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Contribution from individual nearby sources to the spectrum of high-energy cosmic-ray electrons

R. Sedrati*, R. Attallah

Department of Physics, Faculty of Science, Badji Mokhtar University, B.P. 12, 23000 Annaba, Algeria

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ABSTRACT

In the last few years, very important data on high-energy cosmic-ray electrons and positrons from high-precision space-born and ground-based experiments have attracted a great deal of interest. These particles represent a unique probe for studying local comic-ray accelerators because they lose energy very rapidly. These energy losses reduce the lifetime so drastically that high-energy cosmic-ray electrons can attain the Earth only from rather local astrophysical sources. This work aims at calculating, by means of Monte Carlo simulation, the contribution from some known nearby astrophysical sources to the cosmic-ray electron/positron spectra at high energy (≥ 10 GeV). The background to the electron energy spectrum from distant sources is determined with the help of the GALPROP code. The obtained numerical results are compared with a set of experimental data.

1. Introduction

High-energy cosmic rays hit the Earth atmosphere with varying degrees. The main part of this radiation is composed of protons (90%) and atomic nuclei (9%), while only a small fraction (1%) consists of electrons and positrons. However, this component provides rather different and complementary information compared to that of cosmic-ray hadrons. Indeed, cosmic-ray electrons represent unique probes for determining physical conditions in our Universe as well as for constraining current models (codes) dealing with the propagation of Galactic cosmic rays such as GALPROP, DRAGON, and USINE. Different from cosmic-ray hadrons, high-energy cosmic-ray electrons (CREs) have a steeper spectrum because of strong energy losses mainly by synchrotron radiation with Galactic magnetic fields and inverse Compton scattering with interstellar radiation fields. These energy losses restrict the distance from where they come and their lifetime with the result that they can reach us only from nearby sources (≤ 1 kpc at 1 TeV [1]).

Very recently, a new class of high-precision experiments have been set up, among which one can quote the satellite-borne experiments PAMELA, Fermi-LAT, and AMS02, the ground-based experiments H.E.S.S. and MAGIC, and the balloon-borne experiments PPB-BETS, ATIC and AESOP. The experimental data show that the energy spectrum of CREs extends well above 1 TeV and presents spectral features. Most notably, the PAMELA experiment reported a clear excess in the flux of positron fraction up to 100 GeV [2], which was confirmed later by Fermi-LAT [3] and AMS02 [4]. Most of the works proposed to explain these features rely on the well-known diffusion equation. The origin of high-energy electronic component of cosmic rays has been debated inside two main different scenarios: astrophysical sources such as supernova remnants (SNRs) and pulsars, and dark matter origin.

In this work, we investigate the observed local flux of electrons and positrons using a Monte Carlo code we have developed to

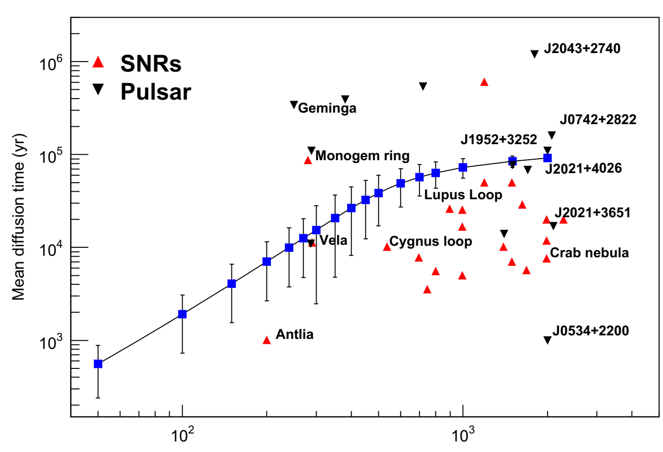

Fig. 1. Mean diffusion time of CREs as a function of the source distance (continuous line). On the same plot are shown some of the most interesting nearby SNRs and pulsars [6–8] with age and distance as coordinates.

* Corresponding author. Tel.: +213 792 61 6602.
E-mail address: rafik.sedrati@univ-annaba.org (R. Sedrati).

