THE SOURCE OF SOLAR AND INTERPLANETARY PARTICLE EVENTS

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ABSTRACT

We propose a theoretical analysis to investigate the origin of delayed events as a plausible alternative to the usual methods of time profile analysis. The source location and energy change processes during particle acceleration are inferred from the intercomparison of observational with theoretical spectra, the latter deduced under the assumption of a quasi-steady state generation process. It is found that whatever the kind of delayed event, the origin may be associated either to solar acceleration or interplanetary acceleration or even to the superposition of both effects; however particles in corrotating events seem to be always preliminarily accelerated in the solar atmosphere.

INTRODUCTION

Concerning the problem of particle generation in delayed events (where for delayed events we are including all those which do not behave as a prompt event: Energetic Storm Particles, Lower Energetic Storm Particles, recurrent events and corrotating or long lived streams) there is at present a great controversy about the origin of these particles: the source, the acceleration and transport processes, energy changes, etc. (e.g. (Ref. 1) and (Ref. 2)). Models supporting solar production propose an acceleration process relatively slow, with respect to that of prompt events, and particle storage with gradual leakage from the solar atmosphere. On the other hand since most of these different events are usually accompanied by interplanetary disturbances, a great variety of proposals for interplanetary production have been developed. However which seems the most common feature of both kinds of models is that all of them are built from the study of solar particle propagation through the analysis of the time profile of the event. Therefore, instead of studying the event time profile we have analysed the energy spectrum of particles, that although it is modulated during propagation and the data only cover in general a short time interval, however assuming that the theoretical curve which approaches nearest the experimental one gives the best representation of the phenomena associated to the particle production, some inferences can be drawn about the different aspects of the generation process (Ref. 3). The main questions which are directly related with the problem of delayed events origin are for instance: is there a continual acceleration at the sun, particle diffusion in solar longitude or particle storage? are the acceleration and propagation processes velocity dependent or not? is there a sweeping or an acceleration which is associated with interplanetary disturbances? does interplanetary acceleration occur behind or ahead of a shock? can the acceleration mechanism be represented by a 1st order Fermi type or by a 2nd order Fermi type? and do convection and adiabatic cooling play an important role on solar particles? Obviously we do not claim to investigate all these several features through this work, neither to delineate a model in this preliminary analysis, but simply to discriminate the less realistic proposals in order to search for the adequated direction to build more promising models.

THE ACCELERATION SPECTRUM

Although an impulsive acceleration process in delayed events cannot be disregarded (e.g. in association with solar or interplanetary neutral current sheets), however taking into account that the total duration of the generation process seems to be longer than in the case of prompt events, we have assumed that the process is a relatively slow one. Therefore a quasi-steady state situation may be considered from the fact that the acceleration stage is too long with respect to the mean escape time of particles and that the time scale for plasma expansion through the interplanetary space is longer than the characteristic diffusion time of particles of kinetic energy higher than 0.3 MeV (Ref. 3). Among the several processes that can affect the particle flux during acceleration we have only considered energy losses by ionization and adiabatic cooling, and particle loss from the acceleration volume either with a constant rate or with a velocity dependent escape time. These later assumptionslead respectively to a velocity independent and to a velocity dependent acceleration rates. We have assumed that particles which have suffered ionization losses have been generated at the sun level, with eventually a plausible contribution of local adiabatic cooling, whereas particles accelerated in the interplanetary medium may eventually lose energy only by adiabatic cooling. Since the acceleration process is assumed to be a slow one, then a 2nd order Fermi-Type mechanism is considered as the fundamental process; however in establishing the energy change rates in the interplanetary space we have included adiabatic heating as a measure of reliance that approaching magnetic structures have been present, and thus, as an indicator that particles have increased their energy by a systematic acceleration of the 1st order Fermi-Type. By following the formalism of the Fermi-age theory (Ref. 4) we have derived the acceleration time of particles as a function of energy and the differential and integral spectra of the accelerated particles under different assumptions of the energy change rate. The intercomparison with experimental spectra has been carried out for 28 delayed events, including seven ESP, five LESP, eight recurrent events and eight long lived streams and the results have been displayed through Tables 1-3 and Fig. 1 to Fig. 3.

