Synchrotron radiation of cosmic ray electrons in the anomalous diffusion model

V. V. BUGAYOV[1], A. A. LAGUTIN[2], A. G. TYUMENTSEV[2], N. V. VOLKOV[2], A. S. KUZMIN[2].
[1] *Department of Physics, Washington University, St. Louis, MO, 63130 USA*
[2] *Department of Theoretical Physics, Altai State University, Barnaul, Lenin Ave. 61, 656049, Russia*
tyumentsev@theory.asu.ru

Abstract: A new study of the cosmic ray electron and synchrotron spectra is presented. Anomalous diffusion model, proposed in our recent papers, is used to describe the particles propagation in fractal-like interstellar medium. The parameters defining the anomalous diffusion have been determined from the analysis of nuclear component. We carried out calculation of the synchrotron spectrum in the frequency range $\sim$ 2 MHz – 2 GHz (corresponding to energies of electrons $\sim 0.2 - 6$ GeV). The computed electron and synchrotron spectra are in a good agreement with the experimental data.

Introduction

The studies of the electron component of cosmic rays and their resulting non-thermal synchrotron radiation in galactic magnetic fields allows to obtain information on the origin, acceleration and propagation of particles in the cosmic objects. Calculations of electron spectrum and spectrum of the non-thermal synchrotron radiation were considered in series of papers (see, for example, [1, 4, 15, 17, 21]). In this work we consider propagation of cosmic ray electrons in the context of anomalous diffusion model, which recently was discussed in the papers [9, 10, 13, 14]. It has been shown that the "knee" in the primary cosmic ray spectrum could be due to large free paths (the so called "Levy flights") of cosmic rays particles between inhomogeneities of magnetic fields – "traps" of the various type. The "Levy flights" are distributed according to inverse power law $\propto Ar^{-3-\alpha}, r \to \infty, \alpha < 2$, where exponent α is defined by fractal features of the interstellar medium.

In [8, 9, 12] an anomalous diffusion (superdiffusion) equation for concentration of the electron in the fractal-like interstellar medium was proposed. This equation has the following form

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

where $D(E,\alpha)$ is the anomalous diffusivity and $(-\triangle)^{\alpha/2}$ is the fractional Laplacian (called "Riss operator" [18]).

The main goal of this paper is calculation of electron and synchrotron spectra in the framework of anomalous diffusion model. To solve this problem we resort to two-component model [8, 9, 12]. The sources were separated into two categories: local sources and distant sources, which provides stationary regime of injection.

Spectrum of cosmic ray electrons

For a point impulse source with the power-law energy spectrum $S(\vec{r},t,E) = S_0 E^{-p}\delta(r)H(T-t)H(t)$ that simulates the process of generation of particles in the nearby young sources (so called local component (L), $r \leq 1$ kpc, and injection time $T \approx 10^4$ yr) a flux of electrons is written as [8, 9, 12]

$$J_L(\vec{r},t,E) = S_0 \int\limits_{\max[0,t-T]}^{\min[t,1/b_2(E+E_2)]} d\tau E_0(\tau)^{-p} \\ \lambda(E,E_0(\tau))^{-3/\alpha}(1-b_2\tau(E+E_2))^{-2} \times \\ \times g_3^{(\alpha)}(\mathrm{r}\lambda(E,E_0(\tau))^{-1/\alpha}). \quad (2)$$

The flux from the distant sources (global component (G), $r > 1$ kpc) is obtained from the steady-

