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# DETERMINATION OF ENERGY SPECTRA OF SOLAR ELECTRONS UNDER DIFFERENT SCENARIOS IN SOLAR FLARE SOURCES

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RESUMEN. Se investiga el espectro de energía de los electrones emitidos en las fulguraciones solares, dentro del marco de tres escenarios diferentes: se utilizan las soluciones de la ec. de Fokker-Planck en la aproximación de un tiempo de vuelo corto de las partículas en la fuente y baja densidad de materia (Geometría-delgada). Los resultados obtenidos se cotejan con espectros observacionales medidos al nivel de la tierra. Esta comparación nos permite inferir acerca del escenario apropiado en cada evento individual de partículas solares y las condiciones físicas que prevalecen en la fuente.

ABSTRACT. The energy spectrum of the solar flare electrons is investigated within the frame of three different scenarios. Solutions of the Fokker Planck equation are employed under the assumption of a short fly time of particles within the source and low density therein (thin-geometry). The obtained results are compared with observational spectra measured at the earth level. This intercomparison allows us to infer about the appropriate scenario in each particular solar event.

*Key words:* COSMIC RAYS — PARTICLE ACCELERATION

## INTRODUCTION

In a previous work (Pérez-Peraza and Gallegos, 1986) we discussed the importance of the energy distribution of energetic particles in Cosmic Ray Sources to draw information about the particle generation process and the astrophysical source itself. Unfortunately, particle fluxes arriving at the observational sites, in the close environment of the earth orbit, or at ground based stations, have been strongly modulated. This modulation takes place in the dense environment of their own sources, through interstellar and interplanetary propagation and in the magnetosphere and atmosphere of our planet. Modulation may involve a variety of electromagnetic (plama and MHD) processes, atomic and nuclear processes. Since particle detection at the source level is not yet possible (with the exception of energetic particles generated in some planetary magnetospheres and in the interplanetary medium), the task of determining source energy spectra becomes a very complex problem. It was discussed in the previously mentioned work, that in order to determine particle spectra at the level of their sources the most general methodology is by demodulation of observational particles fluxes back to the source, or by deconvolution of observational non thermal electromagnetic emissions produced by the interaction of the accelerated particles with the local matter and electromagnetic fields. These methods are strongly model dependent, though the deconvolution of photon fluxes has the advantage that their modulation is lower than for particle fluxes, nevertheless, it is difficult to elucidate whether the concerned electromagnetic radiation has been generated in the source itself during particle acceleration or after in the source environment. In addition the obtained spectra by these methods does not furnish a great deal of information about the source phenomena, for what it is convenient to complete the information by modeling the source phenomenology; to do so, the more general method is by solving the continuity equation in the energy space of the Fokker-Planck type, or, in specific scenarios to use the well known Fermi approximation of the "age-energy"

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analogy.

In the particular case of solar flare particles the problem is less complex, since the time and place of particle generation can be determined with relatively good precision, as well as the time and place of non-thermal electromagnetic emissions, which is not necessarily the same as of particle generation, buy may be generated afterwards during particle transport in the solar atmosphere.

In addition it is now very well known that solar particles, arriving to the earth environment have been generated either in the vicinity of the sun-earth connecting magnetic flux tube at helio longitud of 60°W, or, has been azimuthally transported from any other helio-longitud to that connecting site, while escaping into the interplanetary magnetic field. Therefore demodulation of solar flare particle data is in two steps: interplanetary demodulation (Miroshnichentco & Petrov, 1985) and coronal demodulation (Pérez-Peraza, 1986). Under these circumstances, coronal modulation of solar particles is minimized if the source is relatively close to the connecting sun-earth heliolongitude. In other words if the fast propagation region around the flare site occurs, between 30° and 90°w, therefore the spectrum may be roughly considered as representative of the source spectrum, if the data is taken at the peak flux intensity, to minimize also interplanetary modulation.

Now in order to drawn inferences about the source phenomena what we do is the following: using the theoretical expressions for source spectra derived in a preceding paper (Pérez-Peraza and Gallegos, 1986) we compare them with the observational spectra of electrons at the level of the earth orbit, for those particular conditions where coronal and interplanetary modulation are minimum. In this way by means of a "dilution" of the theoretical flux intensity at the level of the earth, the confrontation of hypothetical and observational fluxes gives us the clues of the physical conditions and particle processes that have taken place during the generation of particles.

