
The Local Interstellar Spectrum of Cosmic Ray Electrons

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Abstract

The local interstellar spectrum of cosmic ray electrons and positrons from 0.8 GeV to 2 TeV is derived by demodulating the measured spectra by balloon and satellite experiments. It can be well represented by a single power law in kinetic energy with spectral index 3.4 over the whole energy range, pushing for the idea that it is not representative of the galactic average. Instead, the spectrum has to reflect the nature of our local bubble, being mostly sensitive to the last nearby supernova.

1. Acceleration and propagation of cosmic ray electrons

The most favored sites for cosmic ray (CR) acceleration are the shock fronts generated by supernova (SN) explosions: the SN emitted power and their estimated rate are compatible with the CR energy density in the Galaxy (of the order of 1 eV cm^{-3}) if the acceleration mechanism has an efficiency of few percent, while the Fermi model of the acceleration by magnetic irregularities naturally produces a power-law spectrum in momentum. Observation of synchrotron X-rays from supernova remnants (SNR) demonstrates that electrons are accelerated by SNR [1]. However, there is no definitive proof of hadronic acceleration by SNR.

The upper limit E_{max} for the energy of particles with charge Ze that are accelerated by a SN shock front is found considering the finite life time and size of the engines: $E_{\text{max}} \sim Z \times 10^{15} \text{ eV}$. The maximum energies (about 10 TeV) of detected gamma rays from SNR, interpreted as the result of inverse Compton scattering of high energy electrons with ambient photons, imply an upper limit to the acceleration of electrons well below this theoretical estimate [2]. On the other hand, the γ -rays emitted by SNR could be produced as well by the hadronic component (via π^0 decay): in this case we would expect not to observe any cut-off in the γ -ray spectrum up to the knee. Recently, Guetta & Amato [3] pointed out that the electronic origin of high energy γ -rays is very probable for the Crab and MSH15-52 SNR, whereas the hadronic component is a possible explanation of the emission from Vela and G343.1-2.3.

Electrons are light particles and suffer large energy losses produced by

electromagnetic processes like bremsstrahlung, synchrotron radiation and inverse Compton scattering, whereas all other CR particles are relatively insensitive to these processes. Thus, while CR protons and stable nuclei propagate for a large fraction of the Galaxy with small energy losses, electrons of energy E diffuse only for distances ~ 1 kpc $(E/\text{TeV})^{-1}$ [4]. On the other hand, the e.m. radiation can be used to map their distribution (averaged along the line of sight) in the Galaxy, suggesting an average source spectral index equal to 2 [1].

Below few GeV, the bremsstrahlung dominates the electron energy losses, producing γ -rays with typical energies of 1–100 MeV. If the source injection spectrum is $\propto p^{-\alpha}$, the observed spectrum should have a spectral index $\gamma \approx \alpha$ at these energies. However, the electron bremsstrahlung is overwhelmed by the π^0 decay spectrum, due to the hadronic CR component [1]. Above 10 GeV inverse Compton and synchrotron radiation are the dominant energy losses, producing photons in the X and radio bands, respectively. The observed spectral index is expected to be $\gamma = \alpha + 1 - \Delta$, where Δ is a small correction that depends on the source spatial distribution [5]. Very high energy electrons at the sources can produce synchrotron radiation in the X band, thanks to the relatively high magnetic field of SNR. This radiation has a power-law spectrum, with index $(\gamma - 1)/2$, that stems out of the thermal component, and it is localized into well defined structures, like the SN shock fronts [6].

Because of the strong electromagnetic losses, electrons diffuse away from the source for a distance that is inversely proportional to their energy. Hence one may describe their distribution in the galactic plane as an ensemble of statistically independent populations, whose dimensions are determined by two effects: (1) diffusion with average propagation length $\ell(E) = 2\sqrt{D(E)t}$ and spatial diffusion coefficient $D(E) \approx D_0(1 + E/E_*)^\delta$, with $D(10 \text{ GeV}) = (1-10) \times 10^{28} \text{ cm}^2 \text{ s}^{-1}$ [5] and $\delta = 0.3-0.8$ [7], and (2) radiative energy losses with characteristic time $t_{\text{rad}} \approx 2.1 \times 10^5 (E/\text{TeV})^{-1} \text{ y}$ [4].

From the observer point of view, the measured CR electron spectrum can not be considered representative of any galactic average: the spectrum is dominated by the most recent SN explosions in the solar system neighborhood, at least at very high energy. Still a galactic component may be important at intermediate energies (10–100 GeV) [5]. In addition, the discrete nature in space and time of the acceleration process can make unpredictable the spectrum above 100 GeV and produce a positive curvature of the spectrum in log-log scale at intermediate energies [1].

