ENERGY LOSS FOR ELECTRONS IN THE HELIOSPHERE AND LOCAL INTERSTELLAR SPECTRUM FOR SOLAR MODULATION

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Galactic Cosmic Rays (GCR) entering the Heliosphere are affected by the solar modulation, which is a combination of diffusion, convection, magnetic drift, and adiabatic energy losses usually seen as a decrease of the flux at low energies (less than ~ 10 GeV). We improved a quasi time-dependent 2D Stochastic Simulation code describing such effects. We focused our attention on the electron modulation, adding energy losses mechanisms in the Heliosphere that can be neglected for protons and ions: inverse Compton, ionization, synchrotron, and bremsstrahlung. These effects have been evaluated in the region affected by the solar magnetic field, up to 100 AU, where the environment conditions are not constant, especially the magnetic field intensity, and the photon density. In our calculation the inverse compton energy losses are dominant, but they contribute only a few percent in comparison with the adiabatic losses. We also compared the Local Interstellar Spectrum (LIS) of primary electrons with experimental data collected in the past years at energies ≥ 20 GeV. We found that, inside one standard deviation, LIS fits the data and can be used in a Monte carlo code reproducing CR propagation in the Heliosphere.

Keywords: cosmic rays; heliosphere; solar modulation; energy losses.

1. Introduction

Electrons and positrons are a small fraction (1%) of the Galactic Cosmic Rays at Earth in the GeV-TeV region of the spectrum. They undergo the same mechanisms of the cosmic ray proton component. Compared to protons, they have a lower mass, a relativistic velocity, and are affected by efficient electromagnetic energy losses. Such losses are the result of inverse Compton scattering, ionization, synchrotron, and bremsstrahlung processes at work in the astrophysical medium in which the electrons are moving. These processes have been already described in literature and applied to the interstellar environment. Due to their energy losses electrons can not diffuse to long distances. Therefore, the sources of Cosmic Ray electrons measured at Earth must be placed close to us ($\lesssim$ 1 Kpc). Moreover, the lifetime of Cosmic Ray electrons moving in the interstellar medium is relatively short. The study of these effects offers a tool to better understand the recent history of the solar system neighborhood. In this paper we concentrate on the esteem of the contribution of the mentioned energy losses mechanisms inside the solar cavity, in order to implement them inside a Montecarlo code of Cosmic Ray propagation in the Heliosphere.

2. Local Interstellar Spectrum

Many authors already described the high energy part of the electrons spectrum in Cosmic Rays. In our approach, starting from some assumptions on Galactic sources of electrons and positrons, particles are propagated in the interstellar medium using a diffusion model[1]. We then obtain primary and secondary fluxes of Cosmic Rays at the border of the Heliosphere: this is what we call Local Interstellar Spectrum (LIS). This diffusive approach allows the use of more realistic models for diffusion constants, still allowing an analytical solution. We focused our attention on the work of Zhang & Cheng[2] who published the following analytical expression for the GCR electrons LIS:

$$J_{lis}(E) = \frac{1600\ \epsilon^{-1.1}}{1 + 11\ \epsilon^{0.9} + 3.2\ \epsilon^{2.15}}\ \ \mathrm{GeV}^{-1}\ \mathrm{m}^{-2}\ \mathrm{sr}^{-1}\ \mathrm{s}^{-1} \tag{1}$$

We compared this LIS with the data of 6 experiments that measured CR fluxes in the past years. For this analysis we selected data at energy $\geq$ 20 GeV, because in this range the effect of solar modulation can be considered negligible. We fitted the data with the expression:

$$F_{lis}(E) = \frac{C\ \epsilon^{\gamma}}{1 + 11\ \epsilon^{0.9} + 3.2\ \epsilon^{2.15}}\ \ \mathrm{GeV}^{-1}\ \mathrm{m}^{-2}\ \mathrm{sr}^{-1}\ \mathrm{s}^{-1} \tag{2}$$

where we introduced the two parameters C and γ to be best-fitted using the experimental data. In Table 1 we report the two parameters calculated for each experiment with their error bars (1 standard deviation). We show the fitted values of the two parameters γ and C for the various experiments in Fig. 1. In the same figure we show also the average value in comparison with the values derived from Eq. 1. We found an agreement between experimental and theoretical values, within one standard deviation. Looking out Fig. 1 we can also get a rough estimation of the amount of statistical and systematic uncertainties for each experiment respect to the others.

Table 1. The parameters C and γ fitted using data by several experiments.