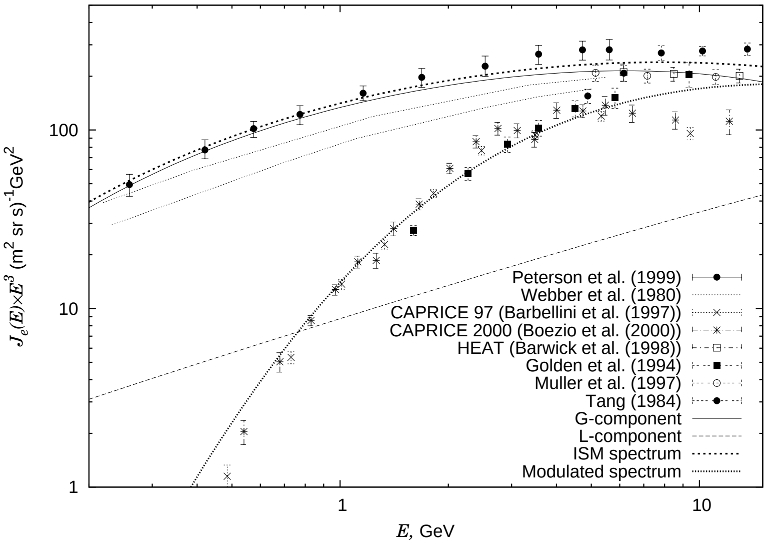

Figure 1: L- and G- components and total energy spectrum of electrons. Experimental data are reported in [2, 3, 5, 7, 16, 17, 19, 21].

state model [9, 12]

$$J_G(\mathrm{r},E) = \frac{S_0}{b(E)}\int\limits_E^\infty dE_0 E_0^{-p}\times$$
$$\lambda(E,E_0)^{-3/\alpha} g_3^{(\alpha)}(\mathrm{r}\lambda(E,E_0)^{-1/\alpha}). \qquad (3)$$

In eq. 2 and eq. 3 $g_3^{(\alpha)}(r)$ is the density of three-dimensional spherically-symmetrical stable distribution with characteristic exponent $\alpha < 2$ [20, 22]. Equation for $E_0(\tau)$ has been presented in form [1]

$$E_0(\tau) = \frac{E+E_1}{1-b_1\tau(E+E_2)/(E_2-E_1)} - E_1,$$

and

$$\lambda(E,E_0(\tau)) = \int\limits_E^{E_0(\tau)} \frac{D(E',\alpha)}{b(E')}dE',$$

where

$$b(E) = b_0 + b_1E + b_2E^2 \approx$$
$$\approx b_2(E+E_1)(E+E_2). \qquad (4)$$

Eq. 4 gives the energy-loss rate of relativistic electrons [1], where $b_0 = 3.06\cdot 10^{-16}n$ (GeV s^{-1}) is for ionization losses in interstellar medium, b_1E with $b_1 = 10^{-15}n$ (s^{-1}) corresponds to the bremsstrahlung energy losses, and b_2E^2 with $b_2 = 1.38\cdot 10^{-16}$ (GeV s)$^{-1}$ represents synchrotron and inverse Compton losses (for $B_\perp \approx 5\mu$G and $\omega \approx 1$ (eV/cm^3)), $E_1 \approx b_0/b_1$, $E_2 \approx b_1/b_2$. As a result the flux of electrons from all types of galactic sources may be presented as

$$J_e(\mathrm{r},E) = \sum_{r\leq 1\mathrm{kpc}} J_L(\vec{r}_i,t_i,E) + J_G(\mathrm{r},E). \qquad (5)$$

The nearby sources characteristics, used in our calculations are given in [12].

The parameters defining the anomalous diffusivity and used in our work have been recently derived from the studies of nuclei propagation [11]: $\alpha = 0.7$, $D(E,\alpha) = D_0E^\delta$ where $D_0 = 2\cdot 10^{-5}\mathrm{pc}^{0.7}\mathrm{yr}^{-1}$ and $\delta = 0.27$. Our calculations show that the best agreement with the experimental data may be obtained if electrons are generated by sources with a spectrum $S \propto E^{-2.6}$ (Fig. 1).

