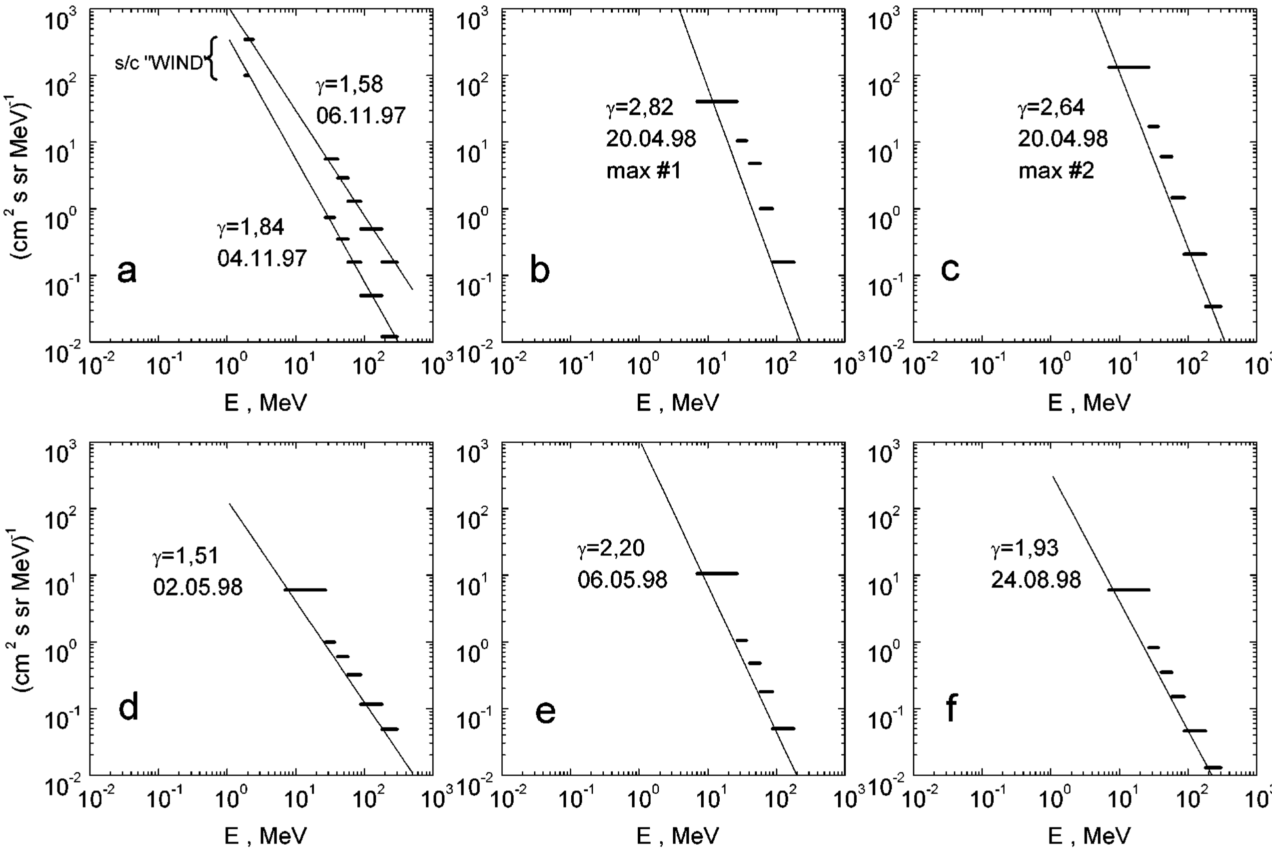

Figure 2: The differential spectrum of SEP for November 4 and 6, 1997, April 20, May 2 and 6, August 24, 1998 events.

