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Where are the pevatrons that form the knee in the spectrum of the cosmic ray nuclear component around 4 PeV?

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Problem

Despite more than 100 years of research, the spatial distribution of the main cosmic rays sources and the mechanisms of particle acceleration in them have not been finally established. Today, there are no reliable experimental data confirming the fact that supernovae accelerate CR nuclei to energies of $\sim 3-4$ PeV, i.e., to the «knee» energy in the CR spectrum.

One of the most actual problem of astrophysics today is to estimate the distance to the main galactic sources — pevatrons, which form a break in the spectrum of the CR nuclear component of about $3-4$ PeV.

Solution of the problem

Main goal

We discusses an approach that made it possible to estimate the distance to the nearest pevatrons, which form a break in the spectrum of the CR nuclear component about $3-4$ PeV.

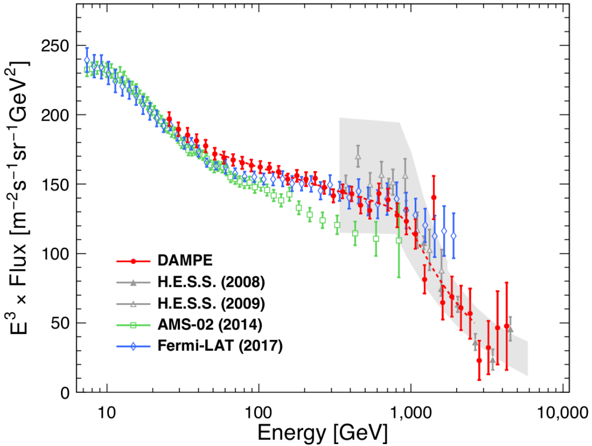
Key assumptions

- Our approach is based on the spectra of nuclei and electrons obtained by the authors in the framework of the superdiffusion model of nonclassical CR diffusion, which have a break.
- We assume that nuclei and electrons+positrons are accelerated by the same type sources and their propagation in an inhomogeneous turbulent galactic medium is characterized by the same diffusion coefficient.
- We use the fact that there is a break in the high-energy cosmic-ray electrons plus positrons spectrum in the region ~ 0.9 TeV.

Break in the CR $e^- + e^+$ spectrum

Direct measurements of high-energy cosmic-ray electrons and positrons spectra in the energy range from 25 GeV to 4.6 TeV with high energy resolution, obtained in the DAMPE experiment, made it possible to establish a break about 0.9 TeV.

An indication of the presence of an inhomogeneity in the spectrum in this energy range was previously obtained by the H.E.S.S. and Fermi-LAT.



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Nonclassical CRs diffusion

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2. Lagutin A.A., Uchaikin V. V. Anomalous diffusion equation: Application to cosmic ray transport // Nucl. Instr. and Meth. in Phys. Res. B. 2003. V. 201. P. 212.
3. Lagutin A.A., Tyumentsev A.G. Spectrum, Mass Composition, and Anisotropy of Cosmic Rays in a Fractal Galaxy // Bull ASU. 2004. Issue 5. P. 4. (in Russian)
4. Lagutin A.A., Volkov N.V. Features of the Energy Spectra of Primary and Secondary Nuclei of Cosmic Rays: A Consistent Astrophysical Interpretation // Bull. RAS. 2021. V. 85. P. 375.
5. Lagutin A.A., Volkov N.V. Non-Classical Diffusion of the Cosmic Rays in the Galaxy: Retrieval of Primary Nuclei Spectra in Sources // Physics of Atomic Nuclei. 2021. V. 84. P. 975.
6. Lagutin A.A., Tyumentsev A.G. Spectrum of Electrons in the Galaxy // Bull ASU. 2004. Issue 5. P. 22. (in Russian)
7. Lagutin A.A., Volkov N.V., Kuzmin A.S., Tyumentsev A.G. Spectrum of Electron Generation in Galactic Sources of Cosmic Rays // Bull. RAS. 2009. V. 73. P. 581.
8. Lagutin A.A., Volkov N.V., Raikin R.I. Interpretation of Fluxes of Cosmic Rays Nuclei and Electrons in the Nonclassical Diffusion Model // Bull. RAS. 2023. (in print).

