PERIODS OF QUASI-STATIONARY CONDITIONS IN INTERPLANETARY SPACE ACCORDING TO SEQUENCES OF SEP EVENTS

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ABSTRACT

The values of the characteristic decay time of particle fluxes in SEP events vary, as a rule, considerably from event to event. We point out, however, that at times sequences of events having similar decay times were observed over long time intervals (up to one month, and even longer in a few cases). The values of the decay times, however, differed among different sequences. The constancy of the decay phase in each consecutive event of these series suggests that the interplanetary medium was in steady state during the event series, and, because of solar rotation, its uniformity within sectors extended to 90-180º in heliolongitude. The very rarely observed long series (up to 2-3 solar rotations) indicate the steadiness and homogeneity of the plasma and the interplanetary magnetic field (IMF) in the entire inner solar system in the course of this time span. It is pointed out that the neutral current sheet of the IMF does not represent a substantial obstacle for energetic charged particles. Both hemispheres are (above and below the current sheet), at least during the series of solar events, invariant with time, uniform and alike from the viewpoint of the propagation of charged particles. The investigation of such sequences of events can also be useful for forecasting characteristics of SEP events.

INTRODUCTION

One of the important characteristics of solar energetic particle (SEP) events is the decay rate of particle flux following the peak intensity. In the case of no additional particle injection during the decay phase of event the decay rate for particles of definite kind and energy is determined by the state of the solar wind plasma and of the interplanetary magnetic field, more specifically, by its inhomogeneity spectrum in the region of particle propagation. The decline of low-energy (1-10 MeV) proton fluxes can often be described by exponential law: $J = J_o \exp(-t/\tau)$, where τ is the characteristic decay time. This may be explained by convective effects and adiabatic deceleration of particles during their propagation in the interplanetary medium.

Our statistical investigation of proton declines indicated (Daibog et al., 2002 COSPAR) that the characteristic decay times in SEP events change in a wide range from about 1 to 100 hours with an average value of $\tau \approx 15$ hours. Simultaneously we discovered that sometimes very long exponential declines exist with nearly constant τ, their duration is at least 3 days and take place rather often; sometimes they last up to 5 days and longer. Longer declines are very seldom observed because at the end of events it is difficult to distinguish solar particles from the background and impossible to assess the state of the interplanetary medium state in the absence of a relevant indicator. However, sometimes it turns out that after a SEP event, the second, third, etc. events follow one by one and thus it is possible to examine the state of the IMF through the longer period of time.

It was pointed out that looking at successive events one can notice the existence of rather long time intervals (two weeks to one month, and even longer in a few cases) during which the characteristic decay phases of events in these periods are very similar. Periods with short decay times can be followed by those with long ones. Large and small events are observed with similar declines. In this paper we examine such sequences of SEP events with similar decay times.

EXPERIMENTAL DATA

The investigation of sequences of SEP events are based on the data from Prognoz 1, 2, IMP 5, 8, Helios 1, 2, VEGA, GRANAT and SOHO s/c within a long time interval from 1971 to 2001. Prognoz, IMP, and GRANAT are Earth orbiting satellites; SOHO is also located near the Earth at the L1 libration point at 0.01 AU upstream of the Earth. Helios was located between 0.3 and 1.0 AU, whereas VEGA was between 0.7 to 1.0 AU, correspondingly, that is why we indicate the radial distances and heliolongitudes of s/c for Helios and VEGA observations. We analyzed the exponential decays of integral fluxes of protons with energies >4 MeV, as well as differential 1-5, 4.6-15, 1-20 MeV fluxes. Both long lasting exponential decays and sequences of events with similar (within a range of 20%) values of τ were selected. Figure 1 shows a pattern of such a decline with $\tau \approx 18$ hours observed throughout about 6 days in July 1982. One of the outstanding events is that of September 23, 1978, studied earlier by Reames et al. (1996, 1997) and Daibog et al. (2000), when, according to Helios 1 and 2 data, an exponential decay with $\tau \approx 33$ hrs was observed for a period of about two weeks.

