PROCEEDINGS OF SCIENCE

Propagation of high-energy cosmic-ray electrons in the interstellar medium

Reda Attallah[*]
Physics Department, Badji Mokhtar University, Annaba, Algeria
E-mail: reda.attallah@univ-annaba.dz

Due to strong energy loss processes during propagation in the Galaxy, mainly by inverse Compton scattering and synchrotron radiation, high-energy cosmic-ray electrons can reach the Earth only from nearby sources. Unfortunately, the exact nature of these sources is still unknown. The experimental data are consistent with astrophysical objects such as SNRs and pulsars but more exotic origin, like the annihilation or decay of dark matter particles, cannot be excluded. This work shows how Monte Carlo simulation of the propagation of high-energy cosmic-ray electrons in the interstellar medium can be implemented to address this issue.

Cosmic Rays and the InterStellar Medium - CRISM 2014,
24-27 June 2014
Montpellier, France

[*]Speaker.

PoS(CRISM2014)045

1. Introduction

Electrons represent only about 1% of cosmic rays. Nonetheless, they are of great interest due to their unique specific features. At high energy, cosmic-ray electrons experience several energy loss processes so strong that their lifetime decreases significantly. As a result, they can reach the Earth only from nearby sources in sharp contrast to other cosmic-ray nuclei. These particles can then be used to probe local cosmic-ray accelerators and shed light on the origin of cosmic rays. Cosmic-ray electrons are also of importance to X-ray and γ-ray astronomies, to dark matter investigation, and to many other issues in astrophysics.

The origin of most cosmic rays, including electrons, is generally based on the idea of acceleration at astrophysical sources and diffusion in turbulent magnetic fields in the Galaxy. Because of the electric charge, cosmic-ray particles are randomly scattered by irregularities in the magnetic field during their propagation through the interstellar medium. This idea is attested by the presence in the cosmic radiation of a much greater proportion of secondary nuclei, such as Li, Be, and B, when compared to the solar elemental abundances. Between injection at sources and observation on the Earth, cosmic rays travel much greater distances than the thickness of the Galactic disk. This result also suggests that diffusion takes place in a confinement volume including the Galactic disk.

As stated above, the detection of high-energy cosmic-ray electrons indicates the presence of nearby sources. These sources should manifest themselves in the energy spectrum which should display special features at very high energy. Recent experimental data show that the energy spectrum of cosmic-ray electrons does have features at very high energy. Most notably, PAMELA reported a significant increase in the positron fraction between 10 and 100 GeV [1, 2], which was confirmed by Fermi-LAT [3] and by AMS-02 up to 350 GeV [4]. This remarkable result is not consistent with the conventional models based on the assumption that positrons arise only from the secondary production of cosmic rays by collision with the interstellar medium [5]. On the other hand, ATIC reported an excess of cosmic-ray electrons between 300 and 600 GeV [6, 7]. PPB-BETS also showed a similar bump-like structure between 100 and 700 GeV [8].

The interpretation of cosmic-ray electron data usually relies on propagation models, the standard method consisting in solving the transport equation. However, the diffusive propagation of cosmic-ray electrons can also be treated using Monte Carlo methods due to its intrinsic random nature. In particular, Monte Carlo modeling of the propagation of high-energy cosmic-ray electrons is significantly simplified because of the proximity of potential sources in addition to the absence of hadronic interactions. This approach, which is the only one to provide information on the electron-by-electron fluctuations, may help to gain new insight into the problem of the origin of high-energy cosmic-ray electrons.

This work shows how to implement a fully 3-dimensional time-dependent Monte Carlo simulation of the propagation of high-energy cosmic-ray electrons in our Galaxy. Its main goal is to investigate the problem of their origin. We contented ourselves with the most natural way to explain the spectral features of the high-energy cosmic-ray electrons, i.e., we assumed an astrophysical origin (nearby pulsars and/or SNRs) to these particles. This study does not cover the other possible scenarios such as dark matter origin. On the other hand, we used the public code GALPROP[1] [5] to estimate the contribution from farther sources to the electron energy spectrum.

