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On the origin of galactic cosmic rays

V S Ptuskin

1. Introduction

Our Galaxy is filled with cosmic rays — that is, a gas consisting of relativistic protons, electrons, and atomic nuclei. Most of these particles were accelerated in supernova remnants and wander in the interstellar magnetic fields over several dozen million years before exiting into intergalactic space. The energy spectrum of cosmic rays has a power-law form with a break (a knee) at 3×10^{15} eV (Fig. 1). The maximum detected energy exceeds 10^{20} eV. With a tiny number density of particles, $N \sim 10^{-10}$ cm^{-3}, which is 10 orders of magnitude smaller than the average interstellar gas density in the galactic disk, $n \sim 1$ cm^{-3}, cosmic rays have the energy density $w_{\rm cr} = 1.5$ eV cm^{-3}, which is comparable to the energy density of galactic magnetic fields and the energy density of turbulent interstellar gas motions. Cosmic

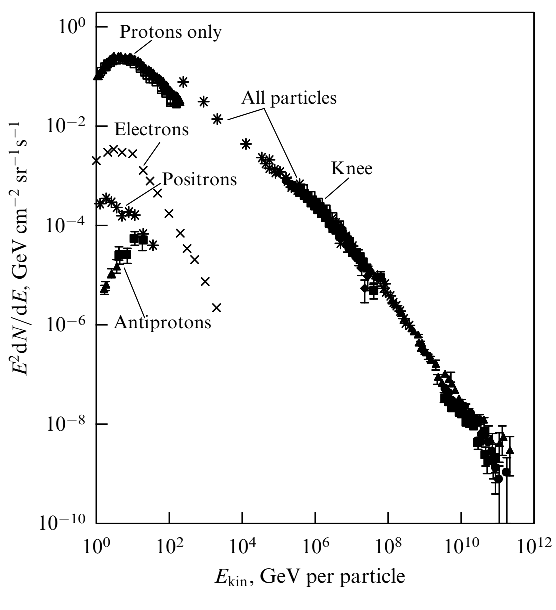

Figure 1. Cosmic ray spectrum with energies exceeding 1 GeV. (Simplified version of the figure from paper [1], where references to the corresponding experiments can be found.)

rays are highly isotropic — the amplitude of the first harmonic of their angular incoming direction distribution is $\delta_{cr} \sim 10^{-3}$ at energies $10^{12}-10^{14}$ eV, where the data are the most robust.

The effective isotropization and mixing of trajectories of charged energetic particles are explained by the action of interstellar magnetic fields. As a result, the direct identification of sources of particles reaching the Earth proves to be impossible. Establishing the synchrotron nature of the main part of nonthermal space radio emission at the beginning of the 1950s enabled probing the properties of remote relativistic electrons of cosmic rays. It is during this period the pioneering papers by V L Ginzburg [2–4] on the theory of cosmic synchrotron radio radiation appeared. Progress in radio astronomy led to the appearance of the astrophysics of cosmic rays and made it clear that the presence of relativistic particles is a universal phenomenon in space conditions. The initial period of development of cosmic ray astrophysics is described in more detail in paper [5] and references cited therein. To the mid-1960s, mostly due to studies conducted by Ginzburg and his collaboration with S I Syrovatskii, the canonical model for the origin of cosmic rays was elaborated (see the monograph by Ginzburg and Syrovatskii [6]). This book became the bible for high-energy astrophysicists. The model developed in Ref. [6] is based on the following statements: most cosmic rays have a galactic origin; cosmic rays diffuse in interstellar magnetic fields and fill up an extended halo, and supernova explosions are the sources of cosmic rays. The booming development of this field of astrophysics is reflected in the book [7], which was intended by Ginzburg as a continuation of the monograph [6]. Book [7] includes, in particular, new topics: gamma-ray astronomy, neutrino astronomy, ultrahigh energy cosmic rays, and the description of acceleration and propagation of cosmic rays on the kinetic level. Later reviews can be found in Refs [8–10]. The present short communication mainly illustrates the developments of studies carried out by Ginzburg and his scientific school. Basically, the results obtained after issuing the review [8] in *Physics–Uspekhi* are mainly included and unsolved problems are formulated.