For description of the spectrum in low-energy range near solar system it is necessary to take into account an effect of solar modulation. The solar

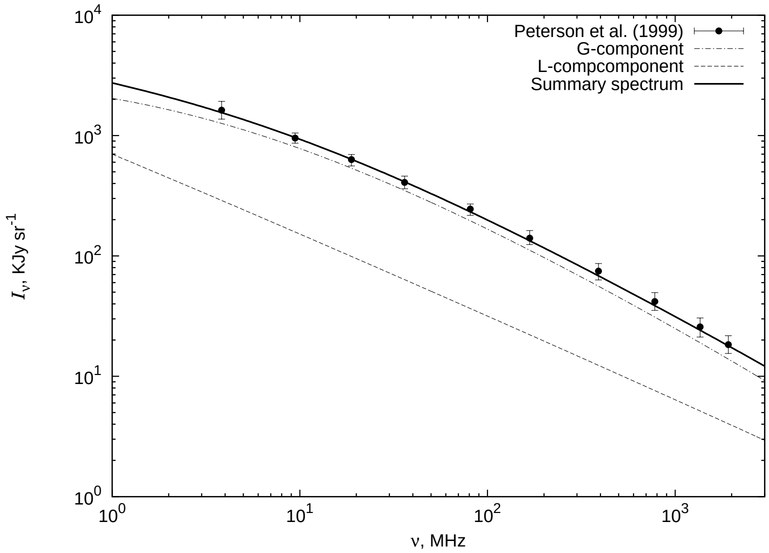

Figure 2: Synchrotron radiation spectrum. Experimental data are taken from [17].

modulation is calculated as [5]

$$J_{mod}(\mathrm{r}, E) = \frac{E^2 - m_e c^2}{[E + \Phi(t)]^2 - m_e c^2} \times \times J_e\left(\mathrm{r}, E + \Phi(t)\right), \qquad (6)$$

where $\Phi(t) = 600$ MeV. Results of calculations of cosmic ray electrons spectrum in ISM and the modulated spectrum in low-energy range are demonstrated in Fig. 1.

Synchrotron radiation spectrum

The synchrotron radiation emitted by relativistic electrons is the most important diagnostic available for the study of the transport of these particles in the interstellar medium.

Intensity of synchrotron radiation I_ν at a given frequency ν is defined by average density of electrons $\rho_e(E) = \int dz J_e(\mathrm{r}, E)$ (z is measured along the line of observation), and equals to [4]

$$I_\nu = \int P_\nu(E) \rho_e(E) dE,$$

where $P_\nu(E)$ is the intensity of radiation at a frequency ν of single electron with the energy E.

For $E >> m_e c^2$ the function $P_\nu(E)$ has the peak at a frequency [6]

$$\nu_m(\mathrm{MHz}) = 16.0 B_\perp(\mu\mathrm{G}) E^2(\mathrm{GeV}).$$

For our purpose (calculation of synchrotron radiation spectrum), it is sufficient to use the delta-approximation in the form $P_\nu(E) = P_0 \delta(\nu - \nu_m)$.

As a result, the intensity of synchrotron radiation is given by the expression [6]

$$I_\nu = P_0 \int dz J_e(\mathrm{r}, E). \qquad (7)$$

The synchrotron spectrum, calculated by eq. 7 with parameters $p \approx 2.6$ and $\alpha = 0.7$ is shown in Fig. 2.

Conclusion

We have carried out new calculations of synchrotron radiation spectra using an anomalous diffusion model to describe cosmic ray electrons propagation in the Galaxy. Comparison of results of calculations of the synchrotron spectrum in the frequency range $\sim$ 2 MHz – 2 GHz (corresponding to energy of electrons $\sim 0.2 - 6$ GeV) with the experimental data allowed us to obtain the conclusion on the spectrum power index of the cosmic ray electrons in the low-energy region. Extensive calculations of the cosmic ray electron and synchrotron spectra show that the best fit of experimental data may be obtained for $p \approx 2.6$.

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References

[1] A. M. Atoyan, F. A. Aharonjan, and H. J. Völk. Electrons and positrons in the galactic cosmic rays. *Phys. Rev. D.*, 52:3265–3275, 1995.

[2] G. Barbiellini, G. Basini, and R. Belotti et al. Measurements of the positron and electron spectra with the CAPRICE experiment. In *Proc. of the 25th ICRC*, volume 4, pages 221–224, 1997.

