Explanation of the knee in the galactic cosmic-ray spectrum

Volodymyr Kryvdyk,[1]
(1) Depart. of Astronomy, Kyiv University, Glushkova 6, 03022, Kyiv, Ukraine

Abstract

A model of cosmic ray propagation is proposed to explain the knee of the cosmic ray energy spectrum in the energy range E =10ˆ14 -10ˆ17 eV. The numerous stellar winds (SW), ionized hydrogen regions (H-II) and supernova remnants (SNR) in the Galaxy are taken into account in this model. The gas density and the magnetic field in these regions are different from the interstellar gas density and the interstellar magnetic field. Therefore they act as scattering centres and magnetic traps for cosmic rays. It is shown that these regions influence cosmic ray propagation in the Galaxy. Our results show that the collision time between cosmic rays and the SNR, SW, and H-II regions is much less than the cosmic ray lifetime in standard models [4,8], in which only the nuclear interaction of the particles with interstellar gas is taken into account. Cosmic ray energies, and thus the cosmic ray spectrum, change due to interactions with these regions.

1. Cosmic-ray propagation in the Galaxy

As assumed, the supernova remnants are the main cosmic-ray sources in the Galaxy [4,6,7,8,14]. The cosmic rays accelerate in the pulsars magnetospheres and the supernova shocks. The accelerated charged particles will pass a some time T_o in SNRs and later on their go out in the interstellar space. After the some time T the cosmic rays escape the Galaxy and go out in the intergalactic space. The cosmic rays loss their energy in consequence of 1) the bremsstrahlung losses in magnetic fields $(\frac{dE}{dt})_{oM}$, 2) adiabatic cooling in expanding regions $(\frac{dE}{dt})_{oA}$, 3) the nuclear interactions with the gas $(\frac{dE}{dt})_{oA}$ and 4) the cosmic-ray outflow from the regions$(\frac{dE}{dt})_{oE}$. The rations between the energy losses for the different mechanisms in the interstellar matter can be written as [11] $J_{1G} = (\frac{dE}{dt})_{oE}/(\frac{dE}{dt})_{oN} \approx 6$, $J_{2G} = (\frac{dE}{dt})_{oE}/(\frac{dE}{dt})_{oM} \approx 10^{25}/E$, $J_{3G} = (\frac{dE}{dt})_{oE}/(\frac{dE}{dt})_{oA} \geq 7$. For SNRs $4.10^2 \leq J_{1s} \leq 10^9$, $2.10^{21}/E \leq J_{2s} \leq 6.10^{24}/E$, $J_{3s} > 1$.

Suppose, in the Galaxy are N_i the sources type i with the volume V_i and power $Q_i(E,t)$. For the cosmic-ray concentration in the Galaxy can be written [11] $n_G = \sum_{i=1}^{N_i} n_i \frac{V_i}{V_G}\frac{T_G}{T_i}$ For our model in which the main cosmic-ray sources in the Galaxy are SNRs, $n_G = N_s n_s \frac{V_s}{V_G}\frac{T_G}{T_s}$,where N_s is the number SNRs in Galaxy. For the particles lifetime in the magnetic trap with radius R_i, having

pp. 295–298

the magnetic field H_i and the magnetic heterogeneities with the radius li , we can written [5,8] $T_i(E) \propto E^{-\mu_i(E)}$,where $\mu_i(E) = 0$ for $R_i >> l_i \geq r_{H_i}$; $\mu_i(E) = \mu_i$ for $R_i >> r_{H_i} \geq l$; $\mu_i(E) = 0$ for $r_{H_i} >> R_i \geq l_i$. Here $r_{H_i}(cm) = E(eV)/300H_i(G)$ is Larmor radius. For the Galaxy as the magnetic trap $H_G \approx 1\mu G$, $R_G \approx 10^{22}cm$, $l_G \approx 3.10^{19}cm$.For the such parameter $\mu_G(E) = 0$ for $E \leq 3.10^{15}eV$; $\mu_G(E) = \mu_G$ for $3.10^{15}eV < E \leq 3.10^{17}eV$; $\mu_G(E) = 0$ for $E > 3.10^{17}eV$.