Superdiffusion of CRs

The equation for the density of particles with energy E at the location **r** and time t, generated in a fractal-like medium by Galactic sources with a distribution density $S(\mathbf{r}, t, E)$ can be written as eqs. (1) and (2).

Nuclear component of CRs

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

$e^- + e^+$ component of CRs

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

$D(E, \alpha) = D_0(\alpha) E^{\delta}$ is the anomalous diffusivity;

$(-\Delta)^{\alpha/2}$ is the fractional Laplacian ("Riesz operator") (reflects a nonlocality of the diffusion process of particles in the interstellar medium);

$B(E)$ is the mean rate of continuous energy losses of electrons and positrons.

In case $\alpha = 2$ from (1) and (2) we obtain the normal diffusion Ginzburg-Syrovatskii equations.

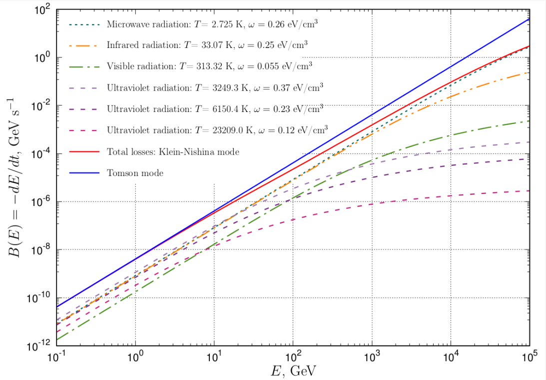
Energy losses

Energy loss mechanisms

- Ionization and bremsstrahlung.
- Synchrotron radiation.
- Inverse Compton scattering[a]:
    - microwave,
    - infrared,
    - visible,
    - ultraviolet

  radiations.

Rate of energy losses



[a] Fang K. et al. // Chin. Phys. Lett., 38(3), 039801 (2021).

Solution of superdiffusion of CRs

The solution of the superdiffusion equations (1) and (2) is found by the Green's function method for point instant source

$$S(\mathbf{r}, t, E) = S_0 E^{-p} \delta(\mathbf{r}) \delta(t).$$

Nuclear component of CRs

$$N(\mathbf{r}, t, E) = S_0 E^{-p} (D(E, \alpha) t)^{-3/\alpha} g_3^{(\alpha)} (\mathbf{r} (D(E, \alpha) t)^{-1/\alpha}). \qquad (3)$$

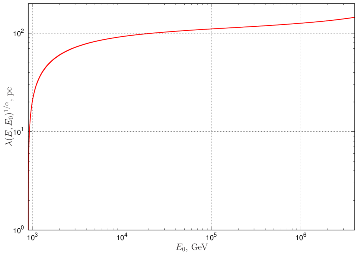
Here $g_3^{(\alpha)}(r)$ is the probability density of three-dimentional sphericaly-symmetrical stable distribution (Uchaikin V.V., Zolotarev V.M. 1999, Chance and stability, VSP. Netherlands, Utrecht.).

Solution of superdiffusion of CRs

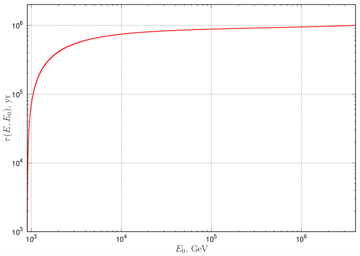
$e^- + e^+$ component of CRs

$$N(\mathbf{r},t,E)=\frac{S_0E^{-p}}{B(E)}\lambda(E,E_0)^{-3/\alpha}g_3^{(\alpha)}(\mathbf{r}\lambda(E,E_0)^{-1/\alpha}). \tag{4}$$

$$\lambda(E,E_0)=\int_E^{E_0}\frac{D(E')}{B(E')}dE'. \tag{5}$$



$$\tau(E,E_0)=\int_E^{E_0}\frac{dE'}{B(E')} \tag{6}$$



Solution of superdiffusion of CRs

Nonrelativistic case

For rate of energy losses in the form $B(E) = bE^2$ GeV/s, where $b = 1.1 \cdot 10^{-16}$ (GeV s)$^{-1}$ we find the solution