I. Dilution of theoretical source energy spectra at the earth level.

The employed source spectra have been derived in Pérez-Peraza and Gallegos (1986), in which general differential form may be expressed as $f(E)N_o$ (particles/eV), where $N_o$ is the absolute number of the accelerated particles and $f(E)$ is the energy distribution function of particles. To transform these units to units of flux we multiply by $(v/V_s)$, where v is the particle velocity and $V_s$ the source volume: $f(E)\ No\ v/V_s$ (particles/eV $cm^2$s). This is the flux at the source level that escapes per 1 $cm^2$ of source surface. Now assuming that the emission is isotropic the total number of particles that crosses the entire source surface is $f(E)\ N_o v 2\pi\ r_s^2/V_s$ (particles eV s) where $r_s$ is the source radius. In order to know the flux at the earth level, that is the number of particles that crosses 1 $cm^2$ of the surface distended at the earth orbit is

$$N(E) = \frac{f(E) N_o v 2\pi r_s^2}{V_s 4\pi r_d^2}\ (\text{part./eVcm}^2\text{sr s}) \qquad (1)$$

where $r_d = 1.5\times10^{13}$ cm

So eq. (1) may be rewritten as

$$N(E) = 6.7\times10^{-17} N_o\, \beta\, r_s^2 f(E)/V_s (\text{part./eVcm}^2\text{sr s}) \qquad (2)$$

As illustration of the transformation of source spectra after dilution, let exemplify with the expressions of the age-energy formalism in Pérez-Peraza and Gallegos (1986), derived within the frame of the 1st scenario, where only local thermal particles are accelerated: for Fermi acceleration we have

$$N(E) = \frac{6.7\times10^{-17} N_o\ \beta r_s^2}{\alpha_f \tau V_s}\ \frac{\{E+(E^2 m^2 c^4)^{05}\}^{-1/\alpha_f\tau}\ \{E_{th}+(E_{th}^2-m^2c^4)^{05}\}^{1/\alpha_f\tau}}{(E^2-m^2c^4)^{05}}\ (\text{part./eVcm}^2\text{sr s}) \qquad (3)$$

where $\beta$ is the electron velocity, in terms of the light velocity, $\alpha_f$ is the acceleration efficiency of the Fermi Process, $\tau$ is the mean confinement time of particles within the source volume and $N_o \sim nV_s\,\zeta$, where $\zeta$ was defined in eq. (12) of the previously mentioned work, n is the particle density and $E_{th}$ = 1.5 kT is the local thermal energy of electrons.

For Betatron acceleration we have

$$N(E) = \frac{6.67\times10^{-17} N_o' \,\beta r_s^2}{\alpha_\beta \tau \, V_s} \frac{(E^2 - m^2c^4)^{-1-(1/2\alpha_\beta\tau)}}{(E_{th}^2 - m^2c^4)^{-1/2\alpha_\beta\tau}} \text{(part./eVcm}^2\text{sr s)} \quad (4)$$

where $\alpha_\beta$ is the efficiency of the Betatron acceleration process and $N_o' = nV_s$ Similarly for Neutral Current sheet acceleration we have

$$N(E) = \frac{6.67\times10^{-17} N_o' \,\beta \, r_s^2}{k_1 \tau \, V_s} \frac{\exp\{-(E^2 - m^2c^4)^{0.5} / \tau k_1\} \exp(E_{th}^2 - m^2c^4)^{0.5} / \tau k_1}{(E^2 - m^2c^4)^{0.5}} \text{(part./eVcm}^2\text{sr s)} \quad (5)$$

where $k_1 = 2.89\times10^{10}\varepsilon$ and $\varepsilon$ = accelerating electric field in the magnetic neutral current sheet. Following the same procedure we have determined the theoretical differential fluxes at the earth level within the frame of the two other scenarios and the Fokker-Planck equation formalism, as described in the previously mentioned paper.

## II. Criteria for comparison of theoretical and observational spectra.

We have selected from the literature three solar electron events, where according to the authors (Lin, 1982; Everson, 1984), coronal azimuthal modulation is not important. since flares have taken place in the range 30-90°W, and flux data corresponds to the peak in intensity, so that interplanetary modulation is also minimized.