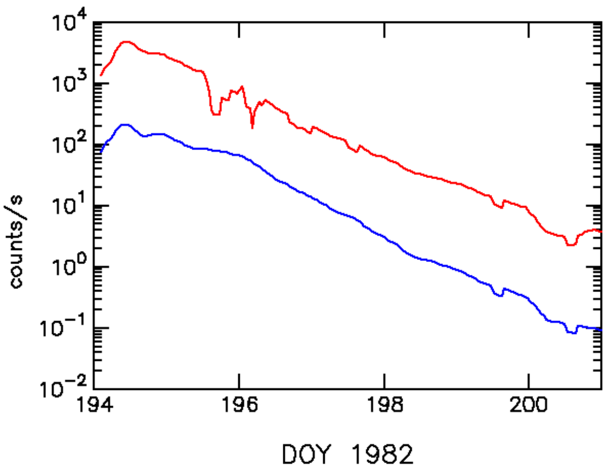

Fig. 1. Helios 1 Kiel experiment proton fluxes in July 1982 in energy channels 4-13 MeV (upper curve) and 13-27 MeV.

In Table 1 exhibited are characteristics of reliably identified sequences of several events, which lasted more than a week in the period of 1971-2001, that is, nearly covering three solar activity cycles. One can see from Table 1 that the values of τ ranged between 5 and 50 hrs, that is, spanned one order of magnitude. This may represent the scale of change of the IM parameters responsible for particle propagation (for example scattering mean free path in the case of diffusive propagation).

The panels of Figure 2 display patterns of sequences with total durations about 19 and 45 days, respectively. The figures suggest that during of a full solar rotation the conditions of interplanetary magnetic field (IMF) were stable everywhere in the inner heliosphere, at least in the vicinity of the solar equatorial plane, and that resulted in practically constant proton decay times in the sequence. It turns out that one month is not the longest duration of sequence. According to Prognoz-1 and 2 data (Vernov et al., 1973) from April to August 1972, that is, in the time interval of 3.5 months, 9 subsequent events were observed with practically coincident declines in the fluxes of 1-5 MeV protons (see Figure 3) with $<\tau> \approx 16.5$ hours. This time period and a similar situation were also registered by IMP 5 at 0.9-1.5 MeV

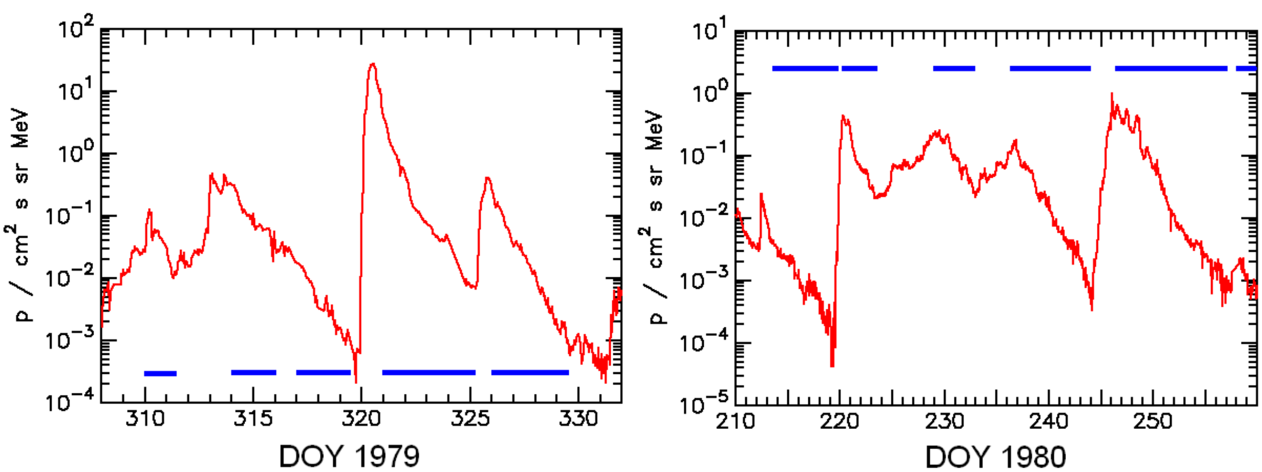

Fig. 2. IMP-8 CPME proton fluxes in November 1979 (left panel, in the 4.6-15 MeV energy channel) and in July-September 1980 (right panel). The decay periods are marked with heavy horizontal lines.

