The Origin of Galactic Cosmic Ray Protons

Naum Grigorov, Ekaterina Tolstaya,
Skobeltsyn Institute of Nuclear Physics, Moscow State University, Leninskie Gory, Moscow 199992, Russia

Abstract

Conditions causing the 'kink' in the proton spectrum in the energy range ~ 1 TeV are considered. The possible approaches to experimental verification of the existence of the discussed process of GCR proton acceleration are analyzed.

Even a brief glance on the spectra of protons and nuclei reveals a striking discrepancy between them: the spectrum of nuclei is purely power-law in a broad range of energies, and the proton spectrum, though power-law has a 'kink' in the region around 1 TeV [1]. This discrepancy can not be achieved in the process of particle propagation in the Galaxy. Since in this process particles with equal rigidity are subject to equal disturbance despite their charge and mass. Therefore, the changes in the spectra, if they were caused by propagation processes would be equally pronounced for protons and nuclei. In other words, the observed discrepancy is acquired in the sources. Therefore, protons and nuclei have different **sources**. Here it should be noted, that sources of nuclei produce particles with a purely power-law spectrum and proton sources produce particles with a 'knee' in the spectrum. A specific feature of the 'knee' in the proton spectrum is that the energy range in which the change of β_p by $0.5 - 0.6$ occurs is very narrow. This circumstance indicates a certain universality of the process of the 'knee' formation, which weakly depends on the concrete features of the source.

We assume, that the main reason for the discrepancy in the spectra of protons and nuclei lies not in the sources, but in the particles themselves. There is one qualitative discrepancy between these two types of particles: protons in the process of acceleration and exit from the source can undergo an unlimited number of inelastic collisions and will still remain nucleons. Whereas nuclei are too 'fragile' formations: after several inelastic collisions they disintegrate into nucleons and no longer exist as nuclei. This discrepancy leads to the fact that protons can be accelerated in a sufficiently dense medium and travel significant thicknesses of material $\sim 10^2 - 10^3 g \cdot cm^{-2}$. Where as nuclei can be accelerated only in low-density medium, i.e. in the conditions of a strongly expanded supernova shell. The possibility of particle acceleration to high energies at the initial stage of the supernova blast is considered in [2]. It was shown in this paper, that acceleration

---

pp. 1845–1848

is possible even in dense layers of the star and the formation of a power-law spectrum of accelerated particles is possible.

Without going into details of the acceleration process, we will consider which particles will be exiting such a source and what spectrum they will have. The blast of the supernova is the final stage of the evolution of the star. Therefore, it is old stars that explode: red giants and super-giants. In these stars all the hydrogen has long burned out and the shells consist of complex nuclei, heavier than hydrogen.

The blast energy is released in the core of the star and in the adjacent regions of the shell. Therefore, acceleration of the particles can begin in sufficiently dense layers of the shell. The accelerated particles will be nuclei, since the shell consists of nuclei. However, accelerated nuclei in dense matter will undergo inelastic collisions and continuously fragmentate into lighter and lighter fragments. Therefore, quite quickly the accelerated nuclei will turn into a flux of energetic protons (neutrons due to instability will also turn into protons). Protons, having velocities, close to the speed of light will quickly begin to leave the acceleration region, and moving through the shell of the star will leave it. Obviously, in this process of exiting the exploded supernova the protons will inevitably have to travel a significant thickness of matter - hundreds and thousands of $g \cdot cm^{-2}$. What will happen to the initial spectrum?

Let us assume, that in the acceleration region the protons have acquired a power-law spectrum of the $I(E) = I_o E^{-\beta}$. the equation, describing the transport of nucleons through matter has the form:

$$\frac{\partial I(E,x)}{\partial x} = -\frac{I(E,x)}{\lambda} + \int\limits_{E}^{\infty} \frac{I(E',x)}{\lambda} P(E',E) dE' \qquad (1)$$

If the effective cross-section σ^{in} of inelastic interaction of protons with matter does not depend on energy, then $\lambda_o = const$ and $I(E,x) = I_o E^{-\beta} e^{-(x/L_o)}$, where the mean-free path for absorption L_o is connected with the mean-free path for interaction by the expression: $\frac{1}{L_o} = \frac{1-\langle u^{\beta-1}\rangle}{\lambda_o}$ and $\langle u^{\beta-1}\rangle = \int\limits_0^1 u^{\beta-1} P(u) du$. In other words, in the considered case the flux of protons coming out of the supernova shell would have the same energy distribution, as was formed in the acceleration zone, but would have lower intensity. However, in reality the effective cross-section of inelastic interaction is energy dependent, as it is shown in Fig.1. This dependence in the first approximation can be described by the function $\sigma^{in}(E) = \sigma_o[1 + b\ln(E/E_o)]$ at $E > E_o$ and $\sigma^{in} = \sigma_o$ at $E < E_o$. For a hydrogen medium, as it is shown in Fig.1. coefficient b is equal to 0.08, for the Earth's atmosphere $b = 0.04 - 0.05$. For such an energy dependence of the cross-section the situation should change. In [3] an approximate solution of equation (1) was obtained for $\sigma^{in}(E) = \sigma_o[1 + b\ln(E/E_o)]$. It has the form $I(E,x) = I_o E^{-(\beta+\delta)} e^{-x/L_o}$, where