RESULTS AND DISCUSSION

According to the results summarized in Tables 1-3, it cannot be attributed to any of the four different kinds of events analysed in this work an unique origin, since most of them may be of solar or interplanetary origin, or even of mixed origin. However corrotating events seem to originate always at the sun level, although particles may be reaccelerated in the interplanetary medium. Events of pure interplanetary origin seem to be the less common, whereas pure solar origin events are the most common, however taking into account the occurrence of mixed origin events, it can be seen that interplanetary acceleration is a phenomenon as frequent as solar acceleration. Fig. 1 shows a typical example of an event of solar origin, where it can be seen that the best representation of the experimental points is given by both, the curve with a velocity independent acceleration rate and ionization in a region of $n = 10^{12}\,cm^{-3}$ and the curve corresponding to a velocity independent acceleration rate with adiabatic cooling. Fig. 2 and Fig. 3 represent an event of mixed origin and an event of pure interplanetary origin respectively. In those events of pure solar origin where we have found that the acceleration process distributes particles in a velocity dependent way and observations show no velocity dispersion, it can be assumed that after acceleration particles have propagated through the corona by a velocity independent diffusion process (e.g. (Ref. 5)). This may be the case of most recurrent and corrotating events. The presence of a magnetic disturbance in the interplanetary space in coincidence with a delayed event of pure solar origin may be taken as indication of a plausible sweeping of particles without interplanetary acceleration. Adiabatic cooling seems to occur most of times when acceleration or reacceleration occurs in the interplanetary medium. In mixed origin events, the reacceleration step is sometimes performed with the same efficiency that solar acceleration, whereas in other events, there is a sharp decrease in efficiency; this may perhaps indicatesthat sometimes the source moves with the coronal plasma while others, the sources are different and the spectrum is practically determined at the sun by a more efficient process. From Table 3, it can be noted that particles distributed by the solar acceleration step in a velocity dependent manner, leave most of times the interplanetary acceleration stage with no-velocity dispersion; this most be explained from inherent features of the interplanetary acceleration process or as it was previously mentioned by a peculiar coronal propagation. It can be inferred that in those events where 1st Fermi acceleration seems to be predominant, the acceleration has taken place ahead of a shock, whereas in these events where 2nd order acceleration has beeen predominant, it has probably taken place behind the shock. Concluding, we propose that together with time profile analysis, a deep study of the energy spectra of particles must be performed in order to interpret more accurately the origin of suprathermal particles.

EVENTS OF SOLAR ORIGIN

Event	Reference	Acceleration Rate $a(s^{-1})$	Maximum Acceleration Time t(s)	Acceleration Medium $n(cm^{-3})$	Acceleration Behavior on (β= V/C)
30-IX-1961 (ESP)	Bryant et al. 1962	0.067	25.4	10^{12}	depend.
8-VII-1966 (ESP) (Core)	Lin et al. 1968	0.0047	2.3	10^{9}	independ.
8-VII-1966 (ESP) (Halo)	Van Allen & Ness, 1967	0.051	35.2	10^{12}	depend.
5-VI-1967 (LESP)	Singer & Montgomery, 1971	0.022-0.032	<83.1	10^{11}-10^{12}	depend.
14-V-1969 (LESP)	Lanzerotti, 1974	0.069	32.4	10^{13}	depend.
27-V-1963 (RE)	Bryant et al. 1965a	0.041	43.4	10^{14}	depend.
2-10-XII-1963 (RE)	Fan et al. 1965	0.036-0.057	<50.2	10^{12}-10^{13}	depend.
18-X-1964 (RE)	"	0.02	81.5	10^{11}	depend.
22-23-VIII-1966 (LLS)	Fan et al. 1968	0.023-0.044	<67.5	10^{10}-10^{13}	depend.
27-VIII-1966 (LLS)	"	0.05	34.3	10^{12}	depend.
13-17-VI-1967 (LLS)	Kinsey, 1970	0.079-0.13	<25.8	10^{12}-10^{13}	depend.
16-XI-1967 (LLS)	Allum et al. 1971	0.025-0.03	<62	10^{10}-10^{11}	depend.
17-IX-1971 (LLS)	McGuire et al. 1975	0.0093-0.013	<156.2	10^{7} -10^{10}	depend.