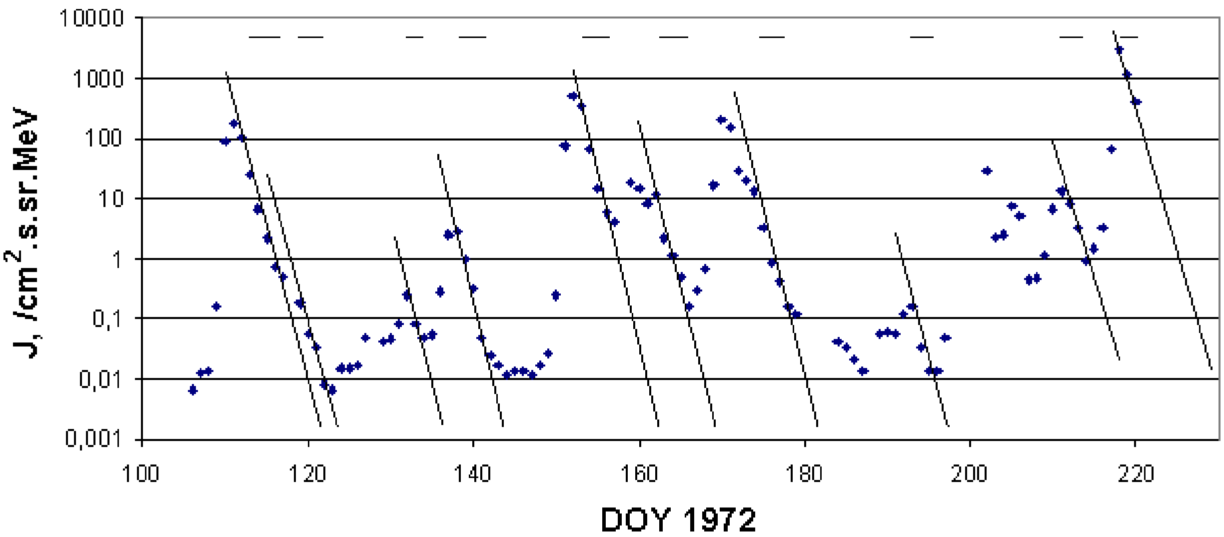

Fig. 3. Prognoz 1 fluxes in April-July 1972. Horizontal bars on top indicate the intervals where decays were fitted; oblique straight lines refer to best-fitting exponentials.

protons (Van Hollebeke et al., 1974). This means that prior to two extremely power flares of August 4 and 7, 1972, the Sun did not create any substantial disturbances and the interplanetary medium was quasi-stationary for more than three months returning to this state after all flares of different power that appeared during that period. This regularity was broken for a short time at the end of July preceding August flares. The existence of such series with coincident decay time suggests that during the time interval of the series the IM was in a steady state near the point of observation. However, as this point (the location of the s/c) travels 13.3º a day relative to the IMF due to solar rotation, the observed series extends to a considerable angle in longitude: about 90º for a week-long series and 180º for 2 weeks. Then, within this region the propagating conditions for energetic particles will be similar (for exponential decays, the values of τ vary very slightly), and consequently, the IMF assumes invariant characteristics, that is, uniform over heliolongitude and constant with time. Does this stability propagate in heliographic latitude, to the different sides of the neutral current sheet? To answer his question we studied the position of the spacecraft (i.e., the Earth) with respect to the neutral sheet during the series observed. It turned out that many series, especially long ones, begin at the one sign of the IMF (with Earth located above – or below – the neutral sheet), and end at an opposite magnetic field