2. Diffusion model of cosmic ray propagation

The motion of cosmic rays with energies below $E \sim 10^{17}$ eV in galactic magnetic fields is usually described as diffusion [6, 7]. The diffusion model constitutes the base for interpreting the spectrum, composition, and anisotropy of cosmic rays, as well as the corresponding radio, X-ray, and gamma-ray astronomical observations. The consistency of these data allows the determination of the basic model parameters. To this end, it is necessary to solve the transport equation for relativistic protons, nuclei, and electrons for a given distribution of sources (supernova remnants) and halo boundary conditions. The transport equation for particles describes their diffusion, convective transfer by the hypothetical galactic wind, and energy changes due to energy losses in the interstellar medium, as well as possible additional acceleration by interstellar turbulence. Cosmic rays also contain secondary nuclei like ^{2}H, ^{3}He, Li, Be, B and some others that are rarely observed in nature, which are produced by the spallation of heavier nuclei interacting with nuclei of the interstellar gas. Over the time spent in the Galaxy, cosmic rays traverse a matter thickness of ~ 10 g cm^{-2} at an energy of ~ 1 GeV per nucleon (at this energy, the maximum ratio of primary to secondary nuclei is observed). Modern detailed calculations of the propagation and nuclear transformation of cosmic rays in the Galaxy include around hundred different stable and radioactive isotopes in the broad energy range.

To model cosmic ray propagation, both the combination of analytical and numerical methods (see Refs [11–14]) and direct numerical calculations [15, 16] are employed. The required total power of cosmic ray sources in the Galaxy is estimated to be $Q_{cr} = 5 \times 10^{40}$ erg s^{-1}, which corresponds to about 15% of the kinetic energy of supernova explosions. Accounting for the selection of ions injected into the acceleration process by the value of the first ionization potential or volatility, the elemental composition of cosmic rays in the sources turns out to be close to that of the solar system and local interstellar medium (see Ref. [9] for more detail). The height of the cosmic ray halo is $H \approx 4$ kpc (or more in the model with galactic wind). According to Ref. [16], the diffusion coefficient of cosmic rays in two main versions of the diffusion model as obtained from statistically reliable data (up to about 100 GeV per nucleon) on secondary nuclei is expressed in the form

$$D = 2.2 \times 10^{28} \beta \left(\frac{R}{R_0}\right)^{0.6} [\mathrm{cm^2\ s^{-1}}] \quad \text{for} \quad R > R_0 = 3\ \mathrm{GV}\,,$$
$$D \sim \beta^{-2} \quad \text{for} \quad R < R_0 \qquad (1)$$

in the pure diffusion model, and

$$D = 5.2 \times 10^{28} \beta \left(\frac{R}{R_0}\right)^{0.34} [\mathrm{cm^2\ s^{-1}}] \quad \text{at all } R \qquad (2)$$

taking into account additional stochastic acceleration of particles by random magnetohydrodynamic (MHD) waves in the interstellar medium with the Alfvén velocity $V_a \approx 36$ km s^{-1} (see also the discussion in Section 3). Here, $R = pc/Z$ is the magnetic rigidity, p is the momentum, Z is the charge, $\beta = v/c$, and v is the particle velocity.

Neither variant (1) nor (2) is problem-free and both require improvement. The strong energy dependence of the diffusion in Eqn (1) in the pure diffusion model leads to an anisotropy exceeding what is observed by more than an order of magnitude at energies $\sim 10^{14}$ eV (see Ref. [17]). On the other hand, the model with additional acceleration gives values of the secondary antiproton flux in cosmic rays lower than those observed (see Ref. [16]). It is also essential that in order to explain the energy spectrum of cosmic rays $\sim E^{-2.7}$, observed for energies $E > 30$ GeV per nucleon, the spectrum in the source be $E^{-2.1}$ in variant (1), and $E^{-2.36}$ in variant (2). Direct measurements of radio and gamma-ray emissions from supernova remnants and the modern theory of particle acceleration in supernova remnants suggest a particle spectrum close to E^{-2}, and in this sense variant (1) looks more attractive.