[3] S. W. Barvick, J. J. Beatty, and C. R. Bower et al. The energy spectra and relative abundances of electrons and positrons in the galactic cosmic radiation. *ApJ*, 498:779–789, 1998.

[4] V. S. Berezinsky, S. V. Bulanov, and V. L. Ginzburg et al. *Astrophysics of cosmic rays*. North Holland, Amsterdam, 1990.

[5] M. Boezio, P. Carlson, and T. Francke et al. The cosmic ray electron and positron spectra measured at 1 AU during solar minimum activity. *ApJ*, 532:653–669, 2000.

[6] V. L. Ginzburg and S. V. Syrovatskii. *Origin of cosmic rays*. Pergamon Press, 1964.

[7] R. L. Golden, C. Grimani, and B. L. Kimbell et al. Observations of cosmic ray electrons and positrons using an imaging calorimeter. *ApJ*, 436:769–775, 1994.

[8] A. A. Lagutin, K. I. Osadchiy, and V. V. Gerasimov. Spectra of cosmic ray electrons and positrons in the Galaxy. *Problems of Atomic Science and Technology*, 6:209–213, 2001.

[9] A. A. Lagutin, K. I. Osadchiy, and D. V. Strelnikov. Propagation of cosmic ray electrons in the Galaxy. In *Proc. of the 27th ICRC*, volume 5, pages 1889–1891, 2001.

[10] A. A. Lagutin, D. V. Sterlnikov, and A. G. Tyumentsev. Mass composition of cosmic rays in anomalous diffusion model: comparison with experiment. In *Proc. of the 27th ICRC*, volume 5, pages 1896–1899, 2001.

[11] A. A. Lagutin and A. G. Tyumentsev. Spectrum, mass composition and anizotropy of cosmic rays in the fractal Galaxy. *Izv. Altai. Gos. Univ.*, 35(4):4–21, 2004 (in Russian).

[12] A. A. Lagutin and A. G. Tyumentsev. Spectrum of electrons in the Galaxy. *Izv. Altai. Gos. Univ.*, 35(4):22–26, 2004 (in Russian).

[13] A. A. Lagutin, A. G. Tyumentsev, and A. V. Yushkov. Energy spectrum and mass composition of primary cosmic rays in the vicinity of the "knee" in a model with two types of sources. *Bulletin of the Russian Academy of Sciences: Physics*, 71, No. 4:590–592, 2007.

[14] A. A. Lagutin and V. V. Uchikin. Anomalous diffusion equation: Application to cosmic ray transport. *NIM B*, 201:212–216, 2003.

[15] I. V. Moskalenko and A. W. Strong. Production and propagation of cosmic rays positrons and electrons. *ApJ*, 493:694–707, 1998.

[16] D. Muller, S. W. Barvick, and J. J. Beatty et al. Energy spectra of electrons and positrons from 5 to 100 GeV. In *Proc. of the 25th ICRC*, volume 4, pages 237–240, 1997.

[17] J. D. Peterson, P. R. Higbie, and J. M. Rockstroh. A new look at galactic polar radio emission and the local interstellar electron spectrum. In *Proc. of the 26th ICRC*, volume OG 3.2, pages 17–20, 1999.

[18] S. G. Samco, A. A. Kilbas, and O. I. Marichev. *Fractional integrals and derivatives — Theory and Applications*. Gordon and Breach, New York, 1993.

[19] K. Tang. The energy spectrum of electrons and cosmic ray confinement: a new measurements and its interpretation. *ApJ*, 278:881–892, 1984.

[20] V. V. Uchaikin and V. M. Zolotarev. *Chance and stability*. VSP. Netherlands, Utrecht, 1999.

[21] W. R. Webber, G. A. Simpson, and H. V. Cane. Radio emission, cosmic ray electrons, and the production of γ-rays in the Galaxy. *ApJ*, 236:448–459, 1980.

[22] V. M. Zolotarev, V. V. Uchaikin, and V. V. Saenko. Superdiffusion and stable law. *ZhETF*, 115:1411–1425, 1999 (in Russian).