To compare the theoretical fluxes with the observational fluxes we have proceeded in the following form: first we give values to the acceleration parameters (the products $\alpha\tau$ or $k_1\tau$), and to the source temperature appearing in the $E_{th}$ value of the derived spectra. In this way we try to fit the shape of the observational spectra. Once the spectral shape is fitted, in order to bring the theoretical fluxes to the scale of the observational fluxes, we use as free parameter the product $nr_s^2$ . In this form we normalize to the data value of minimum energy. We assume that the theoretical spectrum that fits better the observational fluxes reproduce better the kind of phenomenology that has taken place at the source since, as we said before, the kind of chosen data assures the lower degree of modulation of particle fluxes.

For the evaluation of the injection functions q(E) or q(E,t) within the frame of the 2nd and 3rd scenarios discussed in Pérez-Peraza and Gallegos 1986, (that is, when we deal with a secondary acceleration phase and only particles with energy above a certain threshold value $E_i >> 1.5kT$ are able to participate) we fix the value $E_i = 10$ KeV.

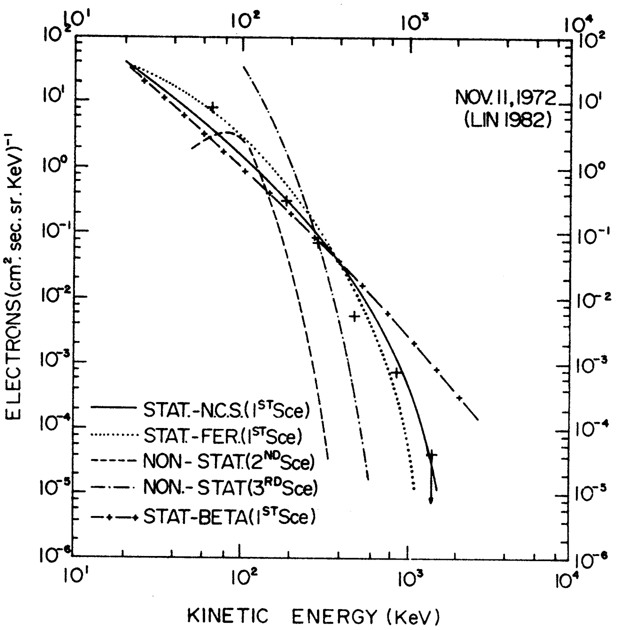
The results of the comparison of theoretical and observational spectra are shown through Figs. 1 to 3.

## III. Results

The analysis of Figs. 1 to 3 indicates that in each of the three considered events the two best fits are within the frame of the 1st scenario (one only acceleration phase, from thermal energies), with the exception of the June 21, 1980 event where the 2nd best option corresponds to the 2nd scenario (acceleration of pre-accelerated particles).

With regard to the acceleration process, the November 11, 1972 event is best described with impulsive acceleration in a magnetic neutral current sheet (N.C.S.), whereas the other two events are best described by stochastic acceleration with a Fermi-type mechanism. To evaluate the acceleration parameters we fix in a somewhat arbitrary form the value of $\tau \sim 0.85-1.5$ s, according to some inferences drawn from the literature. In this way it turns out that the electric field for neutral current sheet acceleration are $\varepsilon \sim (2.65-3)\times10^{-6}$ volt/cm, and that the Fermi acceleration efficiency $\alpha_f \sim 0.2$ $s^{-1}$.

The thermal temperature in the source of solar electrons in these particular turns out to be between $10^6$ and $5\times10^6$ °K; this implies that the probable density in the electron acceleration region of the flare volume is around $10^9-10^{10}$ $cm^{-3}$. Fixing $n \sim 10^{10} cm^{3}$, the most probable value for the source radius turns out to be $r_s \sim 10^{10}$cm, when a Fermi process is considered. When acceleration in a neutral current sheet is considered the obtained value of $r_s \sim 10^5$cm for $n \sim 10^9 cm^{-3}$. On the