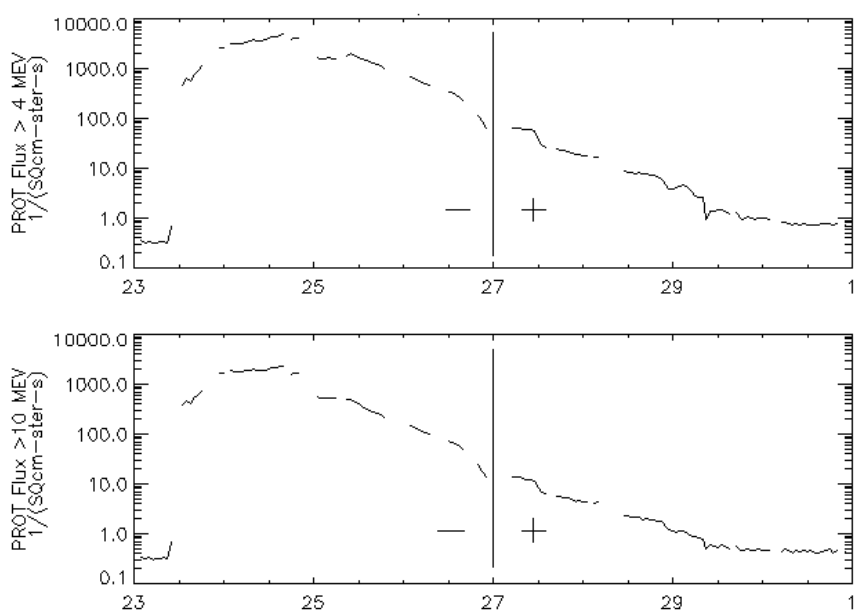

Fig. 4. Proton fluxes between 25 and 29 September 1978 with the current sheet between negative and positive sectors of the interplanetary magnetic field. The values of τ before and after of the intersection of the current sheet are nearly the same.

polarity (the Earth crossed the neutral sheet in between). During this time τ did not change. Figure 4 displays an example of such an event, where the crossing of the neutral sheet takes place in the middle of the decay phase, and the value of τ did not react to the sheet crossing, only the particle fluxes exhibited some fluctuations. This observation suggests that both hemispheres (above and below the sheet) were identical during the event series from the viewpoint of particle propagation. We note that Kahler et al. (1996) pointed out that the onset times, rise times, and peak fluxes are essentially the same for SEP events with flares in the same sector as for those in the opposite polarity sectors. Here we found that decay rate does not change either when the its magnetic polarity connection of the s/c changes.

DISCUSSION

The interpretation of this fact is rather obvious. In the "old diffusion language" we might point out that the scattering mean free path was constant throughout the whole period. In the recent language of exclusive shock acceleration one would formulate this as a similarity of particle holding between the strong magnetic field near the Sun and the shock front as well as of particle acceleration in interplanetary space. It must be noted that due to solar rotation during such considerable periods of time a spacecraft is connected by magnetic field lines to quite different regions on the Sun: both with flare sites and with quiet surface. However, the interplanetary medium remains magnetically homogeneous within a wide angular range that manifests itself in the constancy of τ. This result indicates the existence of long intervals comparable with the period of the solar rotation of quasi constancy of conditions that determine the particle lifetime in the inner heliosphere. If a long duration exponential decay is observed, that means that the IM state is stationary over a wide angular interval (one day of observation due to solar rotation equals to a 13.3° longitude interval). One-week duration of decline with constant τ corresponds to a stability of conditions in about a quarter of inner heliosphere.

In spite of conditional conception of superevents (see for example Müller-Mellin et al., 1986 and Dröge et al., 1992), the most important moment is the high stability of conditions in interplanetary medium in the inner and outer heliosphere for long periods of time. It was natural to suppose that individual SEPs happened during a superevent share common features and one candidate might be the decay time. However, other sequences observed in 1974-1986 do not belong to the periods of superevents, as well as in other 4 superevents the decay times of subsequent SEPs differed from event to event.

