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On the hardening of cosmic ray spectrum

VLADIMIR PTUSKIN[1], VLADIMIR ZIRAKASHVILI[1], EUN-SUK SEO[2]
[1]*Pushkov Institute of Terrestrial Magnetism, Ionosphere and RadioWave Propagation of the Russian Academy of Sciences (IZMIRAN), Troitsk, Moscow region 142190, Russia*
[2]*Department of Physics and Institute of Physical Science and Technology, Univerfsity of Maryland, College Park, MD 20742, USA*
vptuskin@izmiran.ru

Abstract: Data obtained in ATIC-2, CREAM and PAMELA experiments suggest that elemental interstellar spectra of cosmic rays below the knee are not simple power laws and become hard at magnetic rigidity above about 200 GV. We consider possible reasons for this hardening including the concavity of cosmic ray spectrum due to nonlinear nature of diffusive shock acceleration and the transformation of cosmic ray spectrum under the influence of reacceleration of background cosmic rays by supernova blast waves. Possible interpretation of data on increasing with energy helium-to-proton ratio in the model of cosmic ray acceleration by forward and reverse shocks in supernova remnants is suggested.

Keywords: acceleration, reacceleration, SNR

Inroduction

High-accuracy measurements revealed the deviations of cosmic ray spectra from plain power laws at energies 10 to 10^5 Gev/n. It refers, in particular, to the ATIC2 [1], CREAM [2] and PAMELA [3] experiments, see also [4] for additional references. The general net conclusion from these measurements is the presence of spectral hardening in proton, helium and nucleus spectra at magnetic rigidity roughly 200 GV and the increase of He/H ratio in the above energy range.

Without considering other possible interpretations of these results, we focus this work on the refinement of our model of cosmic ray acceleration in supernova remnants [5] that may give the required effects. It should be emphasized that model [5] is in reasonably good agreement with experimentally deduced overall spectrum of cosmic rays in a wide range of energies up to more than 10^9 GeV. However, more work is needed to explain some details of cosmic ray spectrum and composition at energies both below and above the knee.

Three effects are considered below: nonlinear shock modification that leads to the concave spectrum of accelerated particles with a pronounced hardening; account for the acceleration by reverse shock of supernova ejecta material poor in hydrogen; hardening of cosmic ray spectrum due to the reacceleration of interstellar cosmic ray background by supernova shocks.

Spectra of cosmic rays produced by supernova remnants

High efficiency of acceleration leads to the modification of gas flow in the shock precursor by cosmic ray pressure that shapes the concave energy spectrum of cosmic rays, e.g. [6, 7]. The calculations of this effect were fulfilled with the use of a new numerical model of nonlinear shock acceleration described in the paper [8] presented at this Conference; all details of the calculations can be found there. (The code was also used in [9] for modelling of non-thermal emission from the supernova remnant RX J1713.7-3946.) The main difference with the model developed in [5] is the account for particle acceleration at the reverse shock that propagates inward in the ejecta material of a supernova.

Fig.1 shows the overall cosmic ray spectra produced in type IIb (black lines) and Ia (gray lines) supernova remnants by forward (solid lines) and reverse (dash lines) shocks during 10^5 years of their evolution. It is assumed that ions with the mass number A ($A > 1$) and the charge $Z = A/2$ dominate in the composition of ejecta material accelerated by the reverse shock. This type of ions determine the modification of reverse shock and their nucleon number density is shown in Fig.1. The energy density of amplified magnetic field amounts to 5 percent of the dynamical pressure when the shock is strong (the shock velocity exceeds 700 km/s) and the Alfvenic drift is included in the cosmic-ray transport equation downstream of the forward shock. It is assumed that the Kolmogorov-type nonlinear damping controls the

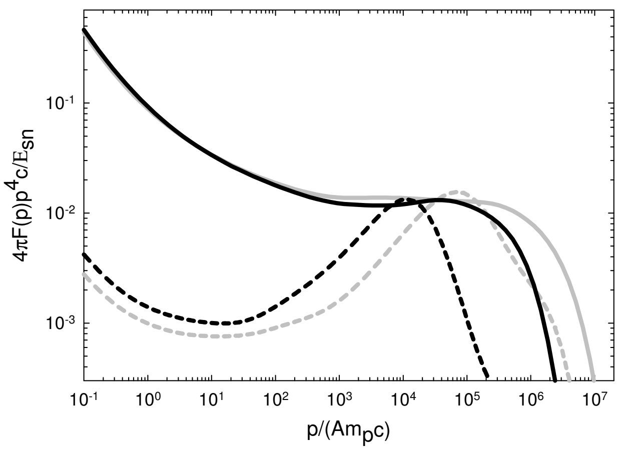

Figure 1: Cosmic ray source spectra produced by forward (solid lines) and reverse shocks (dash lines) in supernovae Type IIb (black lines) and Type Ia (gray lines)

level of turbulence and related value of the diffusion coefficient [10].