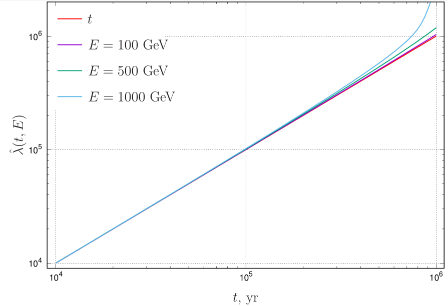
$$N(\mathbf{r}, t, E) = S_0 E^{-p} (1 - btE)^{p-2} \lambda(t, E)^{-3/\alpha} g_3^{(\alpha)}(\mathbf{r}\lambda(t, E)^{-1/\alpha}). \qquad (7)$$

$$\lambda(t, E) = D_0(\alpha) E^{\delta} \hat{\lambda}(t, E), \qquad (8)$$

$$\hat{\lambda}(t, E) = \frac{1 - (1 - btE)^{1-\delta}}{b(1-\delta)E}. \qquad (9)$$

It should be noted that in wide range of parameters

$$\lambda(t, E) = D(E, \alpha) t \qquad (10)$$



Break in the spectrum of $e^- + e^+$

To analyze the energy dependence of the electron concentration, we write solution (7) of the superdiffusion equation (2) in the form $N = N_0 E^{-\eta}$.
It follows from this representation that

$$\eta = -\frac{E}{N}\frac{\partial N}{\partial E}.$$

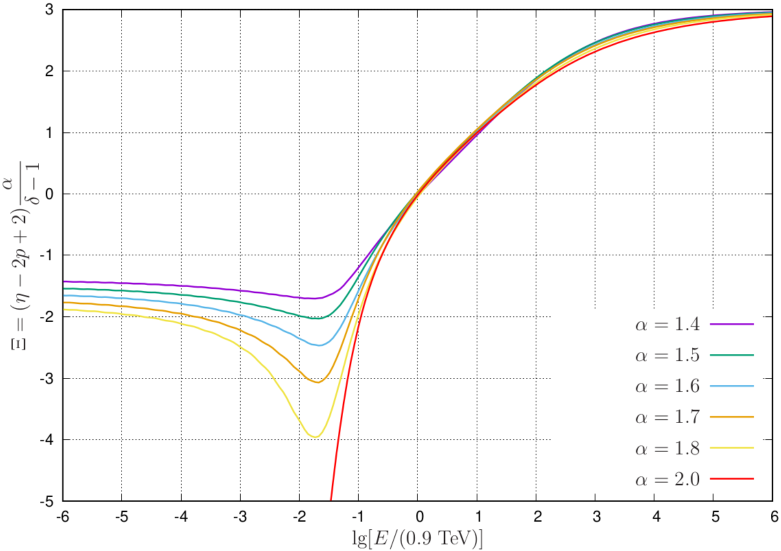
Taking into account the property of the stable law

$$\frac{dg_3^{(\alpha)}(r)}{dr} = -2\pi r g_5^{(\alpha)}(r), \tag{11}$$

we find

$$\eta = 2p-2+\frac{\delta-1}{\alpha}\left[3-\frac{2\pi r^2}{\lambda(t,E)^{1/\alpha}}\frac{g_5^{(\alpha)}(\mathbf{r}\lambda(t,E)^{-1/\alpha})}{g_3^{(\alpha)}(\mathbf{r}\lambda(t,E)^{-1/\alpha})}\right] = 2p-2+\frac{\delta-1}{\alpha}\Xi. \tag{12}$$

Break in the spectrum of $e^- + e^+$



The break points of the n and e components

Subtotal

In the framework of the superdiffusion model of nonclassical CRs diffusion, spectrum have a break. This break is due to the presence of a break in the stable distribution $g_3^{(\alpha)}(r)$ at the value of the argument $r \approx 2.2$.