("Interball-2") is not more than 40 min.
One of the features of this event is that in about 40 hours the temporal profiles (Fig. 1b) of SEP intensities have been essentially modulated, thereby both the character and the time are the same for all energetic channels. It led to the appearance of the second maximum. It appears to be connected with the interplanetary disturbance from the coronal mass ejection. The differential energy spectrum index is $\gamma = 2.82$ for the diffusion maximum and $\gamma = 2.64$ for the modulation region (Fig. 2b, c).
The event on May 2, 1998 (Fig. 1c) is associated with the active region NOAA 8210 where the flare X1/3B (S15W15) with a maximum in H_α at 1342 UT took place which was followed by the coronal mass ejection with a velocity $V \approx 2500$ km/s (McIntosh, 1998). This event was detected with the neutron monitor network. The propagation time (without a scattering) of SEP from the generation place on the Sun to the observation point is ~ 40 min. This event is characterized by a short increase time to the event maximum and a gradual decrease of the intensity for all energies. The differential energy spectrum is the hardest one from all observed events at the rise phase of the 23-rd solar activity cycle, $\gamma = 1.51$ (Fig. 2d).
The event on May 6, 1998 (Fig. 1e) is also associated with an active region NOAA 8210 where the flare X2/1N (S11W65) with a maximum H_α at 0809 UT accompanied by the IV type radiosplash has been taken place (McIntosh, 1998). This event was also detected with neutron monitors. Approximately 35 min after the flare the sharp increase of SEP intensity in the energy region from 7 to 300 MeV started. This event is characterized by the rapid increase of the charged particle intensity to the maximum during a bit of more than 1 hour for the above energies. The differential energy spectrum index at a maximum is $\gamma = 2.20$ (Fig. 2e).
The event on August 24, 1998 is associated with an active region NOAA 8307 where the flare X1/3B

(N30E07) with a maximum H_α at 2212 UT has taken place. This event has been also observed up to relativistic energies. The propagation time (without a scattering) of SEP from the generation place on the Sun to the observation point is more than 1 hour. The temporal intensity profiles (Fig. 1e) during the whole event have been repeatedly modulated. The modulation degree is inversely proportional to the magnetic rigidity of the charged particles. The differential energy spectrum at a maximum is $\gamma = 1.93$ (Fig. 2f).

3 Conclusion:

The above analysis showed that in the events on November 4 and 6, 1997 the SEP generation is in one active region NOAA 8100, in the events May 2 and 6, 1998 the generation of SEP also takes place in one active region NOAA 8210. The intervals between events on November 1997 and May 1998 were nearly equal to the propagation time of flare disturbances from the Sun to the Earth (2-4 days). In the November 4, 1997 event the SEPs propagated in the nondisturbed solar wind, in the November 6, 1997 event — in the presence of the shock wave propagating from the preceding flare. The anisotropy up to relativistic energies and the hard spectrum have been observed (Timofeev et al., 1998). The experimental results have been confirmed by measurements aboard the Ulysses and Wind spacecrafts (Lario et al., 1998; Mason et al., 1999; Möbius et al., 1999) (cf., Fig. 2a).

The rapid arrival of the first particles at the observation point is one of the characteristic peculiarities of the above considered SEP intensity increase events. It points out the rapid coronal transport of the charged particles from the generation place on the Sun to the injection of their into interplanetary medium.

There are extremely hard differential energy spectra in the events on November 4 and 6, 1997, May 2 and August 24, 1998.

It is necessary to note that the events on November 4 and 6, 1997, April 20, May 2 and 6, 1998 were associated with the flares in the southern hemisphere of the Sun and accompanied by large coronal mass ejections. And only the event on August 24, 1998 occurred in the northern hemisphere of the Sun.

4 Acknowledgments:

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References

Krimigis, S.M. 1965, J.Geophys.Res., 70, 2943
Lario, D., Marsden, R.G., Sanderson, T.R., et al. 1998, Geophys.Res.Lett., 25, 3469
Mason, G.M., Cohen, C.M.S., Cummings, A.C., et al. 1999, Geophys.Res.Lett., 26, 141
McIntosh, P.S. 1998, International SCOSTEP Newsletter, 1
Möbius, E., Popeski, M., Klecker, B., et al. 1999, Geophys.Res.Lett., 26, 145
Reinhard, R., & Wibberenz, G. 1974, Solar Physics, 36, 473
Solar-Geophys. Data 1998, NGDC, Boulder, Colo.
Timofeev, V.E., Sosin, I.I, Grigoriev, V.G., & Starodubtsev, S.A. St.Petersburg 1998, In: New Cycle of Activity: Observational and Theoretical Aspects. Proc. Conf. devoted to 50-Anniversary of Mountain Astronomical Station, 173, in Russian