(RE)= Recurrent Events; (LLS)= Long Lived Streams or Corotating Events; (ESP)= Energetic Storm Particles;
(LESP)= Lower Energetic Storm Particles.

Table 1. Events with solar acceleration

EVENTS OF INTERPLANETARY ORIGIN

Event	Reference	Acceleration Rate $a(s^{-1})$	Maximum Acceleration Time t(s)	Acceleration Behavior on (β= V/C)	Net Energy Change Rate
2-X-1961 (ESP)	Bryant et al. 1962	0.028	0.0091	depend.	1st order acceleration and adiabatic cooling.
3-X-1961 (ESP)		0.022	0.015	depend.	2nd order acceleration, adiabatic cooling and probably 1st order acceleration.
11-I-1968 (LESP)	Singer & Montgomery, 1971 Lanzerotti, 1974	0.0073	8.7	indep.	idem
20-II-1968 (LESP)	Singer & Montgomery, 1971	0.018	7.1	depend.	1st order acceleration, adiabatic cooling and probably 2nd order acceleration.
11-II-1963 (RE)	Bryant et al. 1965a	0.0025	5.0	indep.	1st order acceleration and adiabatic cooling.
2-V-1963 (RE)	"	0.0042	3.2	indep.	Adiabatic cooling, 1st and 2nd order acceleration.

(RE)= Recurrent events; (ESP)= Energetic Storm Particles; (LESP)= Lower Energetic Storm Particles.

Table 2. Events with 1st and 2nd order acceleration in the interplanetary space.

EVENTS OF SOLAR AND INTERPLANETARY ORIGIN

Event	Reference	Solar Acceleration Rate $a(s^{-1})$	Solar Acceleration Time t(s)	Acceleration Medium $n(cm^{-3})$	Solar Acceleration Behavior on (β= V/C)	Interplanet. Acceleration Rate $a(s^{-1})$	Interplanet. Acceleration Time $t(s^{-1})$	Interplanet. Acceleration Behavior on (β= V/C)	Net Interplanetary Energy Change Rate
30-V-1967 (ESP)	Singer & Montgomery, 1971 Lanzerotti, 1969	0.0026	3.2	10^{10}	indep.	0.0026	3.2	indep.	2nd order acceleration and adiabatic cooling.
30-V-1967 (LESP)	Rao et al. 1909 Palmeira et al. 1971	0.026-0.031	<67.4	10^{9}	depend.	0.026-0.031	<0.0072	depend.	2nd order acceleration and adiabatic cooling.
29-XI-1968 (ESP)	Lanzerotti, 1974	0.039	40.5	10^{9}	depend.	0.039	0.0042	depend.	idem
10-III-1963 (RE)	Bryant et al. 1965a	0.044	40.3	10^{12}	depend.	0.003	4.6	indep.	idem
5-IV-1963 (RE)	"	0.042	48.1	10^{13}	depend.	0.0017	7.5	indep.	idem
25-VI-1963 (RE)	"	0.46	30.6	10^{12}	depend.	0.0034	4.3	indep.	1st order acceleration
26-VI-1967 (LLS)	Lanzerotti, 1969	0.041	43.7	10^{12}	depend.	0.0015	10.6	indep.	2nd order acceleration and adiabatic cooling.
14-21-VI-1967 (LLS)	Krimigis, 1969	0.0011	1.92	10^{10}	indep.	0.001	2.12	indep.	1st order acceleration.
21-25-VI-1967 (LLS)	Kinsey, 1970	0.029-0.069	<58.9	10^{10}-10^{13}	depend.	0.029	0.0084	depend.	2nd order acceleration and adiabatic cooling.

(RE)= Recurrent Events; (LLS)= Long Lived Streams or Corotating Events; (ESP)= Energetic Storm Particles;
(LESP)= Lower Energetic Storm Particles.

Table 3. Events with acceleration at the solar and interplanetary levels.

