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DELIMINATION OF VALITY OF THEORICAL APPROACHES FOR DERIVATION OF PARTICLE ENERGY SPECTRA

J.Pérez-Peraza* and A. Gallegos

Instituto Nacional de Astrofísica,Optica y Electrónica, (INAOE)
Tonantzintla, A.P. 51 y 216 Puebla, 72000-México

Abstract

We determine the validity of the Fermi"age-energy analogy" for description of particle energy spectra, relative to the exact description by the stationary and non-stationary solutions of the particle continuity equation. The analysis is developed with electron spectra and with non-thermal photon energy spectra. The assumed electromagnetic emission is produced by the interaction of the accelerated electrons with local matter electromagnetic fields.

1. Introduction. The study of the energy spectrum of high energy particles is one of the main tasks of Cosmic Ray Astrophysics, because it contains information about source phenomena: particle generation processes, the nature, structure and location of the source and physical conditions prevailing therein. However, particles arriving at observational sites have been strongly modulated during transport through the environment of their own sources, the interstellar and interplanetary media. Therefore, to determine particle spectra at the source level from observational data, it is usually employed the following methods: by demodulation of observational particle data back to the source, or by infering the particle source spectrum from the deconvolution of nonthermal electromagnetic emissions. Both methods lead to source spectra that may be fitted by an exponential or inverse power low in energy (or rigidity),which by themselves contain limited information about the source phenomenology and source physical conditions. The lacking information must be completed from additional theoretical work; at this regard the most popular methods worked out in the literature are: by developing an acceleration mechanism for the particles to gain energy in the proposed electromagnetic field configuration, and deriving the corresponding particle energy distribution predicted by the mechanism. This is usually employed in scenarios of thin geometry, such that within the time scale of acceleration, energy losses are negligible. A more general method consists in solving a Fokker Planck-type equation including any kind of processes in the source volume during acceleration; however, this may entail a high degree of mathematical complexity, as one considers more and more processes during the generation process. An approximation to the stationary solution, named the Fermi age-energy approach, becomes an useful tool when it is searched for an analytical description of the energy spectrum, with consideration of several energy change processes. In Pérez-Peraza and Gallegos (1987) we determined under which conditions, the exact solutions may be approached by the age-energy analogy. In that work, we considered several scenarios within the frame of thin geometries (particle energy losses are completely negligeables), and for three different acceleration processes. Here we extend that analysis to scenarios with thick geometry (including energy losses). Also, we investigate how accourate is to employ such approaches of particle energy spectra when one is dealing with non-thermal photon emissions produced by the interaction of the accelerated particles with local matter and fields. The analysis is done for relatively simple energy change rates, under the hypothesis that for more complicated situations, the age-energy formalism may be employed within the range of parameters obtained in this work, for which the agreement with the exact solutions is good.

2. Theoretical source energy spectra and astrophysical scenarios. The details of the exact and the approximated formalisms for derivation of particle energy spectra was described in Pérez-Peraza & Gallegos (1987). In the former case the nonstationary energy spectrum is given as:

$$N(E,t) = \frac{e^{-t^{*}/\tau}}{(dE/dt)} \int_{E_0}^{E} \exp(t^{*}/\tau)\, q(E',t)\, dE' + \frac{(dE''/dt)}{(dE/dt} N(E'',0)\, e^{-t/\tau} . \qquad (1)$$

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*ON LEAVE FROM THE INSTITUTO DE GEOFISICA, UNAM.

and the stationary spectrum is:

$$N(E)=\frac{e^{-t^*/\tau}}{(dE/dt)}\int_{E_o}^{E} q(E')e^{t^*/\tau}dE' + \frac{N(E_{th})e^{-t^*/\tau}(dE/dt)_{Eth}}{(dE/dt)}, \qquad (2)$$

where τ is the particle mean confinement time and $E_{th}=0.5kT$
$t^*=\int_{Eth}^{E} dE'/(dE'/dt)$ and E" appears from $t=\int_{E''}^{E} dE'/(dE'/dt)$