Experiment	Year	ΔE (GeV)	C	δC	γ	δγ
PRINCE[3]	1975	5-200	2094,990	440,796	-1,336	0,182
MASS[4]	1991	7.5-45	1314,260	353,374	-1,025	0,177
CAPRICE[5]	1994	0.46-43.6	2304,000	757,602	-1,411	0,252
BETS[6]	1997-8	10-100	1591,800	739,986	-1,064	0,151
NISHIMURA[7]	1996-8	30-300	1536,000	440,769	-1,158	0,265
AMS-01[8]	1998	0.1-40	2304,000	670,023	-1,343	0.127

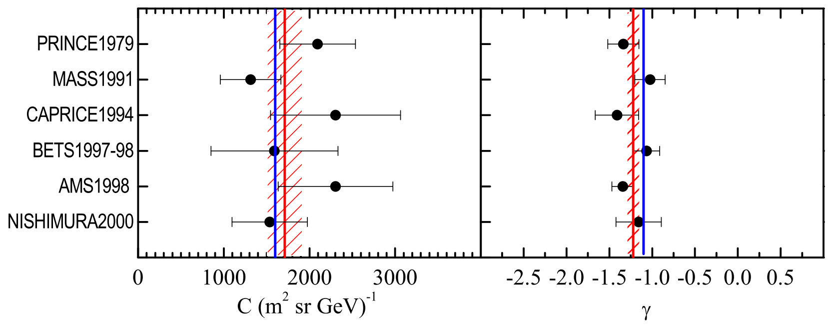

Fig. 1. The parameters C and γ fitted by using the experimental data listed in Table 1. We show also the average value (red line) compared with the theoretical one obtained from Eq. 1 (blue line).

3. Propagation and energy losses

During the last years the AMS-Milano group developed a quasi time-dependent 2D stochastic simulation code able to describe the propagation of Cosmic Rays inside the Heliosphere. We improved the code taking into account also the additional energy losses experienced by Cosmic Rays during the propagation in Heliosphere. In the case of protons (or nuclei) these energy losses can be neglected, while for electrons this assumption is no more valid, due to their small mass. In the following sections we describe several processes producing energy losses in Cosmic Rays.

3.1. *Ionization*

Electrons moving in a region containing gas or plasma lose energy by means of ionization processes. This happens when electrons move across the interstellar medium (ISM) as well as inside the solar cavity. Ionization energy losses are proportional to the logarithm of the electron energy and, in the case of neutral plasma ($n_{ion} \sim n_e$), can be described by the following relation:

$$\left.\frac{dE}{dt}\right|_{ion} = -\frac{3}{4}\sigma_T c(mc^2)n_e\Big[\ln\Big(\frac{E}{mc^2}\Big) + 2\ln\Big(\frac{mc^2}{h\nu_{pl}}\Big)\Big] \tag{3}$$

where E is the energy of electrons, n_e is the atoms density in the ISM (or in the Heliosphere), $\sigma_T = \dfrac{e^4}{6\pi\epsilon_0^2 m^2 c^4}$ is the cross section, and $\nu_{pl} = \dfrac{e}{2\pi}\sqrt{\dfrac{n_e}{\epsilon_0 m}}$ is the plasma frequency.

3.2. *Bremsstrahlung*

Bremsstrahlung energy loss is due to acceleration (or actually deceleration) of electrons interacting with charged particles. It is proportional to the energy of the particle and, in the case of neutral plasma, could be represented by:

$$\left.\frac{dE}{dt}\right|_{brems} = -\frac{3}{8\pi}\sigma_T c\alpha E n_H \phi_H \tag{4}$$

where σ_T is the Thompson cross section, c is the speed of light, α is the fine-structure constant, n_H is the space medium density and $\phi_H = 29.97$ for hydrogen plasma.

3.3. *Syncrotron*

Syncrotron energy loss is proportional to E^2 and it is related to the interaction (and acceleration) of cosmic particles with magnetic fields:

$$\left.\frac{dE}{dt}\right|_{sinc} = -\frac{4\sigma_T c}{3(mc^2)^2} U_{mag} E^2 \tag{5}$$

where $U_{mag} = \frac{B^2}{2\mu_0}\left[\frac{eV}{m^3}\right]$ is the magnetic field density.

3.4. *Inverse-Compton*

The Inverse-Compton energy loss is due to the interaction of ultra-relativistic electrons with the soft background radiation. This process could be described by two cases: Thomson approximation or Klein-Nishina regime. Thomson approximation is valid at low energies. In this case the Compton cross section is used, and the energy loss rate is proportional to E^2. Klein-Nishina is an extreme case where both the energy of the photons and of the particles are very high (e.g. $\frac{4\varepsilon\gamma}{m_e c^2} \gg 1$, where ε is the photon energy, γ is the Lorentz relativistic factor, and $m_e c^2$ is the rest mass of the particle). Defining $\xi = \frac{\gamma k_b T}{m_e c^2}$ (with k_b Boltzmann constant) the Inverse-Compton energy loss in presence of a black body radiation is[9]:

$$-\left.\frac{dE}{dt}\right|_{IC} = \begin{cases} \frac{4}{3}\sigma_T c U_{ph}\left[\left(\frac{E}{mc^2}\right)^2 - 1\right] & \xi < 3.8\cdot 10^{-4} \\ 10^{-45}\frac{E^2(k_b T)^4}{\xi} e^{\sum_{i=0}^{6} c_i (\ln \xi)^i} & 3.8\cdot 10^{-4} \le \xi \le 1.8\cdot 10^3 \\ \frac{\sigma_T}{16}\frac{(m_e c k_b T)^2}{\hbar^3}\ln(4\xi) - 1.9805 & \xi > 1.8\cdot 10^3 \end{cases} \tag{6}$$

where $c_i = \{74.77, -0.1953, -0.0997, 0.004352, 0.0003546, -0.0000301\}$ and U_{ph} is the photon energy density.

