Spectrum and fraction of cosmic ray positrons:
results of the anomalous diffusion approach

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ECRS 2014

Standard approach

Problem

- According to standard scenario, cosmic ray positrons are injected in the Galaxy only in secondary production. Under these assumptions the positron fraction should decrease when the energy increase.
- However, new experimental results obtained in the last decade by PAMELA, Fermi-LAT and AMS-02 collaborations contradict to the standard scenario predictions. An excess of positrons in cosmic rays for the energy $E > 10$ GeV in above experiments was found.

New results on the spectrum of positrons are stimulated the development of new theoretical models to explain this phenomenon. Some of these models imply the existence of a primary sources of positrons.

Motivation

On the basis of identified deviations we offer the possible directions of an expansion for the standard scenario:

1. replacement of the stationary sources model with the non-stationary model,
2. inclusion of the primary positrons sources,
3. taking into account of the nonlocal character of the particles propagation throughout turbulent (fractal-like) medium.

The main goal

Calculation of the energy spectrum of the cosmic ray electrons and positrons in the fractal-like galactic medium under diffrent assumptions about sources as well as establishment of conditions for wich the theoretical results give the self-consistent description of the modern experimental data.

Anomalous diffusion (AD) model

Anomalous diffusion equation

The equation for the concentration of particles with an energy E, generated in a fractal medium by galactic sources with a distribution density $S(\mathbf{r}, t, E)$ can be written as

$$\frac{\partial N(\mathbf{r}, t, E)}{\partial t} = -D(E, \alpha)(-\triangle)^{\alpha/2} N(\mathbf{r}, t, E) + \\ + \frac{\partial (b(E) N(\mathbf{r}, t, E))}{\partial E} + S(\mathbf{r}, t, E). \quad (1)$$

- $D(E, \alpha) = D_0(\alpha) E^{\delta}$ is the anomalous diffusivity;
- $(-\triangle)^{\alpha/2}$ is the fractional Laplacian (reflects a nonlocality of the diffusion process of particles in the interstellar medium);
- $b(E)$ is the mean rate of continuous energy losses.

In case $\alpha = 2$ we obtain the normal diffusion Ginzburg-Syrovatskii equation.

The rate of energy change

The rate of change of the energy of electrons, as well as of positrons, $b(E)$, during their propagation in the medium is attributed to ionization, inverse Compton losses, bremsstrahlung and synchrotron radiation. Here we write $b(E)$ as

$$b(E) = b_0 + b_1 E + b_2 E^2 \approx b_2 (E + E_1)(E + E_2), \tag{2}$$

where $E_1 = b_0/b_1$ and $E_2 = b_1/b_2$.

- $b_0 = 3.06 \cdot 10^{-16} n$ (GeV s^{-1});
- $b_1 = 10^{-15} n$ (s^{-1});
- $b_2 = 1.38 \cdot 10^{-16}$ (GeV$\cdot$ s)$^{-1}$ (for the magnetic field intensity $B = 5\ \mu$G and background photon density $\omega = 1$ (eV cm^{-3}).

The Green's function of the problem

The equation for Green's function

The equation for Green's function $G(\mathbf{r}, t, E; E_0)$ describing electrons and positrons diffusion under condition that the particles started from origin $\mathbf{r}_0 = 0$ at the time $t_0 = 0$ with the energy E_0 has the form

$$\frac{\partial G(\mathbf{r}, t, E; E_0)}{\partial t} = -D(E, \alpha)(-\Delta)^{\alpha/2} G(\mathbf{r}, t, E; E_0) + \\ + \frac{\partial b(E) G(\mathbf{r}, t, E; E_0)}{\partial E} + \delta(\mathbf{r})\delta(t)\delta(E - E_0). \quad (3)$$

The Green's function of the problem

The Green's function

The Green's function of the problem was derived using standard Syrovatskii substitutions and Fourier transform:

$$G(\mathbf{r},t,E;E_0) = \frac{g_3^{(\alpha)}(|\mathbf{r}|\lambda^{-1/\alpha})}{\lambda^{3/\alpha}(1-b_2t(E+E_2))^2}\times$$
$$\times\,\delta\left(E_0 - \left\{\frac{E+E_1}{1-b_1t(E+E_2)/(E_2-E_1)} - E_1\right\}\right)\times$$
$$\times\,H(1-b_2t(E+E_2))H(t). \quad (4)$$

$$\lambda(E,E_0) = \int\limits_E^{E_0(t)} \frac{D(E',\alpha)}{b(E')}dE', \quad E_0(t) = \frac{E+E_1}{1-b_1t(E+E_2)/(E_2-E_1)} - E_1.$$