$q(E',t)$ and $q(E')$ are the source terms, E_o (> 0.5 kT) is the injection energy, $N(E_{th})$ and $(dE/dt)_{E_{th}}$ are the particle thermal spectrum and the energy change rate evaluated at the must probable thermal energy.
On the other hand the spectrum which appears from the well known Fermi age-energy analogy is

$$N(E)dE=N(t)dt=(N_o/\tau)\exp(-t^*/\tau)dt, \qquad (3)$$

where N_o is the initial number of particles participating in the acceleration process.
For the present analysis we have considered within the energy change rate the Fermi acceleration and neutral current sheet acceleration (N.C.S.). Electron energy losses, were given in Pérez-Peraza et, al., (1985): Coulumb collisions (COLL.) Inverse Compton Effect (ICE), Bremsstrahlung (BREM) and synchrotron losses (SYN). In the case of two acceleration stages we used as injection process only (N.C.S.). Our analysis was carried out within the frame of the following scenarios: first, when there is only an acceleration phase of local thermal particles, 2nd. when the spectrum is defined in a secondary acceleration phase of particles injected with energy above a given threshold value, and third, when the spectrum is determined by particles of the populations from and injection process and particles accelerated from thermal background in a secondary phase. Spectra (1) (2) and (3) were explicitely given in Pérez-Peraza and Gallegos (1987) for the three mentioned scenarios, when only acceleration is considered. The expressions for the spectra when electron losses are considered become highly extended to include within the scope of this paper, and will be reported elsewhere. Similarly, the photon spectra from the deconvolution of particle spectra for the (ICE) and (BREM) processes will not be explicitely included, but the procedure was described in Pérez-Peraza et, al., (1985). Within the first scenario the source terms in (1) and (2) are $q(E',t)=q(E')=0$, whereas in (3) No. is the Maxwelliam distribution. In the 2nd scenario we used the injection spectrum from (N.C.S.) for the source terms and N_o. The threshold value for acceleration in the 2nd scenario, when no losses are considered corresponds to the local hydromagnetic velocity, whereas with energy losses the value is imposed by these processes themselves. In the 3rd scenario the source terms and N_o are the addition of the injection spectrum from (N.C.S.) and the local Maxwellian distribution in the acceleration region.
3. Results. For the goal of the research we have proceeded to evaluate ratios between the formalisms given in (1), (2) and (3), for a wide range of parameters prevailing in solar flare sources. The magnetic field strength has been fixed 500 (Gauss) and the mean photon energy density limited to $10^{16} \le W_{ph} \le 5\text{x}10^{16}$ (eV/cm^3). Since the comparisons are by means of ratios, these become independent of the volume and density of the injection and acceleration regions, however, for evaluations of threshold values in the 2nd scenario we used $n=10^8$ cm^{-3}, in the acceleration region. Concerning the analysis with electron spectra, Fig. 1 shows that within the 1st scenario, the ratio is energy-independent, and for the specific chosen parameters, acceleration efficiency $\alpha=2s^{-1}$ and $\tau=4\text{x}10^{-3}$s, the best agreement between the exact and approached formalisms occur for $10^5<T<10^7$ K, with or without losses. Fig. 2 shows that the ratio of the non-stationary to the stationary spectra is energy-dependent and for the selected acceleration mechanism with electric field $\epsilon=3\text{x}10^{-5}$ V/cm. and $\tau=10^{-2}$ s, the only agreement may occur around $5\text{x}10^{7}$ ^{0}k and E<0.4 KeV. Within the frame of the