Thus, we see that the sequences of events with similar τ occur both during and between superevent periods. This means that situation of stable propagation or trapping conditions is not inherent exclusively to the periods of superevents. However, we consider this investigation important for space weather forecast. If a SEP event has occurred during a period of stable high particle background flux (about an order of magnitude higher than quiet value) for a few days, then for the following particle enhancement one may expect the decay time similar to that in a previous event and thus, according to the peak intensity time, the total event duration. This also permits to estimate the total radiation dose through the event.

CONCLUSIONS

1. The existence of consecutive SEP events (series of events) is exhibiting similar characteristics in the decay phase is established. The series consists of 2-3 or more separate events with total time spans of 1-2 weeks and more.
2. The constancy of the decay time of in each consecutive event indicates the stability of the interplanetary medium over the time interval of the series, and, because of solar rotation, its uniformity within sectors extending to 90-180º in heliolongitude.
3. Very rarely, particularly long series appear (as long as one or even 2-3 solar rotations – as observed by IMP 5 and Prognoz 1), suggesting the stability and uniformity of the medium in the inner solar system (within 1 AU, near the plane of Ecliptic) during these time intervals.
4. It is pointed out that the neutral current sheet of the IMF does not represent a substantial obstacle for energetic charged particles. Both hemispheres are (above and below the current sheet), at least during the series of solar events, invariant with time, uniform and alike from the viewpoint of the propagation of charged particles.

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REFERENCES

Daibog, E.I., V.G. Stolpovskii, S.I. Svertilov et al., Invariant spectral characteristics of the decay phases of energetic electron intensity in solar energetic particle events, *Adv. Space Res*. **26** (5) 871-874, 2000.

Daibog, E.I., Yu.I. Logachev, S. Kahler, K. Kecskeméty, Statistical properties of SEP event flux declines, *Adv. Space Res*., **32,** this issue, 2003.

Dröge, W., R. Müller-Mellin, E.W. Cliver, Superevents **-** Their origin and propagation through the heliosphere from 0.3 to 35 AU, *Astrophys. J*., **387**, L97-L100, 1992.

Kahler, S.W., J.M. Kunches, D.F. Smith, Role of current sheets in the modulation of solar energetic particle events, *J. Geophys. Res.,* **101**, 24383-24382, 1996.

Müller-Mellin, R., K. Röhrs, G. Wibberenz, Super-events in the inner solar system and their relation to the solar cycle, in: The Sun and the Heliosphere in Three Dimensions (ed. R.G. Marsden), Hingham, M.A.Reidel, pp349-354, 1986.

Reames, D.V., L.M. Barbier, and C.K. Ng, The spatial distribution of particles accelerated by coronal mass ejection-driven shocks, *Astrophys. J.,* **446**, 473-486, 1996.

Reames, D.V., S.W. Kahler and C.K. Ng, , Spatial and temporal invariance in the spectra of energetic particles in gradual solar events, *Astrophys. J*., **491,** 414-420, 1997.

Van Hollebeke, M.A., J.R.Wang, F.B. McDonald, A catalogue of solar cosmic ray events, X-661-74-27, NASA GSFC, 1974.

Vernov, S.N., N.L. Grigorov N.L., *Izv. AN SSSR, ser. phys.* **37**, 1138, 1973 (in Russian).

