The Knee in Galactic Cosmic Ray Spectrum and Variety in Supernovae

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Abstract

We calculate Galactic cosmic ray (GCR) flux averaged over Supernova explosion energies and types, applying only the formulae of standard model of CR acceleration in Supernova remnants (SNR) and using latest astronomical data on the variety in Supernovae. In the presented model the cosmic ray flux in the whole energy range up to 10^{18} eV is predominantly formed by the most energetic SN explosions. The "knee" in GCR spectrum at energy around $E_{knee} = 3$ PeV can quantitatively be explained by the dominant contribution of Hypernovae. The model sketches all-particle cosmic ray spectrum up to 10^{18} eV.

1. Introduction

Considerable collective efforts have been made during the recent years to clarify the mechanism of diffusive shock acceleration of cosmic rays in Supernova remnants [2]. But the "knee" problem, i.e. the origin of a pronounced change of a spectrum slope from ~ -2.7 to ~ -3.1 at the energy $E_{knee} \sim 3-4$ PeV has not been solved yet. People believe that the "knee" is connected with the upper limit of CR accelerations. This limit is determined essentially by the product of shock radius Rsk, shock velocity Vsk (usually normalized to 1000 km/s), ejected mass Mej, remnant age $Tsnr$, explosion energy $E_{51} = E_{SNR}/10^{51}$ erg [2]. All these values are connected with each other and vary from explosion to explosion. Cut off energy per particle E_{max} can be expressed by the simple formula, if only Sedov phase of SNR expansion is considered [3]

$$E_{max} = Z \cdot E^0_{max}(B, n_H)(E_{51} \cdot Vsk)^{1/3} \qquad (1).$$

The cut off energy depends on the three factors: on the charge of nucleus Z, on the interstellar medium state $E^0_{max} \sim B \cdot n_H^{-1/3}$ (density of protons n_H and the magnetic field B), on the parameters of the explosion: E_{51} and Vsk. The "warm" or "hot" phases of medium are usually chosen as a common places of explosions [1] with the value $E^0_{max} \sim 100$ or 300 TeV respectively. So in (1) the value of E^0_{max} is formally a cut off energy for protons in average SNR with E_{51}=1 and

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$Vsk = 1(1000$ km/s), and this value is by several times smaller than observed value of E_{knee}.

A usual way to raise the E_{max} (up to $10^{16} - 10^{17}$ eV) is increasing the magnetic field in the interior of the progenitor for any class of explosions: explosions into wind of Wolf-Rayet stars or explosions into superbubbles (see the review [2]). But it is clear now that the diversity in parameters of SN explosions E_{51} and Vsk also exists [4], [6].

The main idea of this work (it seems very natural) is an attempt to obtain the cosmic ray particle spectrum averaged over SNe types and explosion energies.

2. The model of "knee", theoretical promises

It was proposed [5] that the total CR flux dN/dE can be expressed

$$dN/dE = \sum_{i=1}^{Nz} \sum_{j=1}^{Ntp} \int_{E_{51}^{min}}^{E_{51}^{max}} \Psi_j(E_{51}) G(E, E_{max}) dE_{51}, \quad (2)$$

where $\sum_i$ is the summation by different cosmic ray nucleus groups Nz; $\sum_j$ is the summation by different types of SNe explosions Ntp; $\Psi_j(E_{51})$ is the explosion energy distribution inside each SN group within the limits of $E_{51}^{min} \div E_{51}^{max}$. In the main variant we used $E_{51}^{min} = 0.1$, $E_{51}^{max} = 80$. Assuming $E_{51} \sim Mej \cdot Vsk^2/2$, we can rewrite the expression (1) as

$$E_{max} = Z \cdot E_{max}^0 \cdot E_{51}^{0.5}, \quad (3)$$

to exclude Vsk from (2).

$G(E, E_{max}) = I_0 E^{-\gamma}$ is the spectrum of cosmic rays in every explosion which may be fitted by the power law with different slope γ in different energy intervals, taking into account noticeable decreasing of γ before E_{max} due to nonlinear reaction of CRs to shock structure [1], [3]: $\gamma = 2.0$ at $10\ GeV < E < E_{max}/5$; $\gamma = 1.70$ at $E_{max}/5 < E < E_{max}$; $\gamma = 5$ at $E > E_{max}$. Intensity of CRs produced in every SNR (I_0) is found from the condition that the fraction of SNR kinetic energy transformed to CRs is proportional to E_{51} [1]:

$$\int G(E, E_{max}) E dE = 0.1 \cdot E_{51}. \quad (4)$$

The function $\Psi(E_{51})$ is unknown distribution. But the aim of this work is to show the dependence of CR flux on this function. We has estimated in [5] that $\Psi(E_{51})$ distribution is probably close to Gaussian logarithmic function with different values of $< \lg E_{51} >$ and $\sigma \lg E_{51}$ for different types of SNe. Here only four main groups of SNe are considered SNIa, SNII, SNIb/c, SNIIn [4] with relative weights: 0.25, 0.45, 0.20, 0.10, with $< lgE_{51} >=$ -0.3, -0.3, 0., 0., with $\sigma \lg E_{51}$ = 0.2, 0.5, 1.2, 1.2 respectively. This choice reflects the established fact that