The interstellar proton and helium spectra calculated with the use of the source functions 1 are presented in Fig.2. We assume that ejecta material does not contain hydrogen so that helium is the most abundant element there. This explains the difference in proton and helium spectra seen in Fig.2. As in [5], the rates of different types of Galactic supernovae included in the calculations are Ia:IIP:Ib/c = 0.32:0.44:0.22; the shock in Type Ib/c supernovae goes through the helium wind of the progenitor Wolf-Rayet star that enriches cosmic rays with helium at energies above 10^5 GeV/n; the interstellar diffusion coefficient increases with magnetic rigidity as $R^{0.6}$ at $R > 5$GV.

The spectra in Fig.2 exhibit hardening at ~ 200 GV. The calculated He/p ratio increases from about 1.6 at 30 GeV/n to about 10 at 10^5 GeV/n and increases further toward the knee.

Reacceleration by supernova remnant shocks

It is known that weak distributed stochastic reacceleration by interstellar MHD turbulence can produces bump in cosmic ray spectrum at energy about 1 Gev/n. This effect is used to explain the observed energy dependence ratios of secondary to primary nucelei [11, 12]. The stochastic reacceleration shapes the spectra of primary nuclei with the hardening at about 30 GeV/n if the value of Alfven velocity is chosen to reproduce the observed B/C ratio. This energy is determined by the competition between decreasing with energy efficiency of stochastic reacceleration and increasing with energy efficiency of diffusive escape from the Galaxy.

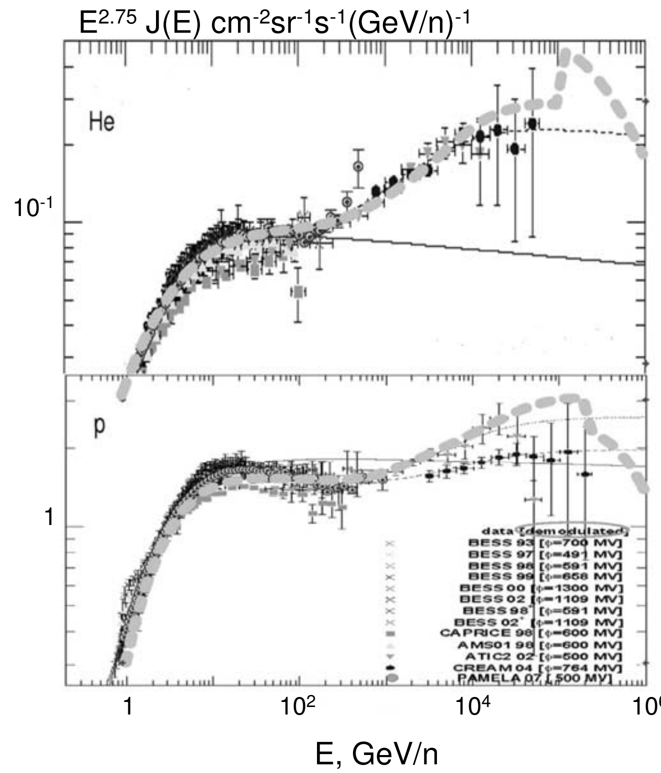

Figure 2: Calculated interstellar spectra of protons and helium are shown by gray dash lines. References to observational data are given in the text.

Another process of cosmic ray reacceleration by shocks (mainly by old extended shocks) produced by supernova explosions was also considered in the literature [13, 14, 15]. The efficient time of particle reacceleration does not depend on energy in this case and the hardening of cosmic ray spectrum is shifted to higher energies compared to the stochastic reacceleration. Here we study this effect. Its efficiency depends on the frequency of supernova explosions and the dependence of maximum energy of accelerated particles on the age of supernova remnant.

We used a simplified treatment for the escape of accelerated particles from supernova remnants [16]. The possible nonlinear modification of shock structure by the cosmic ray pressure is ignored here. Cosmic ray particles with momentum distribution $f(p)$ in the interstellar medium are absorbed and reaccelerated by a supernova shock. The particles return to the interstellar medium from the shock front and from the remnant interior when the maximum momentum $p_m(t)$ of particles accelerated in the remnant of age t becomes smaller than p. The corresponding transport equation is of the form

$$\frac{\partial f}{\partial t} + \hat{T}f + \hat{L}f = q. \quad (1)$$

Here q is the source term that arises as the contribution of shock acceleration of thermal ions. The term $\hat{T}f$ symbol-