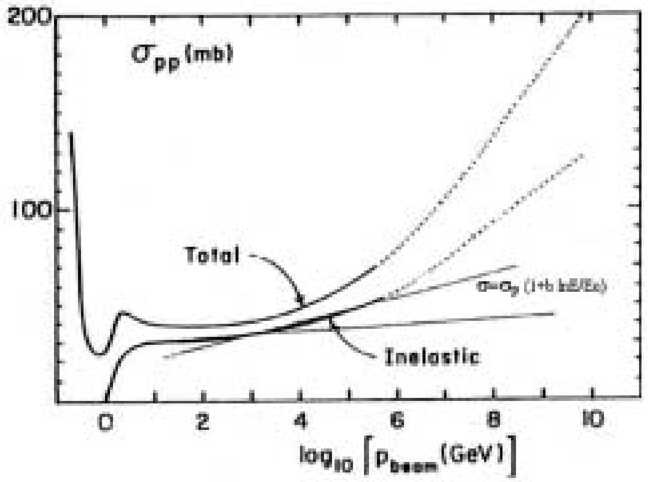

Fig. 1. The effective cross-section for p-p interactions versus energy [4].

$\delta = bx/L_o$. The approximate solution given above corresponds to particles with $E > E_o$ for boundary conditions $I(E, x = 0) = I_o E^{-\beta}$. For particles with $E << E_o$ the solution of equation (1) should correspond to the case $\sigma^{in} = const$, i.e. have the form $I(E, x) = I_o E^{-\beta} e^{-x/L_o}$. Obviously, there should be a region where β changes to $\beta + \delta$.

In order to find out, how wide the region where the change of spectral index from β to $\beta + \delta$ occurs, and how this region changes depending on the amount of travelled matter, we made a Monte-Carlo simulation of the propagation of a flux of nucleons through different thicknesses of matter at $\sigma^{in} = \sigma_o[1 + b \ln(E/E_o)]$. The results of this calculation are shown in Fig.2. Using Fig.2 we can connect the energy E_k at which the bend in the spectrum occurs with the amount of travelled matter x/L_o by an empirical relation $E_k = 3.4(x/L_o)^{-0.8}$ TeV. As it can be seen the position of the kink in the proton spectrum weakly depends on the amount of travelled matter. Therefore, in the observed spectrum, which is a sum of the spectra from numerous sources, in which protons travel different amounts of matter, the blurring of the 'knee' region will be small, i,e, the observed position of the 'knee' will be close to the value of E_o depending on $\sigma^{in} = \sigma_o[1 + b \ln(E/E_o)]$, as it seems to be observed in the experiment, since $E_o \simeq 1 \div 2$TeV.

It is highly probable, that the value of β is the mean value of a large number of β_i values of the spectra from individual sources. The value $\delta = b < x/L_o >$ is also the average of many individual thicknesses of travelled matter in the individual supernovas.

One of the peculiarities of the formation of the observed spectrum is its flattening with increasing energy. This is connected with the fact that the observed spectrum contains a set of spectra with different β_i values. With increasing E the

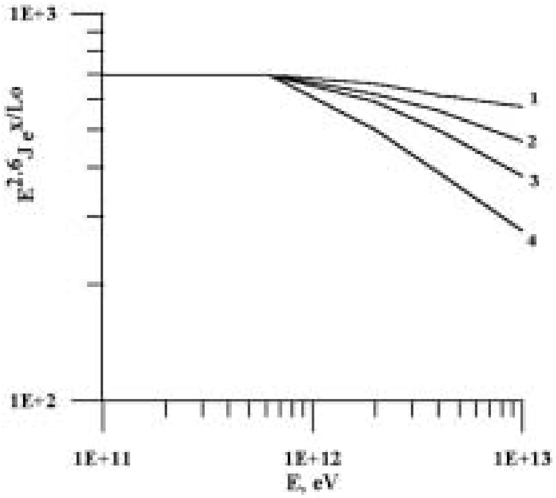

Fig. 2. The proton spectra at different depths $Xg \cdot cm^{-2}$.$1 - X = 100$; $2 - X = 200$; $3 - X = 300$; $4 - X = 450$. Along the vertical axis are arbitrary units.

contribution of the components with greater β_i will decrease and, correspondingly, the contribution of components with smaller values of β_i will increase.This effect can be observed experimentally.

Concluding our discussion on the subject of the proton spectrum, we will stress, that the existence of a 'knee' in the proton spectrum at $E_k \sim 1$ TeV is important evidence that cosmic ray protons are produced in dense objects, in which they travel through hundreds of $g \cdot cm^{-2}$ of matter. This circumstance can be important evidence of the 'stellar' origin of the proton component of galactic cosmic rays.

The considered process of the formation of the proton spectrum with a 'knee' at the energy of ~ 1 TeV does not in no way concern the existing models of nuclei acceleration. Furthermore, since acceleration of nuclei is only possible under the conditions of small density of the medium, the nuclei can be accelerated on the shocks in the shells of the same supernovas, which accelerated the protons, but only at a later stage: the protons are accelerated first, and after a certain time, - the nuclei.

References

1. Grigorov N., Tolstaya E. 2003, Proceedings of the 28th ICRC
2. Colgate S., Johnson M. 1960, Phys. Rev. Lett. 5, 235
3. Grigorov N. 1977, Yadernaya Fizika 25, 788
4. Gaisser T. 1990, Cosmic Rays and Particle Physics, Cambridge University Press