[1] http://galprop.stanford.edu/webrun/

2. Monte Carlo modeling

Throughout their propagation in the interstellar medium, cosmic-ray electrons interact with matter, with magnetic fields, and with radiation. These processes make electrons loose energy and hence distort their injection spectra. The rates of these processes are shown in figure 1 as a function of energy. They include:

- *ionization loss* which is totally negligible at high energy due to its logarithmic dependence upon energy ($\propto \ln E$);
- *bremsstrahlung* which is only important in the GeV energy range because it varies linearly with energy ($\propto E$);
- *synchrotron radiation* in magnetic fields and *inverse Compton scattering* in radiation fields which predominate above a few tens of GeV because they are both proportional to the square energy ($\propto E^2$).

In this work we considered only bremsstrahlung, synchrotron radiation, and inverse Compton scattering. That is to say we focused on cosmic-ray electrons with energies above about 10 GeV. In this case, the total energy loss rate of electrons within Thomson approximation is given by [9]:

$$-\frac{\mathrm{d}E}{\mathrm{d}t} = aE + bE^2 \tag{2.1}$$

with

$$a \simeq 3.7 \times 10^{-16} \ \mathrm{s}^{-1} \ \text{ and } \ b \simeq 1.3 \times 10^{-16} \ \mathrm{GeV}^{-1} \ \mathrm{s}^{-1}. \tag{2.2}$$

The maximum lifetime of a cosmic-ray electron with an energy E anywhere in the Galaxy is therefore:

$$\tau_{\max} = \int_E^{\infty} \frac{\mathrm{d}E}{(-\mathrm{d}E/\mathrm{d}t)} = \frac{1}{a} \ln\left(\frac{a+bE}{bE}\right) \tag{2.3}$$

Since bremsstrahlung becomes negligible above a few tens of GeV, we have then:

$$\tau_{\max} \simeq \frac{1}{bE} \qquad \left(E \gg \frac{a}{b} \simeq 3\ \mathrm{GeV}\right) \tag{2.4}$$

As shown in figure 1 (dashed line), $\tau_{\max}$ decreases very rapidly with energy. For instance, we have $\tau_{\max} \approx 10^5$ yr for $E = 10^3$ GeV, and 10^3 yr for 10^5 GeV.

The average straight-line distance d between the origin and the positions of particles after time t can be estimated using the random walk treatment of free diffusion:

$$d \approx \sqrt{2Dt} \tag{2.5}$$

D, which is the *diffusion coefficient*, is calculated by using the observed ratios of secondary to primary cosmic-ray nuclei (usually B/C):

$$D = D_0 (E/\mathrm{GeV})^{\delta} \tag{2.6}$$

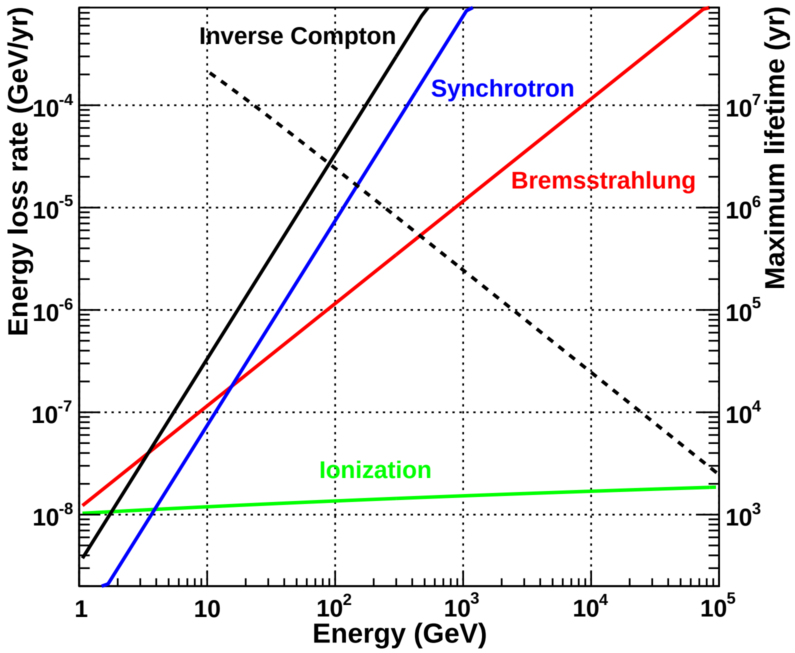

Figure 1: Rates of the different energy-loss processes of cosmic-ray electrons during their propagation in the Galaxy as a function of energy. The dashed line represents the electron maximum lifetime versus energy.