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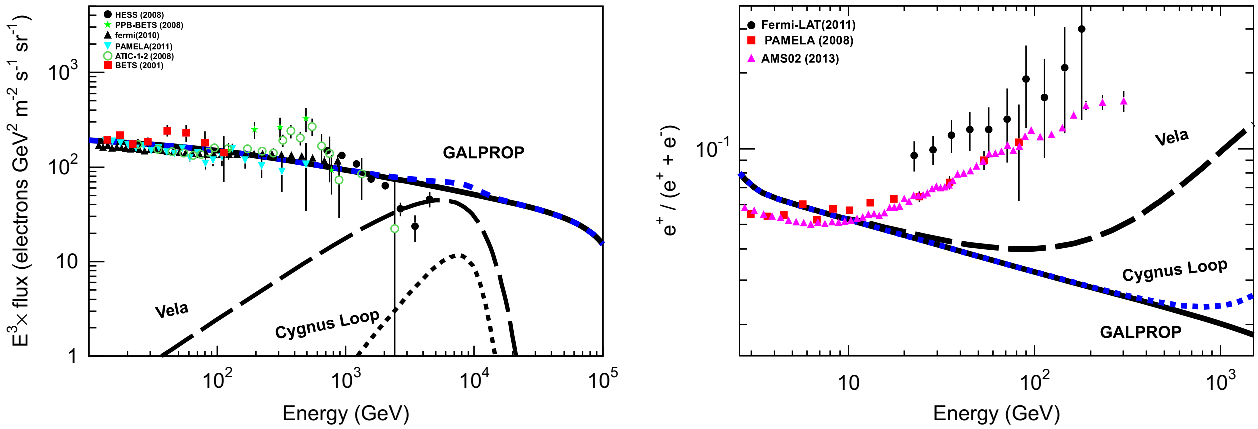

Fig. 2. Energy spectrum of cosmic-ray electrons + positron (left panel) and the corresponding positron/electron fraction (right panel) from some nearby astrophysical sources [6], assuming the same energy cutoff $E_{cut} = 10$ TeV, $Q_0 \cong 10^{48}$ ergs and varying the value γ of each source: Vela ($\gamma = 2.1$), Cygnus Loop ($\gamma = 1.2$) using the relation (1). On the same plot we show the background from distant sources determined with GALPROP and some experimental data [9].

simulate the propagation of CREs through our Galaxy. The CREs background from distant sources has been calculated with the help of the GALPROP code [5]. Several known candidate sources of primary electrons located within 2 kpc from the Earth have been considered.

2. Results and discussion

We start our Monte Carlo calculation by choosing a nearby and appropriate astrophysical source (SNR or pulsar) and fixing its characteristics (distance to the Earth and age). The injection energy spectrum, which is a key quantity, is taken according to the relation [10]

$$Q(E) = Q_0 E^{-\gamma} \exp -(E/E_{cut}) \tag{1}$$

where E is the energy. Q_0, γ and E_{cut} are free parameters selected on the basis of observation. Only energy loss by synchrotron radiation and inverse Compton scattering are considered. The rate of energy loss in this case is given by [11]

$$\frac{dE}{dt} = -bE^2 \tag{2}$$

with $b = (1.2\text{–}1.6) \times 10^{-16}$ GeV s^{-1}. Because of this strong energy loss, electrons with a primary energy in the range 10–10^4 GeV cannot be older than 10^7 years when observed at Earth. When propagating from their sources to the Earth, CREs are scattered on Galactic magnetic irregularities. The mean free path λ is related to the diffusion coefficient D according to the relation [12]

$$D = \frac{1}{3}\lambda v \tag{3}$$

where v is the velocity of the electron. In the considered energy range, the value of λ is on the order of 1–10 pc.

The background to the energy spectrum of CREs is determined with the GALPROP code version 54 [5]. For this study we have chosen the diffusion re-acceleration model [13]. The main formula characterizing this model is given by [14]

$$D(\rho) = D_0 \beta^{\eta} \left(\frac{\rho}{\rho_0}\right)^{\delta} \tag{4}$$

where $D_0 = 4.2 \times 10^{28}$ cm^2 s^{-1}, $\eta = 1$, $\rho_0 = 3$ GV, $\delta = 0.33$. ρ is the rigidity and $\beta = v_a/c$ where $v_a = 20$ km/s is the Alfven velocity [13].

Fig. 1 shows the variation of the mean diffusion time of CREs with the source distance. Within the burst-like approximation, the most appropriate astrophysical sources are those characterized by an age very close to the mean diffusion time. Thus, the closest points to the line (Fig. 1) represent the sources that can give an effective contribution to the local flux of primary cosmic-ray electrons and positrons. Fig. 2 shows the energy spectrum of CREs and the corresponding positron fraction assuming a production of an equal amount of negative electrons and positrons. This calculation shows that nearby astrophysical sources, such as Vela,Cygnus Loop are able to interpret the CRE energy spectrum.

To conclude, Monte Carlo simulation of the propagation of high-energy CREs from nearby sources is feasible and gives similar results to those obtained with the standard method based on the resolution of the transport equation for example [1]. This method can be helpful for the problem of deciding between the two scenarios of the origin of CREs, namely astrophysical sources or dark matter origin.