Diffuse gamma-ray emission reflects the global distribution of cosmic rays in the Galaxy. When interacting with interstellar gas nuclei, the proton-nuclear component of cosmic rays generates continuous gamma-ray emission mainly via the creation and decay of π^0-mesons in the process $pp \to \pi^0 \to \gamma\gamma$. The electron component generates gamma-ray emission by the Compton scattering of interstellar background photons and via bremsstrahlung emission in the interstellar gas. The diffusion model of cosmic ray propagation with the diffusion coefficient which is inferred from near-

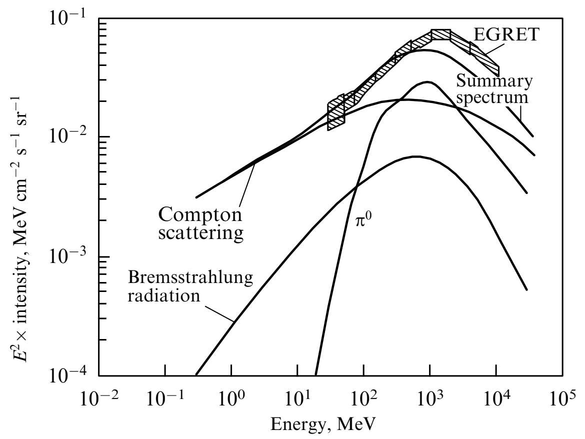

Figure 2. Spectrum of the diffuse galactic gamma-ray emission [19]: the EGRET observational data and results of the corresponding theoretical calculations for different generation mechanisms of gamma-ray emission.

Earth observations and is independent of coordinates everywhere in the Galaxy generally well reproduces the angular and energy distribution of galactic gamma-rays with energies 30 MeV – 10 GeV, obtained by the EGRET (Energetic Gamma Ray Experiment Telescope) experiment [18, 19]. However, the gradient of cosmic ray density was found to be smaller than the predicted one assuming the standard radial distribution of the sources of supernova remnants, which, most likely, calls for improvement of the model (see Ref. [20]).

An enigmatic feature of the EGRET data is an isotropic excess of gamma-ray emission at energies of 1 – 10 GeV with respect to the expected flux calculated using spectral data on protons, nuclei, and electrons observed in cosmic rays near the Earth (Fig. 2). Unless this is an instrumental effect [which will be tested by the GLAST (Gamma-ray Large Area Space Telescope) mission scheduled for launch shortly], the presence of an anomaly in the cosmic ray characteristics in the neighborhood of the solar system is not excluded on a scale of about several hundred parsecs compared to the mean galactic values. There are alternative explanations related to the contribution of hard-spectrum sources to the diffuse emission [21, 22] and to the gamma-ray flux from the hypothetical dark matter annihilation in the galaxy with an extended halo [23]. Here, observations of diffuse gamma-ray emission from the galactic disk at energies of several TeV [24] seem to be very instructive (see the discussion in Ref. [25]).

Note that according to the EGRET data, the application of the 'Ginzburg test' allowed establishing [26] that the number density of cosmic rays with the energies of 1 – 10 GeV in intergalactic space is significantly less than in the Galaxy. The test proposed in Ref. [27] suggests measuring the gamma-ray flux from the Magellanic Clouds in which the mass of gas and the distance are well known. As an elaboration of another earlier paper [28], in which Ginzburg participated, a strong limit on the intergalactic cosmic ray density on cosmological scales was recently obtained [29]. It was shown that cosmic rays accelerated in supernovae and starburst galaxies have an appreciable effect on the thermal history of the Universe at high redshifts. To explain the intergalactic medium temperature of $\sim 10^4$ K at redshifts $z = 2-4$, the present-day energy density (i.e., at $z = 0$) of cosmic rays in intergalactic space must be $10^{-4} - 6 \times 10^{-3}$ eV cm^{-3} under different assumptions in the standard cold dark matter cosmological model with the Λ-term. This value is consistent with the known energy estimates [6 – 8].