$g_3^{(\alpha)}(r)$ is the probability density of three-dimentional sphericaly-symmetrical stable distribution. In case $\alpha = 2$ $g_3^{(2)}(r) \equiv$ the normal distribution (or Gaussian).

Solution of the AD equation

Point impulse source

For a point impulse source with a power energy spectrum

$$S(\mathbf{r}, t, E) = S_i E^{-p} \delta(\mathbf{r}) \Theta(T - t) \Theta(t),$$

which simulate generation of particles in supernovae, the solution has the form

$$N(\mathbf{r}, t, E) = S_i \int\limits_{\max[0, t-T]}^{\min[t, 1/b_2(E+E_2)]} dt' E_0(t')^{-p} \lambda(t', E)^{-3/\alpha} \times$$
$$\times (1 - b_2 t'(E + E_2))^{-2} g_3^{(\alpha)} \left(|\mathbf{r}| \lambda(t', E)^{-1/\alpha} \right). \quad (5)$$

Solution of the AD equation

Point steady source

For a point steady source

$$S(\mathbf{r}, E) = S_c E^{-p} \delta(\mathbf{r})$$

the solution is

$$N(\mathbf{r}, E) = S_c \int_0^{1/b_2(E+E_2)} dt' E_0(t')^{-p} \lambda(t', E)^{-3/\alpha} \times$$
$$\times \left(1 - b_2 t'(E + E_2)\right)^{-2} g_3^{(\alpha)} \left(|\mathbf{r}| \lambda(t', E)^{-1/\alpha} \right). \quad (6)$$

Energy spectrum of electrons and positrons

The particles intensity from all galactic sources was presented as

$$J(\mathbf{r}, t, E) = J_L(\mathbf{r}, t, E) + J_G(\mathbf{r}, E) = \frac{v}{4\pi} N(\mathbf{r}, t, E), \tag{7}$$

where J_L is the local component, i.e. the contribution nearby ($r \leq 1$ kpc) young ($t \leq 10^6$ yr) sources and J_G is the global spectrum component determined by the multiple old ($t \geq 10^6$ yr) distant ($r \geq 1$ kpc) sources.

$$N(\mathbf{r}, t, E) = \sum_{\substack{r_j < 1\ \mathrm{kpc} \\ t_j < 10^6\ \mathrm{yr}}} N(\mathbf{r}_j, t_j, E) + \int\limits_{\mathbf{r}=1\ \mathrm{kpc}}^{\infty} d\mathbf{r} \int\limits_{t=10^6\ \mathrm{yr}}^{\infty} dt N(\mathbf{r}, t, E)$$

Energy spectrum of electrons and positrons

Modulation effects

The fluxes of both electrons and positrons observed in the Solar system are influenced by modulation effects.
We used the model[a]

$$J_{\rm mod}(\mathbf{r}, E) = \frac{E^2 - m_e c^2}{(E + \Phi(t))^2 - m_e c^2} J\left(\mathbf{r}, E + \Phi(t)\right),$$

with the potential $\Phi = 650$ MV.

[a] Gleeson L.J. and Axford W. *ApJ*, 1968.

Sources of electrons and positrons

G-component

Distribution of the sources in the area $r > 1$ kpc was described according to standard scenario (system of steady-state sources).

L-component

To calculate the electrons and positrons spectra from nearby young sources, simulation of the Poisson ensemble of sources was carried out. The Poisson distribution parameter (average number of the sources in the local space) was chosen ~ 10. This estimation corresponds to number of the well-known nearest supernova remnants and pulsars with $t \leqslant 10^6$ yr[a,b].

Coordinates and times of birth of the sources were generated randomly and uniformly in the space region $r < 10^3$ pc and in the time interval $10^4 \leqslant t < 10^6$ yr.