2^{nd} scenario Fig. 3 shows that for an injection process with $\varepsilon=10^{-6}$ V/cm,$\tau=0.1$ s and Fermi acceleration with $\alpha=2s^{-1}$, $\tau=1s$, the best agreement is in $10^{6}<T<10^{7}$ K. Fig 4 shows that for (N.C.S.) injection with $\varepsilon=2x10^{-6}$ V/cm,$\tau=0.1s$ and Fermi acceleration with $\alpha=2.1s^{-1}$,$\tau=1s$, the best agreement is around $5x10^{5}$ °K, however, - with appropiate parameter sets better agreements can be obtained at E>0.5 KeV, where there is stabilization of the ratios.For the 3^{rd} scenario Fig. 5 shows that with $\varepsilon=3x10^{-6}$ V/cm,$\tau=0.1s$,$\alpha=1.2s^{-1}$and $\tau=0.1s$, good agreements are obtained in - $5x10^{5}<T<10^{7}$ °K, at E_6>0.5 KeV. Now concerning photon spectra the behavior of ratio is proportional to that of electrons at high energies: in fact, to produce (ICE) or (BREM) radiations in the range 10 KeV$\leq h\nu<10^{4}$ KeV, high energy electrons are involved. Within the frame of the 2^{nd} scenario, if radiation is from (ICE), Fig.6 shows that for injection with $\varepsilon=3x10^{-6}$ V/cm, $\tau=1.2$ s and Fermi acceleration with $\alpha=0.5s^{-1}$, $\tau=1s$, the agreement is good between $5x10^{5}<T<5x10^{6}$ °K, if no other losses different from (ICE) are considered.