3. Kinetic theory of diffusion

The diffusion of cosmic rays in the Galaxy is explained by their scattering in random magnetic fields. This scattering has a resonance character, so that a particle with gyroradius $r_g = pc/(ZeB)$ is mainly scattered off magnetic field inhomogeneities with the wave number $k_{res} \sim 1/r_g$ (see Refs [7, 30]). In the typical interstellar field $B = 5$ μG, the gyroradius is $r_g = 6.7 \times 10^{11} R_{GV}$ [cm] (here, R_{GV} is the magnetic rigidity of a particle measured in gigavolts). The emerging spatial diffusion turns out to be strongly anisotropic and preferentially occurs along the magnetic field lines. However, strong fluctuations $\delta B/B \sim 1$ on large scales $L \sim 100$ pc make the diffusion isotropic [in a quasistatic field, the diffusion isotropization is nontrivial and is due to stochastic divergence of close magnetic field lines (see Refs [31, 32])]. Assuming magnetic field fluctuations on the resonance scale to be small compared to the total large-scale field, $\delta B_{res} \ll B$, and fluctuations to be isotropic in the space of wave vectors $\mathbf{k}$, one can estimate the diffusion coefficient for $r_g < L$ (i.e., for $E < 10^{17} Z$ [eV]) as the following:

$$D \approx \frac{v r_g}{3} \frac{B^2}{B_{res}^2} \qquad (3)$$

(see Refs [7, 30] for more detail). The observed spectral energy density of the interstellar turbulence has a power-law form: $w(k)\,dk \sim k^{-2+a}\,dk$, where $a \approx 1/3$ in the broad range of wave numbers, $1/(3 \times 10^{20}) < k < 1/10^8$ cm^{-1} [33]. Then, formula (3) yields the estimate $D \approx 4 \times 10^{27} R_{GV}^{1/3}$ [cm^2 s^{-1}], which is consistent with the empirical value in the model with additional acceleration (2). The additional acceleration itself appears as momentum diffusion with the coefficient $D_{pp} \approx p^2 V_a^2 / D$ taking into account a finite velocity of motion ($\sim V_a$) of random inhomogeneities which scatter off particles and provide spatial diffusion. The additional acceleration by the interstellar turbulence can be significant only at relatively small energies and does not affect the energy spectrum of cosmic rays for $E > 30$ GeV per nucleon. Recall that the main acceleration occurs in compact sources — supernova remnants.

The dependence of the diffusion on the magnetic rigidity of particles, $D \sim \beta R^{1/3}$, is typical for the Kolmogorov spectrum for which $a = 1/3$. Theoretically [34], it cannot be excluded that the Kolmogorov spectrum relates only to some part of the interstellar MHD turbulence which includes Alfvén type perturbations strongly elongated along the magnetic field direction. Such perturbations with $\mathbf{kB} = 0$ are ineffective for particle scattering and cannot reproduce the required diffusion coefficient. At the same time, more isotropic perturbations consisting of fast magnetosonic waves with smaller amplitude on the principal scale can exist [35]. This part of turbulence has the Iroshnikov – Kraichnan-like spectrum with parameter $a = 1/2$ and provides the diffusion of cosmic rays with diffusion coefficient $D \sim \beta R^{1/2}$, which is close to the empirical model value (1) if $\delta B/B \sim 0.2$ for these perturbations on the principal scale $L \sim 100$ pc. Notice that here one can explain why the diffusion coefficient (1) has a minimum at $R = R_0 = 3$ GV: a comparatively slow nonlinear Iroshnikov – Kraichnan cascade of the MHD waves cuts off on scales smaller than $1/k \sim 10^{12}$ cm due to damping on cosmic rays. The corresponding self-consistent calculations were done in Ref. [16].

One can state that the kinetic theory gives the diffusion coefficient consistent with the empirical value and in principle explains its dependence on the magnetic rigidity. However, the absence of detailed information on interstellar turbulence makes it impossible to obtain unique predictions and, in particular, to make the ultimate choice between the variants $D \sim \beta R^{1/3}$ and $D \sim \beta R^{1/2}$.

The presence of a nonzero large-scale mean magnetic field in the Galaxy leads to the appearance of the Hall diffusion with the coefficient $D_{\mathrm{H}} = v r_{\mathrm{g}}/3$ which emerges in the antisymmetric part of the diffusion tensor and is strongly dependent on the magnetic rigidity of particles. Owing to this last circumstance, the role of the Hall diffusion (drift) increases with energy, which can lead to the appearance of the knee in the cosmic ray spectrum at energies $\sim 3 \times 10^{15}$ eV due to the passage from the ordinary diffusion to the Hall one [36–38]. Another explanation relates the origin of the bend to particle acceleration processes in supernova remnants (see Section 6).