Now we consider the cosmic- ray propagation in supernova remnants . SNRs are the magnetic traps with the unstable parameters, however for the each fixed time moment SNRs can be considered as the stable traps. The SNR radius increase with the time, therefore we can write$T_s(E,t) \propto R_s(t)E^{-\mu_s(E)}$. For SNRs $10^{15}cm \leq R_s \leq 10^{20}cm$; $10\mu G \leq H_s \leq 1G$; $10^{11}cm \leq l_s \leq 10^{16}cm$. For the such SNR $\mu_s(E) = 0$ for $E \leq 3.10^{13}eV$; $\mu_s(E) = \mu_s$ for $3.10^{13}eV < E \leq 3.10^{17}eV$; $\mu_s(E) = 0$ for $E > 3.10^{17}eV$. SNR radius increase with time as [9,12,15,] $R_s \propto t^{\varepsilon(t)}$, where $\varepsilon = 1$, $\varepsilon = 2/5$, $\varepsilon = 1/4$ accordingly for the stages I, II, III. Therefore $T_s(E) \propto t^{\varepsilon(t)}E^{-\mu_s(E)}$ Now we consider the evolution of the cosmic-ray spectrum accelerating in pulsar and later on passing in supernova remnant. The particle spectrum accelerating in pulsar magnetosphere is $n_s(E,t) \propto t^{-\alpha}E^{-\gamma_o}$.where t is the lifetime pulsar, α is the pulsar luminosity index (for pulsar NP 0532 in the Crab nebula $\alpha \approx 2,3$). This particle spectrum transform due to the propagation both in SNRs and the interstellar medium. For our model this spectrum to look like $n_G(E,t) \propto N_s(R_i(t))n_s(E,t)\frac{V_s(R_i(t))}{V_G}\frac{T_G(E)}{T_s(E,t)}$. The numbers of SNRs in the Galaxy are [12, 15] $N_s(R_s(t)) \propto R_s^{1/\varepsilon(t)} \propto t$.The SNR volume $V_s(R_s(t)) = 4\pi R_s^3(t)/3 \propto t^{3\varepsilon(t)}$. Then we obtain $n_G(E,t) \propto t^{1-\alpha+2\varepsilon(t)}E^{-\gamma_o-\mu_G(E)+\mu_s(E)}$.

For the above parameters $\alpha, \varepsilon, \mu_G, \mu_{SNR}$ the cosmic-ray concentration $n_G(E,t) \propto t^{0,7}E^{-\gamma(E)}$ for the stage I; $n_G(E,t) \propto t^{-0,5}E^{-\gamma(E)}$ for the stage II, $n_G(E,t) \propto t^{-0,8}E^{-\gamma(E)}$ for the stage III.

Here $\gamma(E) = \gamma_o$ for $E \leq 3.10^{13}eV$; $\gamma(E) = \gamma_o - \mu_s$ for $3.10^{13}eV < E \leq 3.10^{15}eV$; $\gamma(E) = \gamma_o - \mu_s + \mu_G$ for $3.10^{15}eV < E \leq 3.10^{17}eV$, $\gamma(E) = \gamma_o$ for $E > 3.10^{17}eV$.

As follows from these results, the cosmic-ray spectrum in the interstellar medium will change essentially due to the propagation in Galaxy. The cosmic-ray spectrum with the energy $E \leq 3.10^{13}eV$ and $E > 3.10^{17}eV$ not change due to the propagation both in SNR and in interstellar medium. The cosmic rays with the energy $3.10^{13}eV < E \leq 3.10^{15}eV$ change their spectrum due to their propagation in supernova remnants. For the cosmic rays with energy $3.10^{15}eV < E \leq 3.10^{17}eV$ the spectrum change due to their propagation both in SNRs and in the interstellar medium.