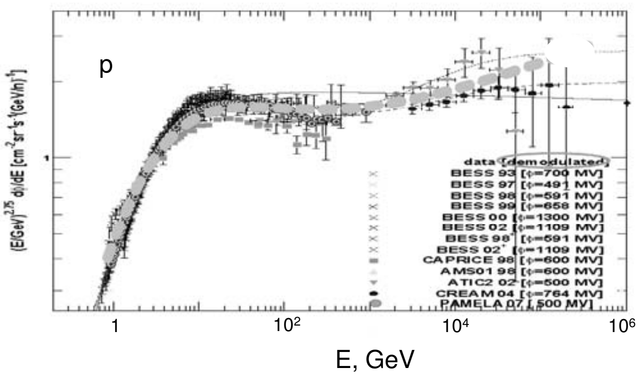

Figure 3: Calculated interstellar proton spectrum in the model with shock reacceleration is shown by gray dash line. References to observational data are given in the text.

ically describes the cosmic ray transport that includes diffusion, nuclear fragmentation, and ionization energy losses in the interstellar gas. The reacceleration of energetic particles is described by the integro-differential operator

$$\hat{L}f(p) = \frac{4\pi\nu}{3(2\gamma-3)}\frac{1}{p^2}\frac{\partial}{\partial p}p^3R_m^3(p)\left[\gamma\int_0^p\frac{dp'}{p'}\left(\frac{p'}{p}\right)^{\gamma}f(p') - (\gamma-3)\int_p^{\infty}\frac{dp'}{p'}\left(\frac{p}{p'}\right)^{\gamma-3}f(p')\right], \qquad (2)$$

where ν is the frequency of supernova explosions in the unit volume, $\gamma = 3\sigma/(\sigma-1)$ is the index of momentum distribution formed by the diffusive shock acceleration mechanism by shocks with compression ratio σ, and $R_m(p)$ is the shock radius at the instant of time when $p_m(t) = p$. Since it is expected that $R_m(p)$ is larger for smaller momenta p, one can say that the reacceleration operator contains an additional source term (the first integral in the last equation) with a spectrum that is steeper than the spectrum of particles injected at the shock front from the thermal pool. The amplitude of this term is determined by the number density of low-energy cosmic rays in the interstellar medium.

The influence of such an reacceleration on the proton spectrum is displayed in Fig.3. (The spectra of other accelerated ions as functions of magnetic rigidity looks similar to the proton spectrum when corrected for different nuclear fragmentation in the course of propagation in the interstellar gas). The hardening of spectrum at about 200 GeV/n is evident. It was assumed in the calculations that the reacceleration is produced by supernova shocks which propagate in the warm interstellar medium with hydrogen number density $n_H = 0.1$ cm^{-3}. The dependence of maximum particle energy on the remnant age was taken in the form $p_m = p_0 t_{kyr}^{-\beta}$. We use the value of $\beta = 2$. It corresponds to the maximum energy determined by the nonlinear damping of Alfven waves in the weak turbulence theory, see [10]. Close value $\beta = 1.8$ corresponds to the wave damping by neutrals. For canonical energy of supernova explosion $E_{SN} = 10^{51}$ erg and frequency of supernova explosins $\nu_{sn} = 0.03$ yr^{-1} in the Galactic disk with radius $R = 10$ kpc we fit the value of parameter $cp_0 \approx 25$ TeV to reproduce the proton spectrum of PAMELA experiment. The PAMELA data were demodulated with potential $\Phi = 550$ MeV. It was also assumed that supernova remnants produce power-law momentum distribution with index $\gamma = 4$, i.e. $q \propto p^{-\gamma}$. The flat halo diffusion model with the halo height $H = 3$ kpc, hydrogen column density of the galactic disk $N_H = 10^{21}$cm^{-2} and diffusion coefficient $D = 3 \cdot 10^{28}(p/mc)^{0.6}v/c$ cm^2 s^{-1} was used. This set of parameters reproduces the observed B/C ratio. The value of $N_H = 10^{21}$ is essential not only for production of secondaries but also for calculation of ionization losses of non-relativistic protons that are reaccelerated by supernova shocks. It should be noted that the found value of $cp_0 = 25$ TeV is not very large. It gives the maximum proton energy only 2.5 GeV in the remnant of $t = 10^5$ years old. At this age the shock velocity is close to 200 km s^{-1} and its radius is 45 pc. The fitted value of p_0 scales with frequency of supernova explosions as $\nu_{sn}^{-5/3}$. So, it can be higher if the supernova rate is lower.

It is clear from Fig.3 that the reacceleration by supernova shocks alone leads to the hardening of cosmic ray spectrum at about 200 GV.

Conclusion

The processes considered in the present work - the nonlinear shock modification that gives the concave spectrum of accelerated particles and the reacceleration of background cosmic rays by supernova shocks - can contribute to the explanation of the hardening of cosmic ray spectra at ~ 200 GV. The difference in the observed spectra of protons and helium can be explained by acceleration at the reverse shock moving through the depleted in hydrogen material of supernova ejecta.

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