4. Collective effects in cosmic rays

Cosmic rays cannot always be considered to be free test particles moving in given regular and random fields. Ginzburg wrote the pioneering paper on the role of collective (plasma) effects during cosmic ray propagation [39] (see also Ref. [40]). The stream instability of cosmic rays with the particle density $N_{\mathrm{cr}}(E) \sim E^{-\gamma+1}$ amplifies MHD waves with the growth rate

$$\Gamma_{\mathrm{cr}}(k) \approx \Omega_{\mathrm{p}} \, \frac{N(r_{\mathrm{g}} > k^{-1})}{n} \left(\frac{v\delta_{\mathrm{cr}}}{(\gamma+2)V_{\mathrm{a}}} - 1 \right) , \qquad (4)$$

where Ω_{p} is the gyrofrequency of thermal protons. Even for a small anisotropy $\delta_{\mathrm{cr}} \approx 10^{-3}$, the instability for galactic cosmic rays with energies ~ 100 GeV develops in about 10^5 years, i.e., rather rapidly for the galactic timescale. The development of the instability leads to isotropization of the angular distribution of particles and turbulence enhancement (see, for example, the papers [41–43] and references cited therein). The effect is more significant close to the sources. As we shall see from the discussion in Section 6, the development of the stream instability of particles at the shock front in a supernova remnant is a prerequisite for cosmic ray acceleration.

Cosmic rays induce, in addition to kinetic effects, significant hydrodynamic effects in the Galaxy. Accounting for cosmic ray pressure is principally important for the formation of a halo filled with gas, a magnetic field, and relativistic particles [44]. The equilibrium distribution of the interstellar medium above the galactic plane in the gravitational field of stars is subjected to the Parker instability [45]. Cosmic rays play a significant role in the development of this instability. Using the diffusion–convective transport equation for cosmic rays, one can show [46] that the instability develops if the polytropic index of the interstellar gas γ_{g} turns out to be less than the critical value

$$\gamma_{\mathrm{g}^*} = 1 + \frac{P_{\mathrm{m0}}}{P_{\mathrm{g}}} \, \frac{0.5P_{\mathrm{g}} + P_{\mathrm{m0}} + P_{\mathrm{cr}}}{P_{\mathrm{g}} + 1.5P_{\mathrm{m0}} + P_{\mathrm{mt}} + P_{\mathrm{cr}}} \, , \qquad (5)$$

where P_{g}, P_{m0}, P_{mt}, and P_{cr} are the pressures of gas, regular and random galactic magnetic fields, and cosmic rays, respectively. The instability gives rise to large-scale turbulence and helps sustain an almost equipartition energy distribution among cosmic rays, magnetic fields, and turbulent gas motions. The characteristic time for instability development is $\sim 10^7$ years in the gaseous disk of the Galaxy, and $\sim 10^8$ years in the gas halo. Paper [47] showed that magnetic arches and loops appearing above the galactic disk due to the action of cosmic rays are necessary for a $\alpha\omega$-dynamo to operate, which is the primary mechanism of magnetic field generation in the Galaxy.

It is possible that the gas in the halo is not in static equilibrium but is involved in large-scale convective motions (the galactic wind). The existence of the supersonic galactic wind in our Galaxy due to the high temperature of the interstellar gas in the galactic disk appears unlikely since the actual gas temperature is not high enough. However, the galactic wind can be supported by cosmic ray pressure. In Refs [48, 49], a model is constructed in which cosmic rays, after leaving the sources (supernova remnants), determine the wind outflow in the rotating Galaxy with a frozen magnetic field. Here, the stream instability of cosmic rays exiting the Galaxy along the spiral magnetic field leads to the MHD turbulence generation, which self-consistently determines the transfer of relativistic particles. The outflow velocity is ~ 30 km s^{-1} at a distance of ~ 3 kpc; it becomes supersonic at a distance of ~ 20 kpc, and speeds up to a velocity of ~ 400 km s^{-1} several hundred kiloparsecs away. The external pressure of the intergalactic gas produces a shock wave at a distance of ~ 300 kpc. In this model, the diffusion coefficient of particles is not given independently and is consistently calculated, being dependent on the power of sources and the spectrum of accelerated particles. Remarkably, the obtained transport coefficients and other model parameters are consistent with the empirical diffusion model for cosmic ray propagation in the version with the galactic wind [7, 13].