where $D_0 = 1\text{-}5 \times 10^{28}$ cm^2/s and $\delta = 0.3\text{-}0.6$. A reasonable limit to the distance of potential sources of high-energy cosmic-ray electrons can be estimated when replacing t with the maximum lifetime. For typical values of the different constants, one obtains $d \approx 1.8\text{-}0.4$ kpc for 10-1000 GeV. The sources of high-energy cosmic-ray electrons are definitely within a few kpc.

Assuming the *burst-like approximation* [10] (point-like and instantaneous sources), the actual Monte Carlo calculation starts from the selected source where one electron is picked with an energy E and injected into space with a random direction (homogeneous and isotropic diffusion). The path length l is generated according to the probability distribution:

$$P(l) \propto \exp(-l/\lambda) \tag{2.7}$$

where $\lambda = 3D/c$. Between two scatterings, the electron is supposed to have rectilinear motion because the angle of deflection at high energy is negligible. After travelling the distance l, the electron energy is adjusted taking into account the energy loss rate given by relation (2.1). The time of diffusion is calculated taking the instant of injection as the origin of time. The whole process is iterated until:

1. either the electron goes beyond the boundaries of the confinement region (flat halo diffusion model), in which case it is discarded (free escape);

2. or the electron does not reach the solar system within a time corresponding to a cutoff energy of 10 GeV, in which case it is also discarded;

3. or else the electron crosses a sphere centered on the Sun, in which case the electron and all its characteristics are recorded.

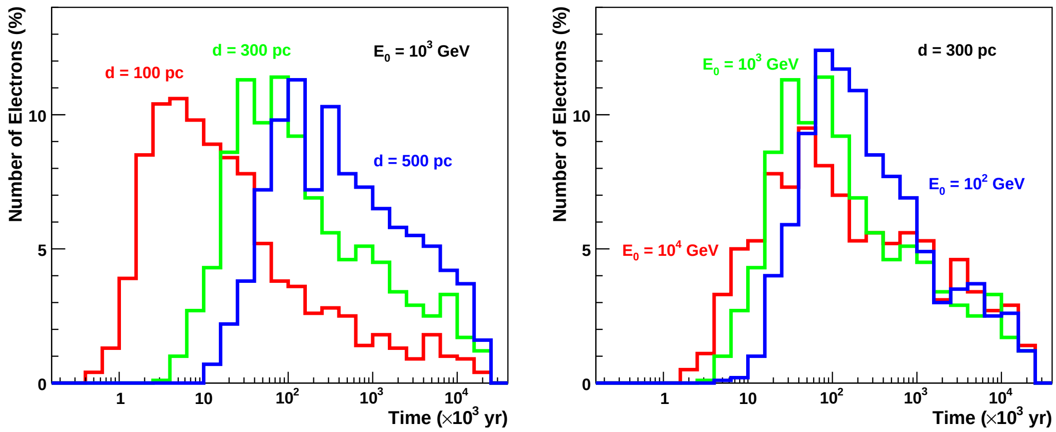

Figure 2: Lifetime distributions of the cosmic-ray electrons observed in the vicinity of the Earth for different distances d from the solar system of the source and different values of the injected energy E_0.

