Investigating the origin of high-energy cosmic-ray electrons with Monte Carlo simulation

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Abstract. Due to severe radiative energy losses during propagation, high-energy cosmic-ray electrons can reach Earth only from nearby sources. Although these sources clearly manifest themselves in the special features of the energy spectrum observed by recent space-borne experiments, especially the increase in the positron fraction, their exact nature is still a matter of debate. The standard method for interpreting cosmic-ray electron data consists in solving appropriate transport equations. It can be supplemented with a Monte Carlo approach taking advantage of the intrinsic random nature of cosmic-ray diffusive propagation. This analysis gives valuable information on the electron-by-electron fluctuations and hence allows to address the issue from a different angle. Here we show how to implement a fully three-dimensional Monte Carlo simulation of the propagation of high-energy cosmic-ray electrons from nearby sources and discuss the "single-source" astrophysical scenario.

1. Introduction
High-energy cosmic-ray electrons are subject to strong energy losses, mainly by synchrotron radiation in magnetic fields and inverse Compton scattering in radiation fields [1]. As a result, they can only originate from nearby sources, which are yet to be identified. It is very likely that these sources are behind the special spectral features of cosmic-ray electrons observed very recently by several space-borne experiments (PAMELA, Fermi-LAT and AMS-02). The most noteworthy of these features is certainly the increase in the positron fraction above \( \sim 10 \text{ GeV} \) [2–5]. This remarkable result is not consistent with conventional models, which rather predict a positron fraction falling smoothly with energy [6]. Several scenarios have been put forward to account for these spectral anomalies. To some, they may be attributed to the contribution from some local sources such as supernova remnants (SNRs) [7,8] or pulsars [9,10]. For others, they can result from the annihilation or decay of dark-matter particles [11–13]. However, none of these explanations is yet conclusive [14].

The energy spectrum of cosmic-ray electrons is usually interpreted in the context of propagation models and the standard method consists of solving transport equations [15, 16]. However, the intrinsic random nature of the diffusive propagation of cosmic-ray electrons makes it possible to use Monte Carlo simulation [17]. This approach is particularly suitable at very high energy where only a few sources are expected to dominate the energy spectrum. It complements the traditional method by providing valuable information about the electron-by-electron fluctuations. Here we show how to implement a fully 3-dimensional time-dependent Monte Carlo simulation of the propagation of high-energy cosmic-ray electrons. We have considered only the energy region above 10 GeV where the solar modulation is negligible.
and focused on the astrophysical scenario, assuming a pulsar/SNR origin. We have used a two-component approach and separated the local source contribution from the contribution of distant sources [18]. The latter is estimated with the public code GALPROP [19]. To speed up calculations we have benefited from C++/MPI parallel programming on an HPC cluster system.

2. Simulation setup

Assuming homogeneous and isotropic diffusion, a single electron is injected into space from a selected source with a random three-dimensional direction. Its energy is sampled according to a power law with an exponential cutoff ($E_{\text{cut}}$),

$$Q(E) = Q_0 E^{-\gamma} \exp\left(-E/E_{\text{cut}}\right),$$

(1)

where $\gamma$ is the spectral index and $Q_0$ a normalization factor. Here $\gamma = 2$ and $E_{\text{cut}} = 5$ TeV. The path length $l$ is generated according to an exponential probability distribution ($\propto \exp(-l/\lambda)$), where $\lambda \propto E_0^{0.33}$ is the mean free path. After traveling the distance $l$, the electron energy is adjusted taking into account the energy loss rate (synchrotron+IC+bremsstrahlung) given by

$$-\frac{dE}{dt} = a_0 E + b_0 E^2,$$

(2)

with $a_0 \simeq 3.7 \times 10^{-16}$ s$^{-1}$ and $b_0 \simeq 1.3 \times 10^{-16}$ GeV$^{-1}$ s$^{-1}$ [20]. The elapsed time ($t$) is calculated by considering a delay of 20 kyr with respect to the source birth. The electron continues to propagate until it crosses a shell of 1 pc radius centered on the Sun, in which case it is recorded (observed). If the electron reaches the boundaries of the confinement region, it is discarded (free escape) and a new one is simulated starting from the source. The geometry of the confinement region has the shape of a cylindrical slab with a 20 kpc radius and a 4 kpc height. If the electron does not reach the solar system or the boundaries of the confinement volume within a maximum time of $2 \times 10^7$ yr, corresponding to a minimum energy of 10 GeV, it is also discarded and the next electron is considered.