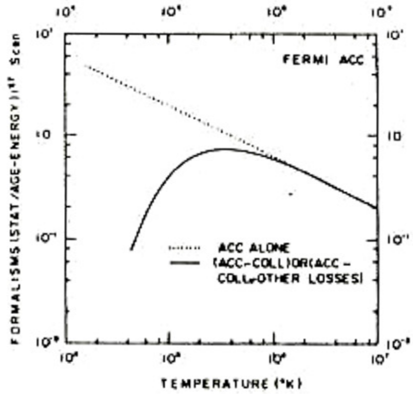


Fig. 1

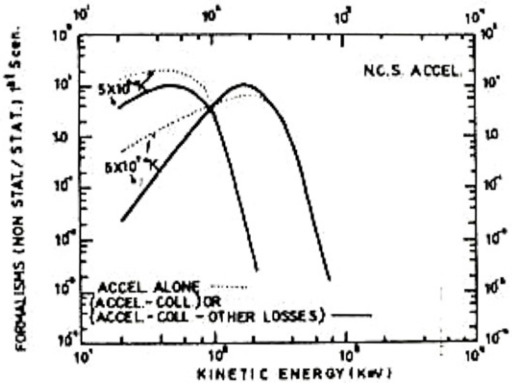


Fig.2

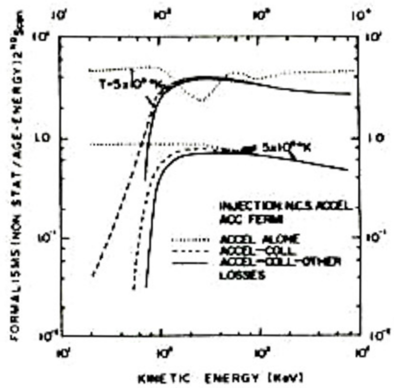


Fig.3

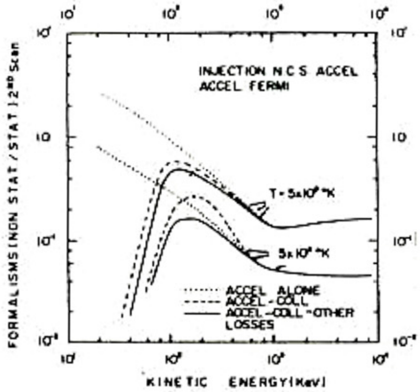


Fig.4

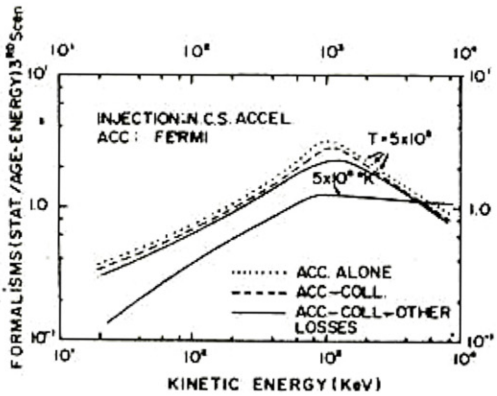


Fig.5

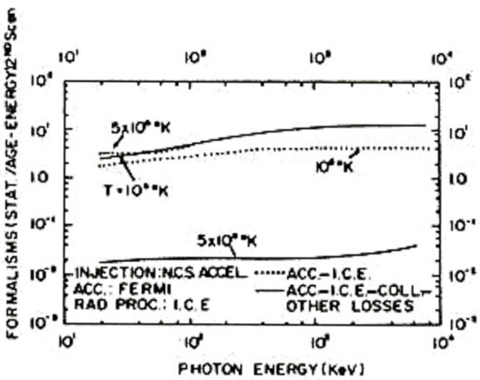
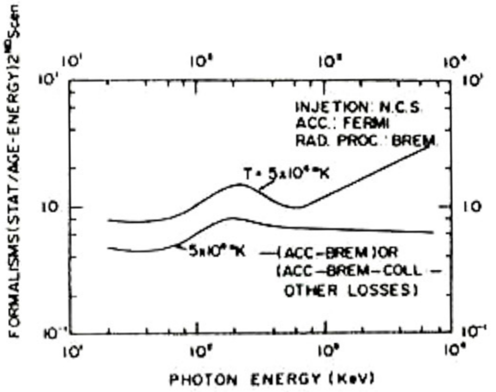


Fig.6



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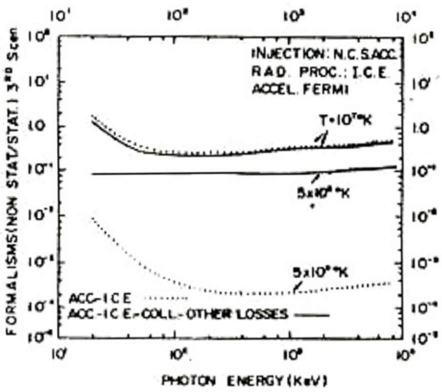

Fig. 8

As far as (BREM) is considered. Fig.7 shows that the agreement is good in $10^5<T<10^7$ °K for the specific set $\varepsilon=10^{-6}$V/cm, $\tau=0.1$s, and $\alpha=2.5s^{-1}$, $\tau=1$s. Within the frame of the 3rd scenario, Fig. 8 shows that the agreement is good around 10^7 °K for the specific set $\varepsilon=10^{-7}$V/cm, $\tau=0.1$s and - - $\alpha=2.5s^{-1}$, $\tau=1$s.

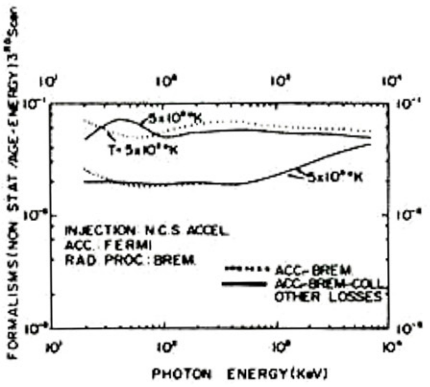

Fig. 9

For (BREM) radiation, Fig. 9 shows that there is not good agreement for the chosen parameter set: $\varepsilon=1.2\times10^{-6}$V/cm, $\tau=0.2$s and $\alpha=1.2$ s^{-1}, $\tau=1$s, - though the agreement could be better for different and well chosen parameter sets and lower temperature.

4. Conclusions. This analysis shows that the range of conditions where the age-energy approach may replace the exact solutions for description of energy spectra of electrons is highly sensible, to the assumed scenario: when there is only one acceleration stage of the thermal background particles (1st scenario), the substitution of the approached formalism for the exact formalisms is not completely justified, as was shown with Figs. (1) and (2). Replacements between formalisms may be done within the frame of the 2nd and 3rd scenarios, though approaches to the non-stationary solution are better obtained at high particle energies. It is realized, that in general, better agreements may be fitted at high energies, because both the acceleration and deceleration rates have a trend toward stabilization, since they are dependents on the parameter β(particle velocity in terms of the light velocity), which increases very slowly toward the unit at high energies. For this reason the agreement between formalisms with photon spectra appears better, since in this case high energy electrons are involved.

References

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