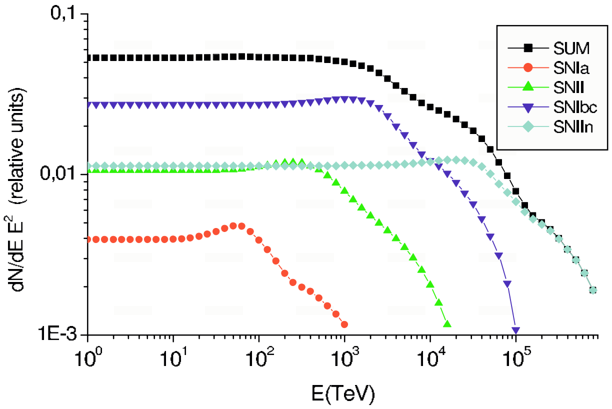

Fig. 1. Contribution of different type of SNe to total CR all particle spectrum (in relative units).

only SNIa have apparently very small diversity in energy, while even among the classical SNII the diversity in energy is about one order of magnitude (E_{51}=0.6-5) [4]. Besides Hypernovae with very high explosion energy ($E_{51} = 10 - 60$) were discovered in recent years [4], [6] and they were attributed to SNIbc and SNIIn types. We have chosen E^0_{max}= 100 TeV, 300 TeV, 300 TeV, 4500 TeV for above mentioned 4 types of SNe, since SNII, SNIb/c are usually found in active star formation zones, where "hot" phase of interstellar medium is expected, while SNIa very often is observed far from active star formation zones. SNIIn in accordance with the definition demonstrate the strong interaction with circumstellar medium [4] and their remnants are expected to be expanding in medium with higher value of B.

All nuclei of cosmic rays are divided here in 5 rough groups: p, He, (C, N, O), (Mg, Si, Ne), Fe with relative intensities 0.36, 0.25, 0.15, 0.13, 0.15, respectively.

3. All particles cosmic ray spectrum, numerical results.

The CR flux calculated by (2) is presented in Fig. 1 and in Fig. 2. One can see from Fig.1 that CR flux from SNIb/c has the knee at higher energy, than CR flux from SNII due to the appearance of very high energy explosions with parameters of Hypernovae among them and due to (3). Besides, the contribution of CRs originated from SNIb/c is stressed significantly due to condition (4), and the "knee" in total CR flux is formed by SNIb/c. CR flux from SNIIn has a "knee" even at larger value of E due to higher value of E^0_{max}.

In the proposed model (see Fig. 2) the location of "knee" is determined by an abrupt fall of protons originated in most energetic SNe; the change of a spectrum slope beyond the "knee" (in the interval $E_{knee} \div 26 \times E_{knee}$) is mainly

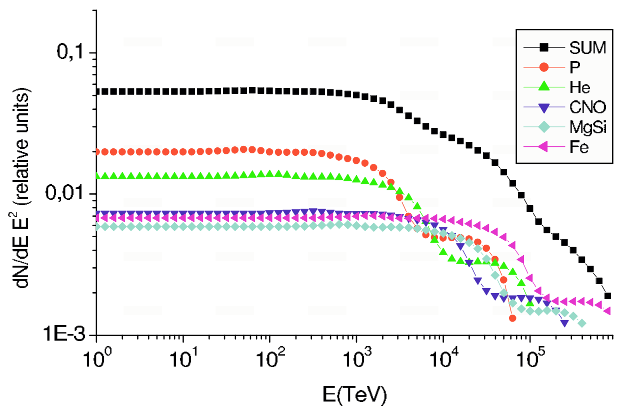

Fig. 2. Spectra of different cosmic ray nuclei.

determined by the subsequent abrupt fall of other nuclei and especially by the fraction of Fe-nuclei in CR flux. The contribution of CRs originated in SNIIn exploding into specific circumstellar medium with large magnetic field becomes predominant in the range $E > 26 \times E_{knee}$. As a result, every nuclear component of CRs should have two steps, and the all-particle spectrum beyond the "knee" being formed by a sum of double steps. The chemical composition of CRs in this region $3 \cdot 10^{15} - 10^{18}$ eV is much heavier than in the region before the "knee".

It was shown in [5] that the fraction of events with $E_{51} \sim 30$ responsible for formation of the knee in the CR spectrum should be $\sim 2 \pm 1\%$. It means that with a usual SN-rate of about 10^{-2} year^{-1} the Hypernova-rate should be about 2×10^{-4} year^{-1}. Taking into account that the time of CR life in our Galaxy is about $3 \cdot\ 10^7$ year one can estimate that about $6 \cdot 10^3$ explosions provide the intensity of low energy CRs in our Galaxy, but only several ones at high energies [5].

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