Duration of the particle generation by the local sources was assumed to be $T \approx 10^4$ yr.

[a] Hooper D., Blasi P., Serpico P. D. *JCAP.*, 2009.

[b] Gendelev L., Profumo S., Dormody M. *JCAP.*, 2010.

The sources of positrons

Acceleration in SNRs. Physical mechanisms

1. The secondary production (nuclei interactions) takes place in the same region where cosmic rays are being accelerated (Blasi P. *Phys. Rev. Lett.*, 2009).
2. The nonlinear kinetic model (Berezhko E.G. and Ksenofontov L.T. *J. Phys.: Conf. Ser.*, 2013).
3. Decay of radioactive nuclei from SN ejecta $\rightarrow$ positrons $\rightarrow$ diffusive shock acceleration (Erlykin A.D. and Wolfendale A.W. *Astropart. Phys.*, 2013).

Other hypotheses

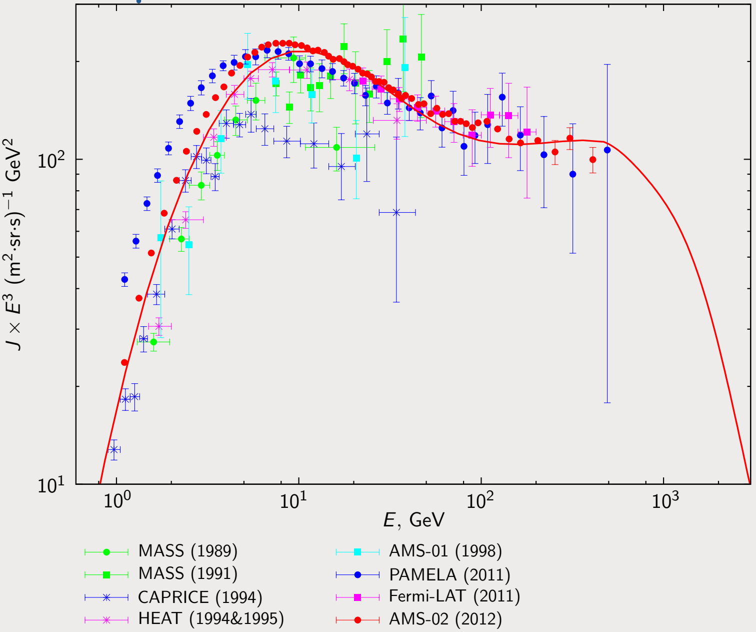
- Nearby pulsars.
- Annihilation of dark matter particles.

Parameters of the AD model

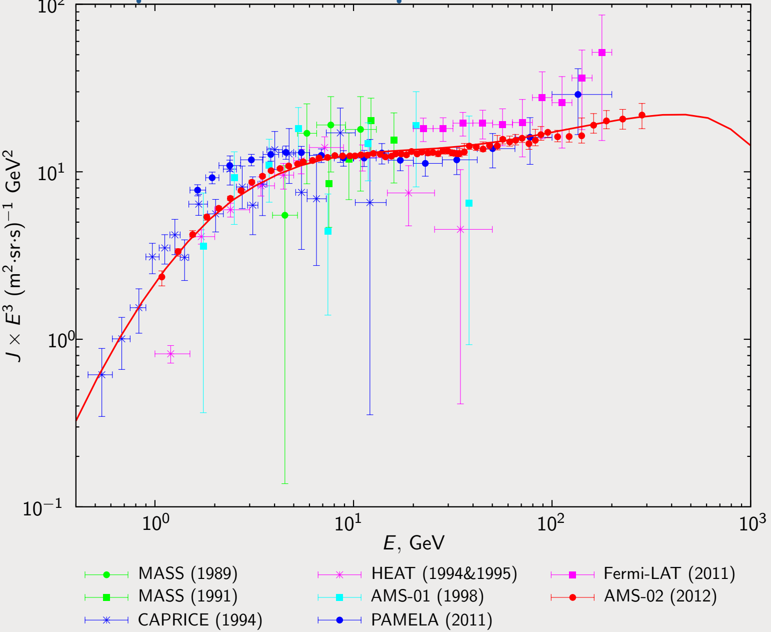
- The exponent $\alpha \approx 1.4$ (based on the results of the investigations of particles diffusion in the cosmic and laboratory plasma[a,b].
- Anomalous diffusivity $D_0(\alpha) \approx 2 \cdot 10^{-4}$ pc$^{1.4}$/yr and $\delta \approx 0.27$ (from an analysis of nuclear component of cosmic rays[c]).
- The exponent of injection spectrum $p \approx 2.85$[c].