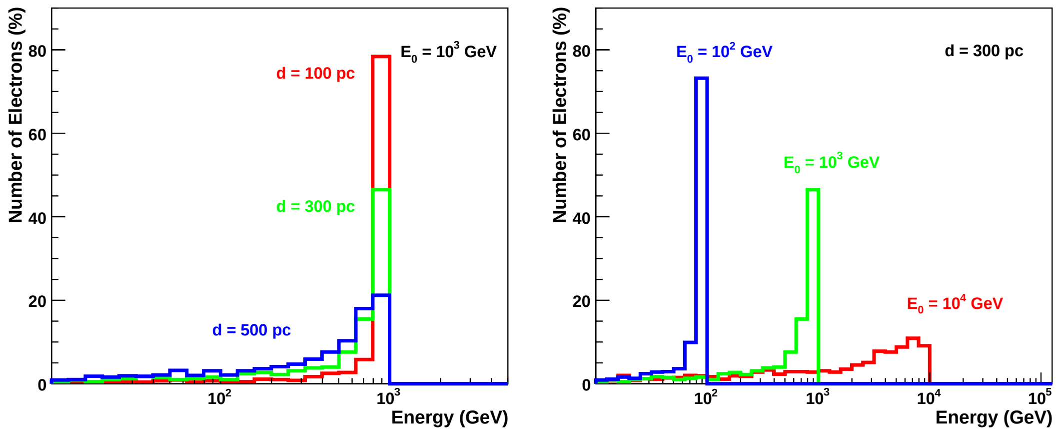

Figure 3: Energy distributions of the cosmic-ray electrons observed in the vicinity of the Earth for different distances d from the solar system of the source and different values of the injected energy E_0.

3. Results and discussion

To examine the effects of propagation, we first considered a cosmic-ray electron source with a fixed energy located at different distances from the solar system and calculated the lifetime and energy distributions of the electrons reaching the Earth (figures 2-3). As shown in figure 2, the lifetime distribution is severely right-skewed (skewness $\sim +4$), i.e., it is characterized by a rapid rise followed by a steady decline with a very long tail (Note the logarithmic scale on the abscissa in figures 2-3). Around 50% of the electrons reach the Earth within a few tens kyr while the rest arrive later within a much longer period ($\sim 10^4$ kyr). When the distance of the source increases (left panel), the lifetime distribution is shifted to the right because electrons spend more time travelling from farther sources. On the contrary, when the initial energy increases (right panel), the lifetime distribution hardly changes. Though the mean free path increases with energy which makes higher-energy electrons spend less time when diffusing from the same source, this effect is counterbalanced by the energy loss mechanisms which become stronger for higher-energy electrons.

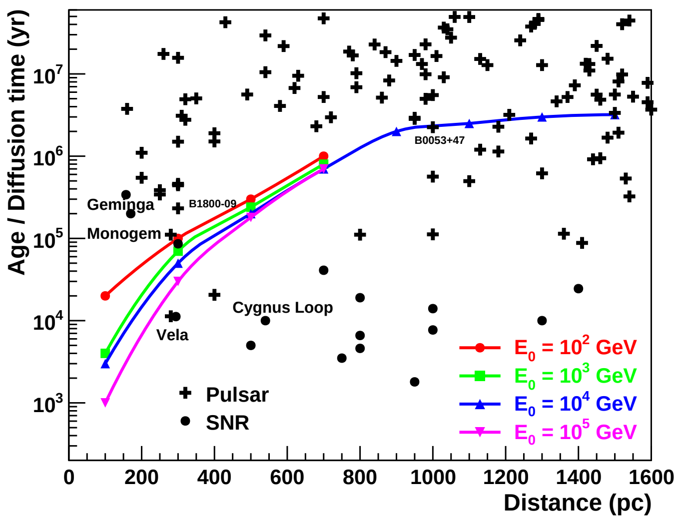

Figure 4: Electron diffusion time at the peak of the lifetime distribution as a function of the source distance. On the same graphics are superimposed nearby pulsars and SNRs with age and distance as coordinates.

In contrast, the electron energy distributions are highly left-skewed (skewness ~ -2) as shown in figure 3. The distribution grows very slowly up to the maximum and then falls very sharply. The higher-energy part of the spectrum concerns the electrons which reach the Earth quite early, whereas the lower-energy part involves the electrons which arrive quite late. The latter have diffused in the confinement volume a much longer time and thus have lost more energy. When the distance of the source increases, the energy distribution flattens because electrons experience more energy loss when they originate from farther sources. On the other hand, when the initial energy increases, the energy distribution is naturally shifted to the right. It also flattens due to harder energy loss at high energy.