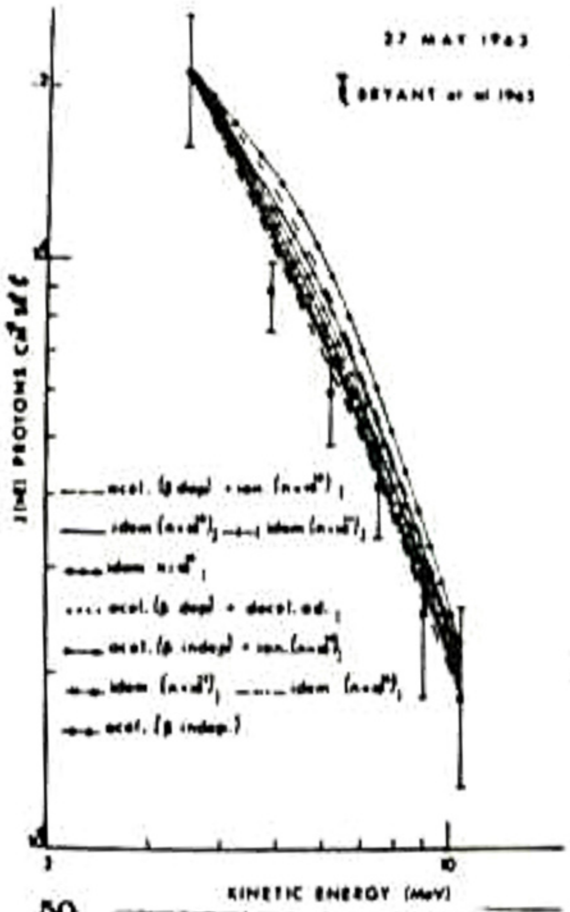

Fig.1 Event of solar origin. Exp. data (Ref. 6)

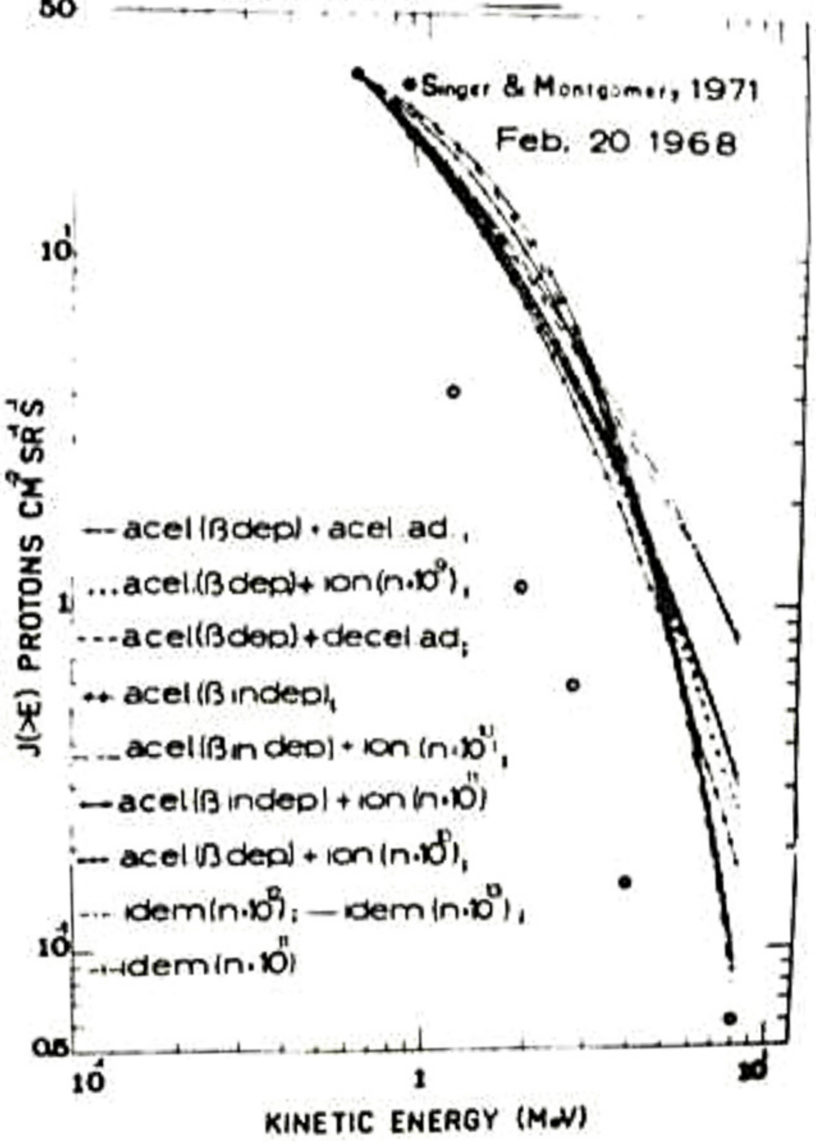

Fig.3 Event of mixed origin. Exp. data (Ref. 7)