5. Cosmic rays in supernova remnants

There are a lot of observations evidencing the presence of relativistic particles in shell-like supernova remnants. The results of the observations can be summarized briefly as follows.

(1) Supernova remnants are sources of synchrotron radio emission which suggests the presence of relativistic electrons there with a total energy of $10^{48}-10^{49}$ erg and the spectrum $E^{-1.9}-E^{-2.5}$ in the particle energy range 50 MeV – 30 GeV [6, 50, 51]. This is sufficient to provide the electron density observed in cosmic rays, assuming a galactic supernova explosion rate of $\nu_{\mathrm{sn}} \sim 1/30$ y^{-1}.

(2) Synchrotron emission in the X-ray range up to several keV was established first for SN 1006 [52] and then for other young supernova remnants with ages of 300–2000 years, including Cas A, RX J1713.7-3946, RX J0852-46, Tycho, RCW 86, and Kepler, suggesting the presence of electrons with energies up to $\sim 10^{13}$ eV and possibly higher. The emission is generated in a narrow region immediately behind the shock front, in which downstream electrons, accelerated at the front, lose energy via synchrotron radiation. The size of the emission region enables determination of the magnetic field intensity, which turns out to be quite significant up to several hundred microgauss (see Ref. [53]).

(3) The presence of the proton-nuclear component of cosmic rays can in principal be established from gamma-ray emission of supernova remnants, originated in the process $\mathrm{pp} \to \pi^0 \to \gamma\gamma$ which is effective in relatively high-density

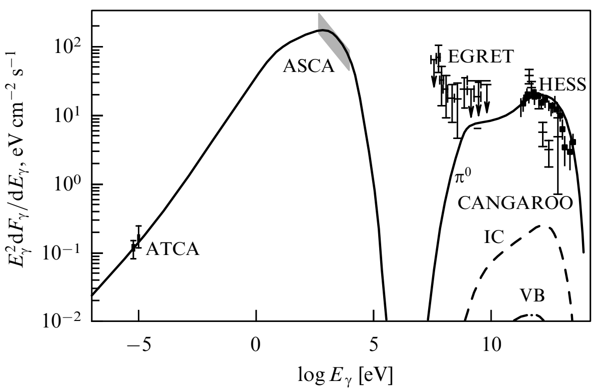

Figure 3. The emission spectrum of the supernova RX J1713.7-3946 remnant and its modeling [62]; F_γ is the photon flux in units [cm^{-2} s^{-1} eV^{-1}]. The results of calculations for the synchrotron radiation and gamma-ray emission due to π^0-decays are shown by solid lines; the dashed line depicts the contribution from the Compton scattering (IC), the dash-dotted line involves the bremsstrahlung radiation (VB). (ATCA: Australia Telescope Compact Array, ASCA: Advanced Satellite for Cosmology and Astrophysics, CANGAROO: Collaboration of Australia and Nippon for a Gamma-Ray Observatory in the Outback, and HESS: High Energy Stereoscopic System.)

regions. The analysis of the EGRET data for gamma-photon energies of 30 MeV – 30 GeV indicates the presence of the expected excess of the emission from several extended supernova remnants, including γ Cygni, IC433, and Monoceros [54, 55]. Testing this result is expected from the GLAST mission.