From these preliminary calculations, one can deduce the following:

- The lifetime distribution depends more on the distance of the source than the initial energy at injection;
- The contribution of a source to the observed electron spectrum is more effective if its age is around the diffusion time at the lifetime distribution maximum;
- There exist a “right timing” of electron emission for each position of the source.

Assuming the burst-like approximation, it can be argued that the lifetime of cosmic-ray electrons on arrival to the Earth is approximately equal to the age of the astrophysical source. The most likely sources of high-energy cosmic-ray electrons should hence lie very close to the curve corresponding to the variation of the diffusion time at the peak of the lifetime distribution with the distance of the source (figure 4). Superimposing nearby astrophysical sources (pulsars and SNRs) on the same graphics, one can notice that well-known objects such as Vela, Geminga, and especially Monogem, located at about 300 pc, are by far the most interesting sources. These objects are our best candidates since they have the most appropriate age for their distance.

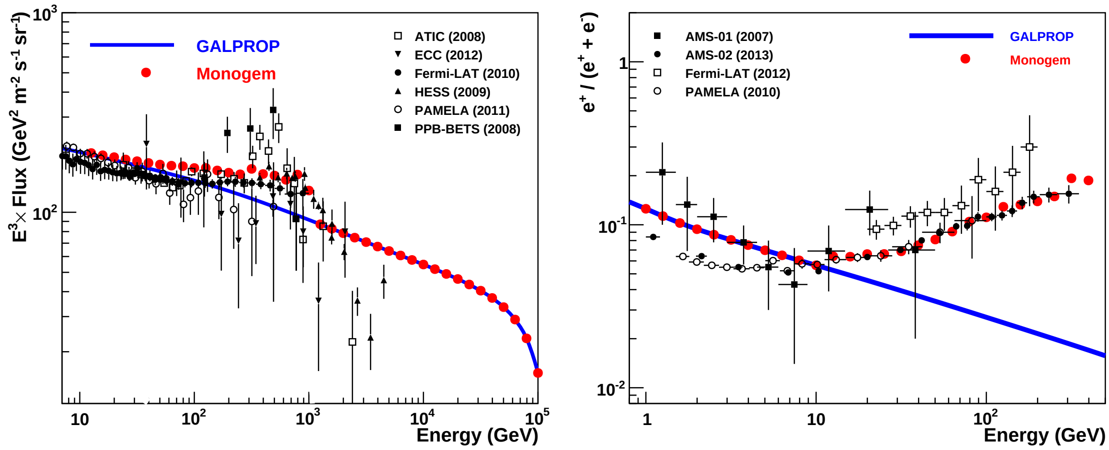

Figure 5: Calculated energy spectrum of cosmic-ray electrons reaching the Earth from Monogem pulsar (left panel) with corresponding positron fraction (right panel). In fact, the contribution from Monogem is added to the background (estimated with GALPROP) which represents the contribution from all other distant sources. The obtained results are compared with recent data [2, 3, 4, 6, 11, 12, 13, 14, 15, 16].

The "right" distance and the "right" timing is a necessary but not sufficient condition for the sources of high-energy cosmic-ray electrons. The injection energy spectrum $Q(E)$ has also a great influence on the observed electron flux. Though this quantity is not very well known, it is usually expressed as:

$$Q(E) = Q_0 E^{-\gamma} \exp(-E/E_{cut}) \tag{3.1}$$

The free parameters Q_0, γ, and $E_{\rm cut}$ are estimated on the basis of experimental or theoretical studies. The spectral index $\gamma \lesssim 2$ for pulsars and $\gamma \gtrsim 2$ for SNRs. The cutoff energy $E_{\rm cut}$ is in the range 100 GeV - 100 TeV. The parameter Q_0 is determined through the normalization:

$$\int_0^\infty Q(E)\ E\ \mathrm{d}E = \eta W \approx 10^{48}\ \ \mathrm{erg} \tag{3.2}$$

where ηW is the spin down energy of the pulsar which transforms into electron-positron pairs.