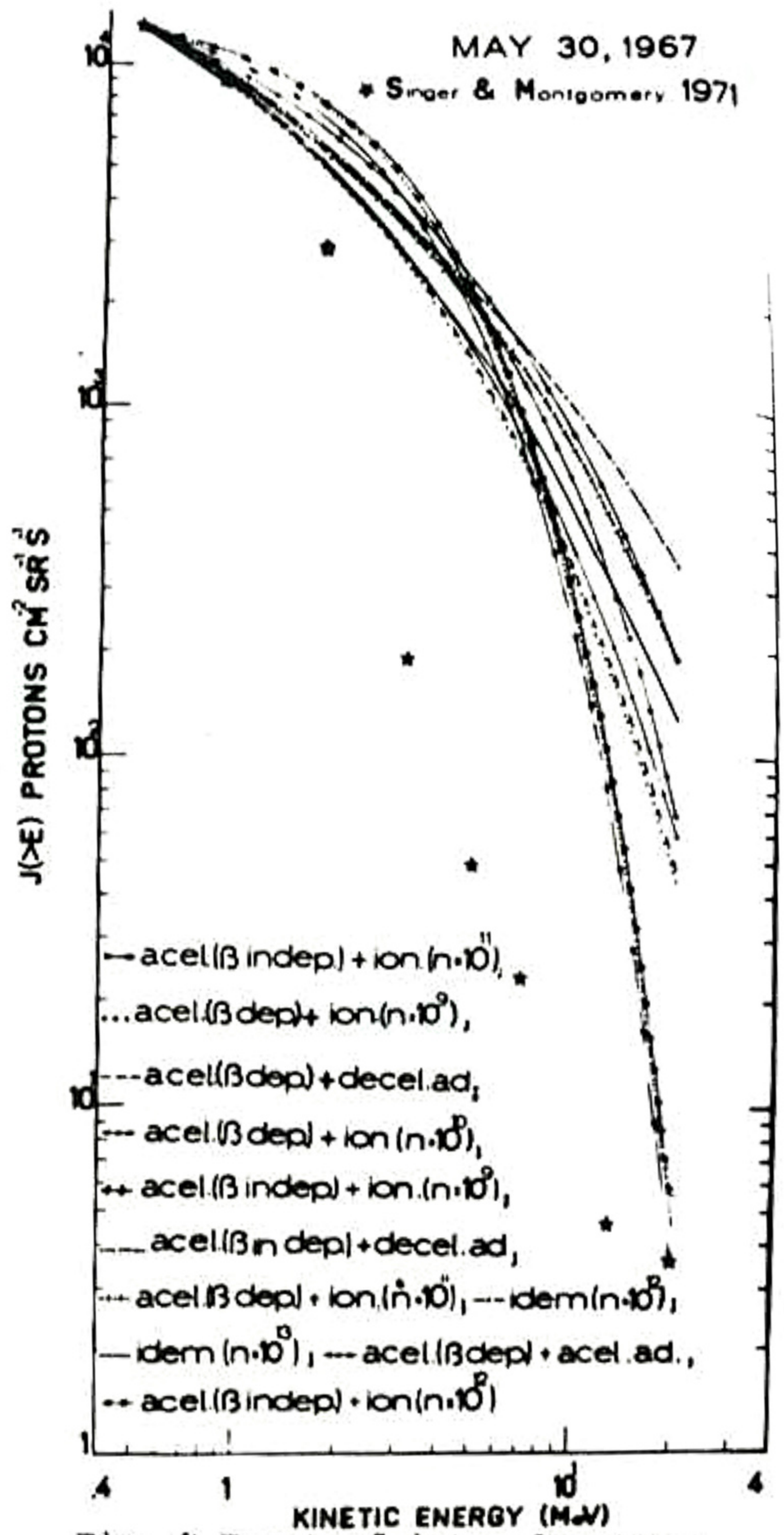

Fig. 2 Event of interplanetary origin. Experimental data (Ref.7)

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