[a] Greco A. et al. *J. Geophys. Res.*, 2003.
[b] Perri S., Zimbardo G. *J. Geophys. Res.*, 2008.
[c] Lagutin A.A., Tyumentsev A.G. *Izv. Altai. Gos. Univ.*, 2004 (in Russian).

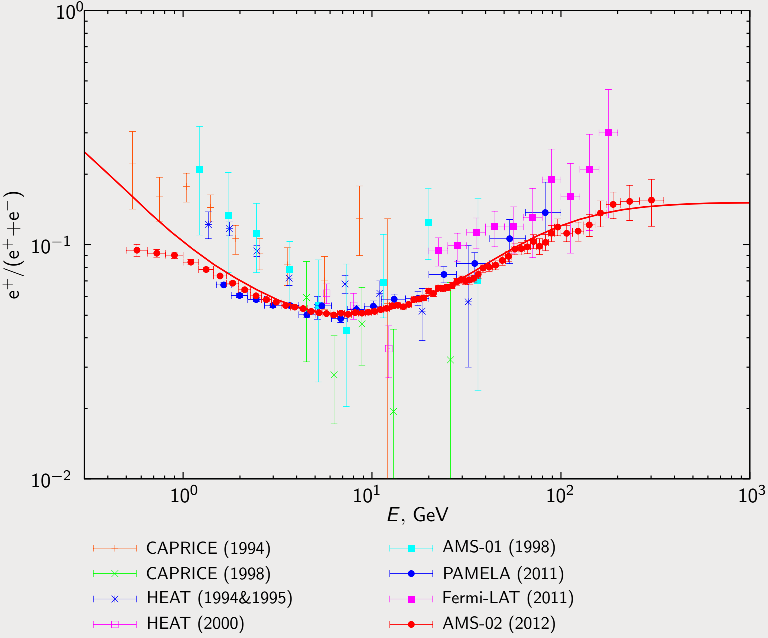
Results: Spectrum of electrons



Results: Spectrum of positrons



Results: Positrons fraction



AMS-02 'minimal model'

In the work of AMS-02 collaboration[a] the electron and positron energy spectra were described by the expression

$$\Phi_{e^\pm} = C_{e^\pm} E^{-p_{e^\pm}} + C_s E^{-p_s} \exp(-E/E_{\text{cut}}). \tag{8}$$

- First term describes the contribution of the diffuse power law spectra of electrons and positrons.
- Second term relates to the contribution of a single common (dominant) source of electrons and positrons.

[a] Aguilar M. et al. *Phys. Rev. Lett.*, 2013.

AMS-02 'minimal model'

Approximation of the AD results with 'minimal model' in the energy range $1 \div 350$ GeV (without cutoff) gives the following results.

Comparison of the AD data approximation with AMS-02 results

	AMS-02	The anomalous diffusion model
$p_{e^-} - p_{e^+}$	-0.63 ± 0.03	-0.65 ± 0.02
$p_{e^-} - p_s$	0.66 ± 0.05	0.79 ± 0.02
C_{e^+}/C_{e^-}	0.091 ± 0.001	0.097 ± 0.0008
C_s/C_{e^-}	0.0078 ± 0.0012	0.0053 ± 0.0004

Results and conclusions

We perform an analysis of the experimental data on high energy electrons and positrons, in the framework of the anomalous diffusion model. The anomaly in this model is related to the nonlocal nature of the particles diffusion process in a turbulent (fractal) Galactic medium.

Results

- The self-consistent description of the experimental data can be obtained if we assume that both positrons and electrons are injected into the interstellar medium by the sources with the same spectral exponent $p \approx 2.85$.
- Taking into account the highest accuracy AMS-02 measurements of the spectra of electrons and positrons, we have also found that the positron to electron ratio increases to a constant value of ~ 0.15 for energies $E > 300$ GeV.

Thank you for your attention!