2. The direct measurements of CR electrons

The local interstellar spectrum (LIS) of CR electrons measured by recent experiments is shown in figure 1. The correction for the solar modulation has

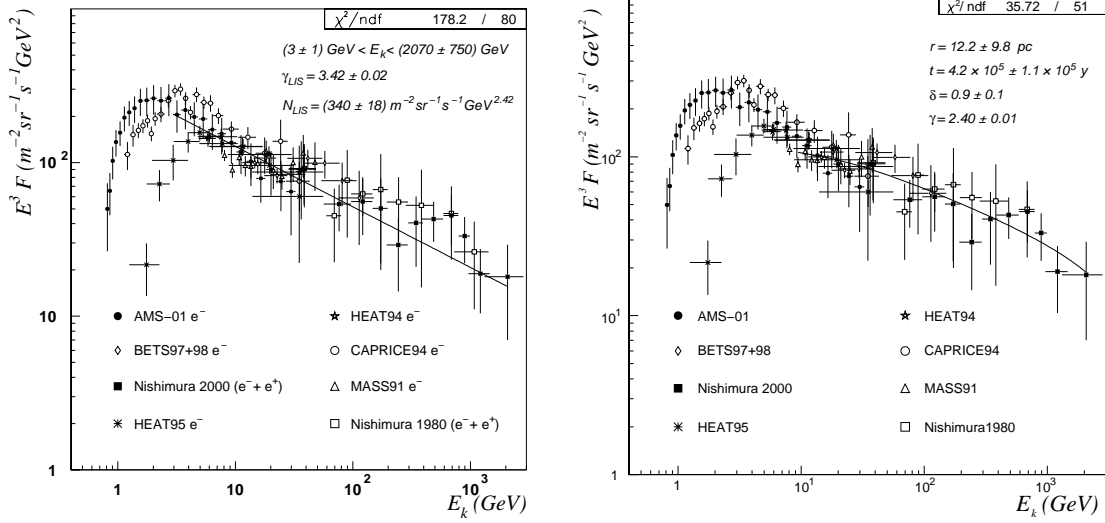


Fig. 1. Local interstellar spectrum of cosmic ray electrons with single power-law fit (left) and single source model fit (right). All data sets were re-normalized to the same value at 20 GeV.

been carried on with the spherical adiabatic model of Gleeson & Axford [8]. In addition, all data points were re-normalized to the flux measured by AMS-01 at 20 GeV, in order to reduce the spread, assuming that systematic errors in the acceptance calculations do not affect the spectral index [9].

The left panel shows that a global fit with a single power-law from 3 GeV up to 2 TeV seems to be not excluded even though the spread of the data set is still visible after the re-normalization. The unique spectral index over this large energy range may be explained with the hypothesis that the measured spectrum is produced by a single nearby source, with spectral index 2.4. In this case the shock compression ratio $R = \rho_2/\rho_1$, where ρ_1 and ρ_2 are the upstream and downstream densities respectively, can be estimated from the relation $\gamma \simeq (R+2)/(R-1)$ [10]. One obtains $R = 2.14$, a value that is quite different from the number usually adopted in the models of CR acceleration. The usual compression ratio $R = 4.0$ (obtained with high Alfvénic Mach numbers [10]) corresponds to a spectral index of the injection spectrum equal to 2.0, in agreement with the average spectral index ($\simeq 0.5$) of the diffuse synchrotron radiation in the Galaxy [1]. However, a source spectral index of 2.4, corresponding to a synchrotron spectral index of 0.7, is still compatible with some of the SNR of the Green’s catalogue [11].

The highest energy points may suggest a spectral change or a cut-off near 1 TeV, but the large error bars do not allow to draw any definite conclusion. A possible fit of the measured spectra above 10 GeV with the single source model of Atoyan et al. [5] is shown in the right panel of figure 1. The best fit is obtained with a recent and nearby source with age $(4.2 \pm 1.1) \times 10^5$ y and distance 12.2 ± 9.8

pc from the solar system, with injection spectral index 2.4. Again, this result suggests that we observe cosmic ray electrons accelerated by a nearby single burst-like process, rather than multiple sources (as considered in ref. [1]). In addition, this model suggests that the SN explosion happened not so long time ago, and that the value for δ is quite high compared to the usual value of 0.6 adopted in the literature, even if it is compatible with recent simulations by Maurin et al. [7], who find a better agreement to the secondary/primary ratio if $\delta = 0.8\text{--}0.9$.

Kobayashi et al. [4] took into consideration several nearby SNR, concluding that Vela (distance 250 pc, age 20 ky) should dominate the observed spectrum, considered a superposition of few single source models. However, Guetta & Amato [3] considered the SNR whose TeV gamma rays has been detected and conclude that the high energy photons coming from Vela are likely due to hadronic processes instead of inverse Compton scattering of accelerated electrons with ambient photons. In addition, our fit shows that the single source must be nearer than Vela: it is probably the last SN among those that contributed to the formation of the local bubble [12]. Thus the site where the measured CR electrons were accelerated is still a matter of debate.

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3. References

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