(4) In about the last five years, reliable evidence has appeared on TeV gamma-ray emission from the shells of young supernova RX J1713.7-3946 [56 – 58], Cas A [59], RX J0852-46 [60] remnants, and approximately three other supernova remnants (their identification is not always unique), which were detected in the course of the galactic plane survey for $-30° < l < 30°$ carried out by the HESS (High Energy Stereoscopic System) experiment [61], which registers Cherenkov atmospheric emission. The emission spectrum is close to E^{-2}, with the maximum photon energy detected reaching ~ 40 TeV. Most likely, the emission is produced by protons and nuclei accelerated up to energies $E \sim 5 \times 10^{14}$ eV per nucleon (see the discussion in Refs [56 – 62]). Electrons can also be the source of TeV photons through Compton up-scattering of the background radiation, but this mechanism requires comparatively low values of the magnetic field within the limits 10 – 30 μG (the field value is determined from the ratio of the Compton-to-synchrotron emission fluxes), which generally is not supported by observational data. Paper [61] concludes that observations of TeV emission from shell-like supernova remnants suggest that around 20% of kinetic energy of the expanding supernova shell is, on average, transferred to the proton-nuclear component of cosmic rays and that supernova remnants can produce this radiation for about 10^4 years. This conclusion supports the idea that supernova remnants are the principal sources of cosmic rays in the Galaxy.

Figure 3 shows an example of calculations of the emission from a supernova remnant in the entire range of the electromagnetic spectrum. The calculations were carried out in paper [62] for the source RX J1713.7-3946. It should be noted that the density ratio of the accelerated electrons to protons required by this simulation turns out to be an order of magnitude smaller than the directly observed cosmic ray value $\sim 1 - 2\%$ at an energy of 1 GeV.

6. Particle acceleration in supernova remnants

Let us now discuss the cosmic ray acceleration mechanism in supernova remnants, which is a version of the first-order Fermi acceleration [63]. The acceleration occurs in the shock-compressed gas stream due to numerous intersections of the shock front by rapid diffusing particles [64, 65] (see also reviews in Ref. [9]). The momentum distribution of particles has the form $N(p) \sim p^{-(r+2)/(r-1)}$, where r is the gas compression in the shock, so that $N(p) \sim p^{-2}$ for the maximum compression $r = 4$ of ideal monatomic gas in the strong shock without radiation loss. The acceleration turns out to be quite significant and for large Mach numbers of the shock wave, $M \gg 1$, the pressure of accelerated particles at the shock front reaches the values of $P_{\rm cr} = \xi_{\rm cr} \rho u_{\rm sh}^2$, where $\xi_{\rm cr} \sim 0.5$ [66] (here, ρ is the interstellar gas density, and $u_{\rm sh}$ is the shock front velocity). Such a high efficiency of the acceleration modifies the shock wave profile due to cosmic ray pressure. As a result, the spectrum of accelerated particles at very high energies becomes more flat (hard) than p^{-2}, and for energies below several GeV per nucleon, just the opposite, it becomes more steep.

To accelerate particles on a spherical shock front with radius $R_{\rm sh}$, the following condition must be satisfied:

$$D(p) \leqslant 0.1 u_{\rm sh} R_{\rm sh} , \qquad (6)$$

where the numerical value of the factor on the right-hand side is approximate.

The maximum value in the r.h.s. of relation (6), which is on the order of $10^{28} (W_{51}/n)^{2/5}$ [cm^2 s^{-1}], is attained at the beginning of the Sedov stage of the evolution of the shock generated by a supernova explosion with the kinetic energy $W = 10^{51} W_{51}$ [erg] in the interstellar medium with the density n [cm^{-3}]. The standard diffusion coefficient (1) or (2) of cosmic rays in the interstellar medium is too high to provide the acceleration. The necessary anomalously low value of the diffusion coefficient can be self-consistently provided by accelerated particles themselves due to the stream instability in the shock wave precursor which has the characteristic size $D(p)/u_{\rm sh}$ [65, 67]. The Bohm limit in the interstellar magnetic field, $D = D_{\rm B} = v r_{\rm g}/3$, which assumes a random field amplification up to the values of $\delta B \approx B_{\rm ism}$ on scales necessary for the resonance scattering of particles, has been used for a long time as the most optimistic estimate for the diffusion coefficient appearing in this way. Then, formula (6) gives the estimate $E_{\max} \approx 10^{14} Z$ [eV] of the maximal energy of accelerated particles at the beginning of the Sedov stage and yields weak dependence $E_{\max} \sim t^{-1/5}$ at later times. Under these assumptions, numerical modeling of cosmic ray acceleration and the supernova remnant evolution have been carried out [66, 68].