Table 1

Onset date of yy.mm.dd	s/c, E_p (MeV)	N	ΔT, days	τ, hours	distance from Sun heliolongitude
1971.04.02	IMP-5; 0.9–1.5	9	108	11.2 ÷ 24.0	
1972.04.20	P-1,-2; 1.0- 5.0	9	101	14.6 ÷ 24.2	
1974.12.22	H-1; 4 – 13	3	16	11.0 ÷ 14.0	R=0.95; $\varphi=-7^o$
1976.03.16	IMP-8; 4-12.5	3	15	40.0 ÷ 42.0	
1978.04.01	H-1; 4 – 13	5	23	7.0 ÷ 10.0	R=0.6; $\varphi=-60^o$
1978.06.11	IMP-8; 4-12.5	2	10	22.0 ÷ 23.0	
1978.07.14	IMP-8; 4-12.5	2	14	23.0 ÷ 24.0	
1979.02.27	H-1; 4 – 13	2	6	13.7 ÷ 14.5	R=1.0; $\varphi=-60^o$
1979.02.18	H-2; 4 – 13	4	25	12.5 ÷ 19.0	R=1.0; $\varphi=-15^o$
1979.06.04	IMP-8; 4-12.5	6	61	15.0 ÷ 18.0	
1979.07.07	IMP-8; >4	3	46	17.5 ÷ 22.0	
1979.08.05	H-1,-2; 4 – 13	2	18	16.5 ÷ 19.0	R=0.9; $\varphi=120^o$ H1 R=0.9; $\varphi=170^o$ H2
1979.11.06	IMP-8; 4.6-15	5	19	12.0 ÷ 17.0	
1980.05.27	H-1; 4 – 13	7	14	4.0 ÷ 8.5	R=0.4; $\varphi=-30^o$
1980.07.19	IMP-8; 4-12.5	2	12	22.0 ÷ 22.5	
1980.08.02	IMP-8; 4.5-15	6	45	33.5 ÷ 38.0	
1980.12.01	IMP-8; 2-4.6	5	26	17.0 ÷ 18.0	
1981.05.12	H-1; 4 – 13	3	8	11.5 ÷ 13.0	R=0.7; $\varphi=-100^o$
1981.07.02	IMP-8; 4.5-15.0	3	33	31.0 ÷ 37.5	
1981.08.28	IMP-8; 4.5-15.0	3	32	48.0 ÷ 53.0	
1981.11.16	IMP-8; 4.5-15.0	2	11	7.3 ÷ 7.6	
1981.11.24	H-1; 4 – 13	3	24	13.5 ÷ 16.0	R=0.7; $\varphi=80^o$

1981.12.09	IMP-8; 4.5-15.0	2	4	9.0 ÷ 12.0	
1982.01.03	IMP-8; 4.5-15.0	2	14	18.0 ÷ 19.3	
1982.06.03	H-1; 4 – 13	3	9	7.0 ÷ 10.8 ±1	R=0.6; $\varphi=-120^o$
1982.07.10	H-1; 4 – 13	3	20	15.0 ÷ 19.0	R=0.5; $\varphi=-105^o$
1983.05.12	IMP-8, > 4	4	5	9.0 ÷ 13.0	
1984.02.16	IMP-8, > 4	2	8	17.7 ÷ 17.7	
1986.01.19	Vega-1; 4.5-13	3	25	13.2 ÷ 15.6	
1990.03.31	GRANAT; 1-20*	5	60	20.0 ÷ 24.5	
1990.08.06	GRANAT; 1-20*	2	15	20.0 ÷ 23.0	
1991.03.25	GRANAT; 1-20*	2	15	36.5 ÷ 38.0	
1991.05.13	GRANAT; 1-20*	6	37	10.0 ÷ 12.0	
1992.11.24	GRANAT; 1-20*	3	15	11.8 ÷ 12.5	
1997.10.07	SOHO; 0.7-6	4	27	10.5 ÷ 15	
1997.11.05	IMP-8; 4.6-15.0	2	4	15.0 ÷ 18.0	
1998.01.19	SOHO; 0.7-6	3	18	12.5 ÷ 14.5	
1998.10.21	SOHO; 0.7-6	4	32	11 ÷ 15.5	
1999.05.27	SOHO; 0.7-6	2	12	18 ÷ 20	
2001.04.12	IMP-8; 4.6-15.0	3	7	11.7 ÷ 14.5	

N – a number of solar events in a sequence
ΔT - sequence duration from the first event onset to the end of the last one
*) – data s/c GRANAT see in (http://nssdcftp.gsfc.nasa.gov/ spacecraft_data/russian_msu/granat/)

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