In the next step, we calculated the flux of cosmic-ray electrons from the most interesting object (according to our previous calculation), i.e. Monogem pulsar, using an appropriate combination of the free parameters ($\gamma = 2.0$, $E_{\rm cut} = 1$ TeV, and $\eta W = 10^{45}$ erg). Assuming a 2-component model, we added the contribution from Monogem to the background, represented here by the output of GALPROP (figure 5). As you can see, we can reproduce not only the hardening observed in the cosmic-ray electron spectrum by different experiments (left panel) but also the increase in the positron fraction (right panel). In particular, our results agree very well with AMS-02 data. We obtained similar results with other nearby pulsars, of course after tuning the free parameters. There is no reason that only one pulsar influences the flux of cosmic-ray electrons at high energy, especially since the lifetime distribution of the observed electrons is characterized by a very long tail. Perhaps that is the reason why anisotropy has not been observed so far.

4. Conclusion

Although there is universal agreement that the high-energy cosmic-ray electrons should originate from nearby sources, the exact nature of these sources is still very controversial. Monte Carlo simulation may be of great help in our quest for the origin of these particles, in particular, and the origin of all cosmic rays in general.

References

[1] O. Adriani et al., *An anomalous positron abundance in cosmic rays with energies 1.5-100 GeV*, Nature **458** (2009) 607 [arXiv:0810.4995].

[2] O. Adriani et al., *A statistical procedure for the identification of positrons in the PAMELA experiment*, Astropart. Phys. **34** (2010) 1 [arXiv:1001.3522].

[3] M. Ackermann et al. (Fermi LAT Collab.), *Measurement of separate cosmic-ray electron and positron spectra with the Fermi Large Area Telescope*, Phys. Rev. Lett. **108** (2012) 011103 [arXiv:1109.0521].

[4] M. Aguilar et al. (AMS Collab.), *First result from the Alpha Magnetic Spectrometer on the International Space Station: Precision measurement of the positron fraction in primary cosmic rays of 0.5-350 GeV*, Phys. Rev. Lett. **110** (2013) 141102.

[5] I. V. Moskalenko and A. W. Strong, *Production and propagation of cosmic-ray positrons and electrons*, Astrophys. J. **493** (1998) 694 [arXiv:astro-ph/9710124].

[6] J. Chang et al., *An excess of cosmic ray electrons at energies of 300-800 GeV*, Nature **456** (2008) 362.

[7] A. D. Panov et al., *Possible structure in the cosmic ray electron spectrum measured by the ATIC-2 and ATIC-4 experiments*, Astrophys. Space Sci. Trans. **7** (2011) 119 [arXiv:1104.3452].

[8] K. Yoshida et al., *Cosmic-ray electron spectrum above 100 GeV from PPB-BETS experiment in Antarctica*, Adv. Space Res. **42** (2008) 1670.

[9] M. S. Longair, *High Energy Astrophysics*, Cambridge University Press, Cambridge 2011.

[10] C. S. Shen, *Pulsars and very high-energy cosmic-ray electrons*, Astrophys. J. **162** (1970) L181.

[11] T. Kobayashi et al., *Observations of high-energy cosmic-ray electrons from 30 GeV to 3 TeV with emulsion chambers*, Astrophys. J. **760** (2012) 146 [arXiv:1210.2813].

[12] M. Ackermann et al. (Fermi LAT Collab.), *Fermi LAT observations of cosmic-ray electrons from 7 GeV to 1 TeV*, Phys. Rev. D **82** (2010) 092004 [arXiv:1008.3999].

[13] F. Aharonian et al. (HESS Collab.), *Probing the ATIC peak in the cosmic-ray electron spectrum with H.E.S.S.*, Astron. Astrophys. **508** (2009) 561 [arXiv:0905.0105].

[14] O. Adriani et al., *Cosmic-ray electron flux measured by the PAMELA experiment between 1 and 625 GeV*, Phys. Rev. Lett. **106** (2011) 201101 [arXiv:1103.2880].

[15] S. Torii et al., *High-energy electron observations by PPB-BETS flight in Antarctica*, (2008) arXiv:0809.0760 [astro-ph].

[16] M. Aguilar et al. (AMS-01 Collab.), *Cosmic-ray positron fraction measurement from 1 to 30 GeV with AMS-01*, Phys. Lett. B **646** (2007) 145 [arXiv:astro-ph/0703154].

PoS(CRISM2014)045