n component:

$$N(\mathbf{r}, t, E) \sim g_3^{(\alpha)}\left(\mathbf{r}(D(E,\alpha)t)^{-1/\alpha}\right) \Rightarrow \mathbf{r}_n(D_0(\alpha)E_n^\delta t_n)^{-1/\alpha} = 2.2$$

e component:

$$N(\mathbf{r}, t, E) \sim g_3^{(\alpha)}\left(\mathbf{r}\lambda(t,E))^{-1/\alpha}\right) \Rightarrow \mathbf{r}_e(D_0(\alpha)E_e^\delta \hat{\lambda}(t_e, E_e))^{-1/\alpha} = 2.2$$

We assume that nuclei and electrons+positrons are accelerated by the same type sources. Due to this assumption

$$\mathbf{r}_n(D_0(\alpha)E_n^\delta t_n)^{-1/\alpha} = \mathbf{r}_e(D_0(\alpha)E_e^\delta \hat{\lambda}(t_e, E_e))^{-1/\alpha}. \tag{13}$$

The break points of the n and e components

It follows from the eq. (13) that

$$\mathbf{r}_n(E_n^\delta t_n)^{-1/\alpha} = \mathbf{r}_e(E_e^\delta \hat{\lambda}(t_e, E_e))^{-1/\alpha},$$

or

$$\mathbf{r}_n = \mathbf{r}_e \left[\left(\frac{E_n}{E_e} \right)^\delta \frac{t_n}{\hat{\lambda}(t_e, E_e)} \right]^{1/\alpha} \equiv \mathbf{r}_e \xi. \tag{14}$$

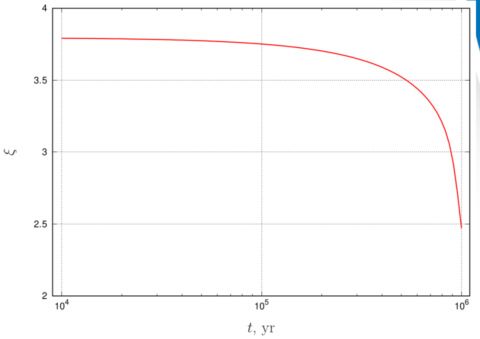
The estimates obtained within the framework of the proposed approach are almost diffusion model independent.

The break points of the n and e components

Parameters

- Sources of nuclei and electrons accelerate particles during a time equal to $t_n = t_e \approx 10^5$ yr.
- $E_n = 1$ PeV, $E_e = 0.9$ TeV.

p	2.85
α	1.7
$D_0(\alpha)$	10^{-3} pc$^{1.7}$/yr
δ	0.27



Results

$$\mathbf{r}_n = 3.75\mathbf{r}_e.$$

Results and conclusions

- Since the rate of energy loss is $B(E) = bE^2$ GeV/s, the "lifetime" of the CR electrons is described by the expression

$$t = E/B(E) \approx 3 \cdot 10^8 (E/1\ \text{GeV})^{-1}\ \text{yr}. \tag{15}$$

- It follows from this that the TeV-energy electrons observed on Earth were produced by sources $\sim 10^5$ years ago.
- During this time, in the superdiffusion mode $\overline{r^2} \sim 2D(E,\alpha)t^{3-\alpha}$, diffusion radius $r \sim 200$ pc.
- From the relation $\mathbf{r}_n = 3.75\mathbf{r}_e$ we obtain that **pevatrons, which form a break in the spectrum of the nuclear component of cosmic rays of about $3-4$ PeV, are located at distances of the order of 0.75 kpc from the Earth**.

Thanks

Questions and Comments

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Template of this presentation `https://github.com/deuslirio/UFGTeX-Presentation`

The most likely candidates for pevatrons

Source	r, pc	$t, 10^5$ yr
Monoceros	600	0.46
Cyg. Loop	770	0.20
CTB 13	600	0.32
S 149	700	0.43
STB 72	700	0.32
CTB 1	900	0.47
HB 21	800	0.23
HB 9	800	0.27