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R. SEDRATI and R. ATTALLAH

Department of Physics, Faculty of Science, University Badji Mokhtar,
B. P. 12, 23000 Annaba, Algeria

The Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA) has now provided a very accurate measurement of the spectrum of cosmic-ray electrons and positrons. These results are consistent with a single power-law, but visually they suggest an excess emission from about 100 GeV to 1 TeV, which leads to the emergence of a debate about the existence and the source of this excess: Could come from nearby pulsars or dark-matter annihilation? We do not know, each one has its reasons. In this work we will try to study this controversy by clarifying this spectrum using the GALPROP code.

1 Introduction

Knowledge of the primary cosmic ray electron spectrum near the earth $\leq$1kpc allows us to understand several astrophysical problems. In fact, the first hint for the existence of this type of rays in our Galaxy ($MilkyWay$)came from the interpretation in 1950 of the non-thermal radio noise[1]. The first direct observation of primary cosmic ray electrons was made in 1960 [2,3], in the energy ranges of 100 MeV to several TeV. Since then, the electron spectrum has been extensively investigated.

Before 2008, the high-energy electron spectrum E_e $\geq$10 GeV was measured by balloon borne experiments [4] and by a single space mission AMS-01 [5]. To date, we have at hand data from new instruments, such as Pamela [6], Fermi [7],H.E.S.S[8], and ATIC [9]. These measurements represent a unique probe for studying the origin and diffusive propagation of high energy cosmic-ray electrons in the interstellar medium within the GeVTeV energy range, as well as for constrain current models of the observed Galactic diffuse gamma-ray emission [10] such as the cosmic ray propagation package GALPROP [11].

In this work, we explore the possibility of interpreting the aforementioned data sets concerning the electrons spectrum by a model with reacceleration for the production and propagation of positrons and electrons in the Galaxy. In this framework, we start with obtaining a set of propagation parameters which reproduce the cosmic-ray B/C ratio, then we perform the calculation of the spectra of positrons and electrons using the GALPROP code. we compare with recent observations reported by ATIC, Fermi, HESS, and other experiments.

2 Results and discussion

In this study, we have chosen the diffusion reacceleration model, which has been used in a number of studies utilizing the GALPROP code. This model is two dimensional (2D) with cylindrical symmetry in the Galaxy, and the basic coordinates are (R, z, p) where R is Galactocentric radius, z the distance from the Galactic plane and p the total particle momentum. The propagation region is bounded by R_h= 30 kpc and vertical boundaries (halo size) $Z = z_h$. The spatial diffusion coefcient is given by [12]:

$$D_{xx} = \beta D_0 \left(\frac{\rho}{\rho_0}\right)^{\delta} \tag{1}$$

Where $D_0 = 5.5 \times 10^{28} sm^2 s^{-1}$ is a free normalization at the fixed rigidity,$\rho_0 = 4GV$. The power-law index is $\delta = 1/3$ for Kolmogorov diffusion. The main free parameter in this relation is the Alfven speed $v_0 = 30km/s$. The injection spectrum of nucleons is assumed to be a power law in momentum, $q(p) \propto p^{\gamma_0}$ the value of $\gamma = 2.4$ can vary with species.

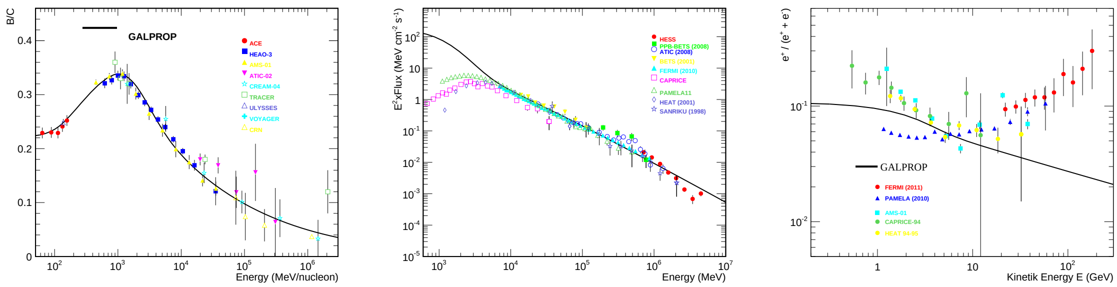

Figure 1: The *left panel* show B/C ratio which is computed by our model given above and compared with experimental data.The electron $\left(e^{+}+e^{-}\right)$ spectrum is shown for the same model in *center panel* and the corresponding positron fraction $\left(e^{+}/\left(e^{+}+e^{-}\right)\right)$ curve computed under the same conditions is shown in the *Right panel* and compared with experimental data.

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