3.5. *Energy loss in the heliosphere*

The heliosphere dynamics is strongly related to the Sun activity. While in the intergalactic medium it is possible to account for average quantities, in the solar cavity we need to evaluate them locally, as a function of the distance from the Sun. The plasma density measured at $r_0 = 1$ AU is $n_{pl}(1\text{AU}) \approx 8 - 9$ protons/cm^3. Using the continuity equation it is possible to estimate the plasma density in the Heliosphere at every distance from the Sun:

$$n_{pl} = n_{pl}(1\text{AU})\left(\frac{r_0}{r}\right)^2. \tag{7}$$

Moreover, assuming that the electromagnetic emission of the Sun has a black body behavior, we can estimate the photon density inside the Heliosphere:

$$U_{ph} = \frac{L_\theta}{4\pi c}\left(\frac{r_0}{r}\right)^2 \tag{8}$$

where $L_\theta = 3.846 \cdot 10^{26}$ W.

As heliospheric magnetic field (HMF) we used a modified Parker field, according to Jokipii & Kota[10], that enhanced the magnitude of HMF in the polar regions. A comparison among the several energy loss processes inside the Heliosphere at 1 AU is shown in Figure 2. We found that Inverse-Compton is the dominant process, due to the large quantity of photons emitted by the Sun.

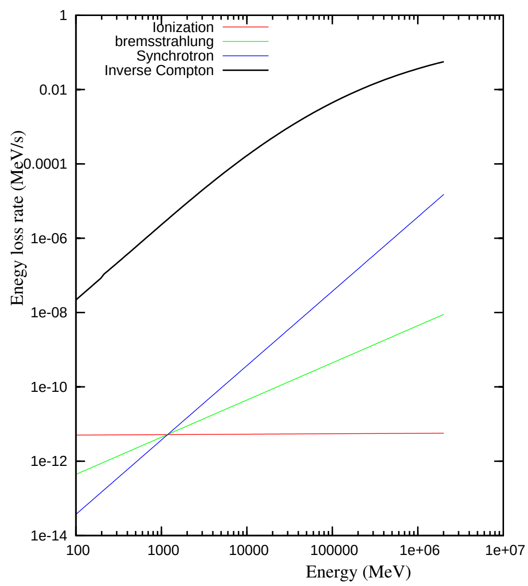

Fig. 2. Energy loss rate of electrons inside the heliosphere at 1 AU, which is due to several processes.

We estimated the importance of these energy loss processes inside the Heliosphere, in comparison with the adiabatic energy losses. We used our MonteCarlo simulation code of the Heliosphere[11] and adapted it to take into account these processes[12]. We first estimated the average time of permanence of GCR leptons inside the Heliosphere, considering only particles reaching the Earth. From the time spent in the Heliosphere by these particles, we estimated the total energy loss due to the Inverse-Compton process

(ΔE_{IC}), neglecting other losses. We compared ΔE_{IC} with the total energy lost by the same particles in the Heliosphere. We estimated the adiabatic energy loss (ΔE_{FF}) by using a Force Field approach[13]. Using a typical modulation potential occurring in periods of medium solar activity ($\Phi = 550$ MV), we estimated an adiabatic energy loss $\Delta E_{FF} = 0.55$ GeV, roughly constant at all energies. In Table 2 we compare the two energy losses. The Inverse-Compton one is always several order of magnitude lower than the total energy loss. At energies around 10 GeV the Inverse-Compton energy loss is 5% of the adiabatic one.

Table 2. Energy loss estimation for different initial energy of the particle.

E_0 (GeV)	ΔE_{IC} (GeV) $\times 10^{-3}$	$\Delta E_{IC}/E_0$ %	ΔE_{FF} (GeV)	$\Delta E_{FF}/E_0$ %	$\Delta E_{IC}/\Delta E_{FF}$ %
1	0.145	0.014	0.55	55	0.025
10	1.056	0.010	0.55	5.5	0.192
10^2	2.335	0.0023	0.55	0.55	0.42
10^3	1.815	0.00018	0.55	0.055	0.33

4. Conclusions

In this contribution we compared theoretical LIS for electrons with experimental data. In our analysis we used datasets of several experiments operated in different periods. We considered only data at energies higher than 20 GeV, where the solar modulation is negligible. Moreover we improved our MonteCarlo model of Cosmic Ray electrons propagation, introducing additional energy losses mechanisms, such as inverse Compton scattering, ionization, synchrotron and bremsstrahlung. We found that the major contribution is due to the Inverse-Compton process. Anyway this is not exceeding a few percent of the total energy loss in the Heliosphere, always dominated by the adiabatic process.

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