3. Results

As a first step of our analysis, we calculated the energy spectra of the observed cosmic-ray electrons from the closest objects. As illustrated in figure 1, Monogem is predominant. B1742-30, Geminga and B1822-09 also contribute but are all weaker. By the way, the observation by HESS of a steepening in the cosmic-ray electron energy spectrum at $\sim 1$ TeV [21, 22] supports the scenario of middle-aged objects, just like Monogem, B1742-30, Geminga and B1822-09.

In the next step, we calculated the flux of cosmic-ray electrons from only Monogem. Assuming a two-component model, we superimposed the contribution from this source on the distant-source spectrum (background), given here by GALPROP [23, 24]. As can seen in figure 2, the contribution from Monogem reproduces well the increase in the positron fraction. The other candidate sources also reproduce the data, but after tuning the injection parameters.

To assess the degree of anisotropy induced by the candidate sources, we analyzed the distribution of arrival directions by using the spherical harmonic method in galactic coordinates within the framework of HEALPix [25]. Mollweide view for Monogem is illustrated in figure 3. In case of the absence of any background the obtained amplitudes of dipole anisotropy, given in table 1, are not consistent with Fermi data, which set the upper limit of $\delta$ above 60 GeV at 0.5% [26]. Obviously, the observations do not support the scenario of one single dominating source at high energy. In case of the existence of an overwhelming background (one order of magnitude higher than the source signal), the obtained values are more in line with the experimental bound. Moreover, the calculations indicate clearly that there is not just one but several key objects, namely Monogem, B1742-30, Geminga and B1822-09 (see figure 1).
Figure 1. Electron energy spectra from the candidate sources.

Figure 2. Positron fraction induced by Monogem.

Figure 3. Mollweide view of Monogem dipole anisotropy.

Monogem and Geminga are located too close on the sky dome, and so are B1742-30 and B1822-09. But the first duo is roughly diametrically opposite to the second one, which would offset the effect of anisotropy. Indeed, if we put aside Geminga and B1822-09, and assume that only Monogem and B1722-30 contribute to the electron spectrum at high energy, 50% each, the dipole anisotropy is reduced by a factor 3. In sum, the non-observation of anisotropy, which challenges to some extent the astrophysical scenario, can be explained simply if we assume the existence at high energy of at least two dominant sources in such a configuration that one cancel out the effect of the other, and/or the existence of an overwhelming background.

Table 1. Amplitude of the dipole anisotropy ($\delta$) for the candidate sources in case of the absence of any background and, in brackets, in case of the existence of an overwhelming background.

| Source      | Monogem | B1742-30 | Geminga | B1822-09 |
|-------------|---------|----------|---------|----------|
| $\delta$ (%)| 7.1 (0.8)| 1.8 (0.3)| 2.2 (0.3)| 3.6 (0.3)|
4. Conclusion
The problem of the spectral peculiarities observed at high energy for cosmic-ray electrons is generally tackled by solving the transport equation describing the galactic propagation of these particles. This work demonstrates the feasibility and the relevance of fully three-dimensional time-dependent Monte Carlo approach, which can supplement the standard method by providing additional information on the electron-by-electron fluctuations. It is particularly efficient at investigating deeply the “single-source” astrophysical scenario.

The calculations show in the first place that middle-aged nearby pulsars, such as Monogem, B1722-30, Geminga and B1822-09, may well be the best potential sources of high-energy cosmic-ray electrons. These objects reproduce correctly the high-energy spectral data. The non-observation of anisotropy, which conflicts with the thesis of one single dominant object, can be explained simply if we consider the geometrical configuration of the candidate sources. Indeed, Monogem and Geminga are located close together on the sky dome, but B1742-30 and B1822-09 are situated just in the opposite side. In this way, anisotropy can be considerably diluted. In addition, an overwhelming isotropic background, likely to arise from other distant sources, can also reduce anisotropy significantly.

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