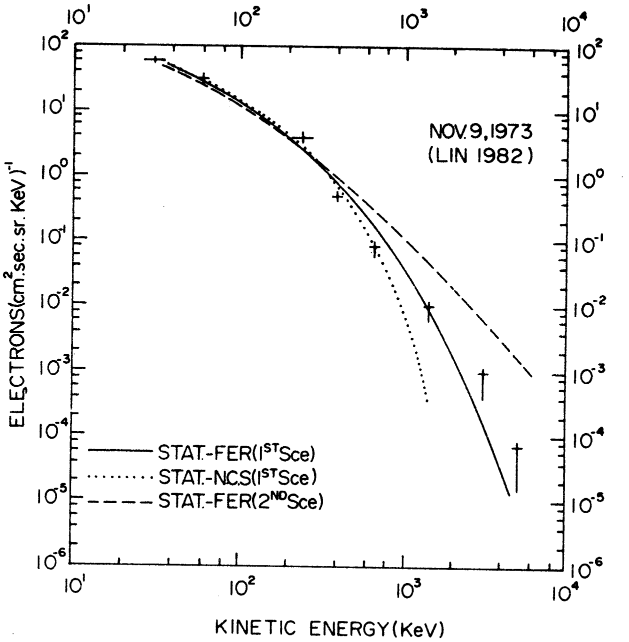




Fig. 1. Comparison of theoretical and observational spectra.

Fig. 2. Same as Figure 1.

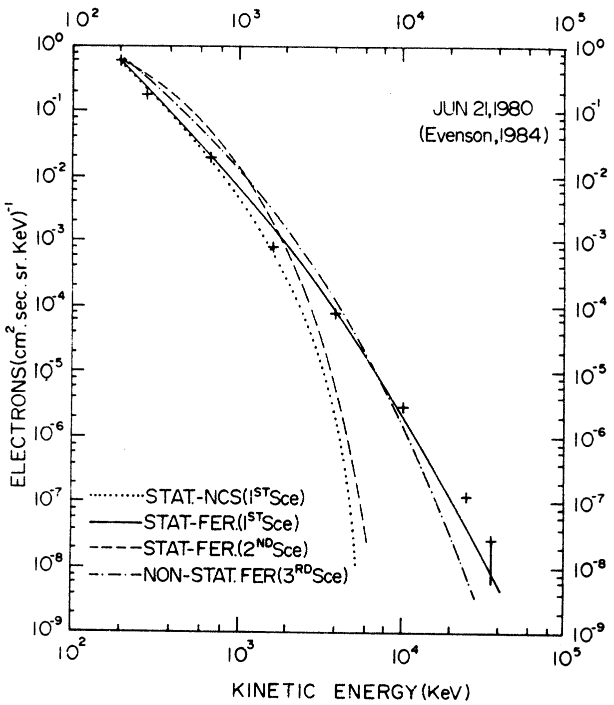



Fig. 3. Same as Figure 1.

other hand, under the assumption of two acceleration phases (2nd scenario) as could be the case of the June 21, 1980 event, the figures are $T \sim 10^7$ °K, $n \sim 10^9\ cm^{-3}$ , $r_s = 10^5$ cm and $\varepsilon \sim 10^{-7}$ volt/cm.

Finally, concerning the employed formalisms for the theoretical spectra, the comparison was basically made between the stationary and non-stationary solutions of the Fokker-Planck continuity equation; it should be pointed out that according to Pérez-Peraza and Gallegos (1986) the formalism of the Fermi"age-energy" analogy may be involved within the stationary solution of the Fokker-Planck equation.

For the spectra derived from the non-stationary solutions of the continuity equation, we evaluated it at the elapsed time between the $H_\alpha$ flare and the peak intensity of electron fluxes. We found that in all cases the spectra derived from the stationary solutions describe better the observational spectra.

IV. Conclusions.

From the previous analysis we conclude that the major amount of electrons generated in the three events under consideration come from the local population of electrons with thermal distribution. This supports the occurrence of a unique acceleration phase,with perhaps an eventual contribution of a secondary phase,in the June 21, 1980 event.

The fact that the stationary formalism is the best option may be interpreted as that a high temporal homogeneity of the process is reached very fast in the source, perhaps within the time scale of the mean confinement time of particles in such a volume. This implies that a value of $\tau \sim 1$s could be considered as a relatively long confinement time, what in turn would favorize the establishment of an stochastic acceleration process of the Fermi-type. This may be the case of the November 9, 1973 and June 21, 1980 events where the extended source dimensions inferred in this work and the extended energy range observed (200 KeV-20MeV) support á Fermi process, whereas for the November 11, 1982, where we found small source dimensions, and the displayed energy range is not very extended ( < 2 MeV), an impulsive acceleration process such as neutral current sheet acceleration has been found.

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