The parameters γ_o, μ_G, μ_s may be estimate,.using the experimental date about of the cosmic-ray spectrum. The experimental cosmic-ray spectrum in the near-Earth space is [1,2,3,4,10,13], $n(E) \propto E^{-\gamma(E)}$,where $\gamma(E) = 2.7$ for $E \leq 3.10^{13}eV$; $\gamma(E) = 2.4 \div 2.7$ for $3.10^{13}eV < E \leq 3.10^{15}eV$, $\gamma(E) = 3.4$ for $3.10^{15}eV < E \leq 3.10^{17}eV$, $\gamma(E) = 2.7$ for $E > 3.10^{17}eV$. From these results we obtain $\gamma_o = 2.7$, $\mu_G = 1$, $\mu_s = 0.0 \div 0.3$.

As follows from the comparison of the obtaining theoretical spectrum and the experimental spectrum , these spectrums well agree. The both spectrum have the same values of energy $E_1 \approx 3.10^{13}eV$, $E_2 \approx 3.10^{15}eV$, $E_1 \approx 3.10^{17}eV$ where the power index of the spectrum will change. This fact conform our model of the propagation and formation cosmic-ray spectrum in Galaxy.

2. Conclusions

From obtaining results we can to draw the next conclusions.. The initial cosmic-ray spectrum in sources change due to its propagation both in the sources and the interstellar medium. If the initial cosmic-ray spectrum in sources is power-series with the constant index γ_o, then later on this spectrum transform due to the propagation in the interstellar medium in the spectrum with the power-index depending on the particle energy $\gamma = \gamma(E)$. The spectrum for the cosmic ray with energy $E \leq 3.10^{13}eV$ and $E > 3.10^{17}eV$ not change due to their propagation both in SNRs and the interstellar medium since in this case the cosmic-ray lifetime not depend on the energy both for SNR and the Galaxy. For cosmic rays with the energy $3.10^{13}eV < E \leq 3.10^{15}eV$ the spectrum change due their propagation in SNRs. For the cosmic rays with the energy $3.10^{15}eV < E \leq 3.10^{17}eV$ the spectrum will change due to their propagation both in SNRs and in the interstellar medium. As result the cosmic-ray spectrum near Earth differ from their spectrum in the sources. The power-index of the cosmic-ray spectrum will change due to their propagation, and the knee will arise in the energy range $E \propto 10^{14} - 10^{17}eV$. Just this knee we observed in the cosmic-ray spectrum near Earth.

3. References

1. Abu -Zayyad, T.. et all. 2001, ApJ, 556, 686
2. Apanasenko, A.V. et al, 2001a, in Proc. 27th ICRC., Hamburg, Germany, 07-15 Aug. 2001, p.1626
3. Apanasenko, A. V.. et al, 2001b, Astropart. Phys., 16, 13
4. Berezinskii, V. S.et al. 1984, The astrophysics of cosmic rays (Izdatel'stvo Nauka, Moscow. In Russian)
5. Dorman, L.I. 1975, in Experimantal and theoretical fundamentals of the astrophysics of cosmic-ray (Izdatel'stvo Nauka, Moscow. In Russian)
6. Erlykin, A. D., Wolfendale, A. W., 2001, AdSpR, 27, 803

7. Erlykin, A. D., Wolfendale, A. W., 2000, A&A, 356, L63
8. Ginzburg, V.L., Syrovatskii, S.I., 1963, Origin of cosmic rays (Izdatel'stvo AN USSNR, Moscow. In Russian). (English: Ginzburg, V. L., Syrovatskii, S. I.,1964, *The* Origin of Cosmic Rays , Macmillan, New York)
9. Gorbatskii, V.G. 1977, Space gas dynamics (Izdatel'stvo Nauka, Moscow. In Russian)
10. Hillas, A.M. 1974, Phil.Trans. Roy., A277, 413
11. Kryvdyk, V. 2002 , A&A, 400, 1
12. Lozinskaia, T.A. 1986, Supernovae and stellar wind: interaction
13. Muraishi, H., Yanagita, S., Yoshida, T., 2001, in Proc. 27th ICRC, Hamburg, Germany, 2001, p.1995
14. Strong, A.W., Moskalenko, I.V. 1998, ApJ, 509, 212
15. Woltjer L. 1972, ARA&A, 10, 129