The development of the theory of strong stream instability in the shock wave precursor [69 – 72] has shown that the use of the Bohm acceleration limit in the interstellar magnetic field is incorrect. For $u_{\rm sh} \gg 10^3$ km s^{-1}, random fields are amplified up to the level $\delta B \gg B_{\rm ism}$, and for $u_{\rm sh} < 10^3$ km s^{-1} random fields $\delta B < B_{\rm ism}$ and rapidly decrease with supernova remnant age due to turbulence dissipation. According to estimates [70], in extreme conditions, which apparently can be realized at the initial stage of shell expansion in supernovae SN Ib/c (SN1998 bw, for example), the random field can be as high as

$$\delta B_{\max} \sim 10^3 \, \frac{u_{\rm sh}}{3\times10^4 \ {\rm km\ s^{-1}}} \, n^{1/2} \ [\mu{\rm G}] \,, \qquad (7)$$

and the maximal energy of accelerated particles can reach

$$E_{\max} \sim 10^{17} Z \, \frac{u_{\rm sh}}{3\times10^4 \ {\rm km^2\ s^{-2}}} \, \frac{\xi_{\rm cr}}{0.5} \, M_{\rm ej}^{1/3} n^{1/6} \ [{\rm eV}] \qquad (8)$$

(here, $M_{\rm ej}$ is the mass of the ejecta measured in solar masses). As was pointed out in Section 5, the presence of a strong magnetic field is confirmed by X-ray observations of young supernova remnants. A very strong field amplification in young supernova remnants is indirect evidence of the acceleration of protons, which is accompanied by a strong stream instability. The predicted strong dependence $E_{\max}(t)$ allows one to understand why TeV gamma-ray emission is observed only from young supernova remnants.

The theoretical spectrum of the sources of galactic cosmic rays was computed in Ref. [72] by means of averaging the spectrum of particles accelerated and injected into the interstellar medium during the supernova remnant lifetime. The averaged source of high-energy protons turned out to have a power-law energy spectrum with a sharp kink near $E_{\rm k}$ close to the energy of the bend:

$$Q \sim \xi_{\rm cr} v_{\rm sn} W E^{-2} \quad \text{for} \quad E \leqslant E_{\rm k} \,, \qquad (9)$$

where $E_{\rm k} = 4\times10^{15}(\xi_{\rm cr}/0.5) W_{51} M_{\rm ej}^{-2/3} n^{1/6}$ [eV], and

$$Q \sim E^{-s} \quad \text{for} \quad E > E_{\rm k} \,, \qquad (10)$$

where $s = 3.5-5$ in different variants of the model. Particles with energies $E < E_{\rm k}$ are accelerated at the Sedov stage; particles with energies $E > E_{\rm k}$ are accelerated at the earlier stage of free expansion when the maximum energy of individual particles is high but the total number of accelerated particles is relatively small, which explains the steep form of the spectrum. For each type of ions, the break appears at the energy $ZE_{\rm k}$ proportional to the charge. These results are basically consistent with observations of the spectrum and composition of cosmic rays [73] and apparently explain the presence of the knee in the spectrum of all particles at an energy of 3×10^{15} eV. To refine the theory, a population analysis taking into account the dispersion of parameters entering formula (9) is needed (see Ref. [74]).

7. Ultrahigh energies

The statement that the density of cosmic rays in the intergalactic space is relatively small as compared to the galactic one relates to particles with not too high an energy, which are effectively accelerated in the galactic sources and are well confined in the galactic magnetic fields. The observed cosmic rays with the highest energies, which apparently have extragalactic origin, are more homogeneously distributed in the Universe. The spectrum of particles with energies exceeding 10^{17} eV as obtained in the HiRes experiment (High Resolution Fly's Eye) is shown in Fig. 4. The sharp flux decrease for $E > 6\times10^{19}$ eV evidences the presence of the blackbody spectral cut-off predicted in papers [76, 77], which is caused by the photopion energy loss in a time on the order of about 4×10^9 years due to the interaction of particles (protons) with cosmic microwave background photons. At proton energies 3×10^{20} eV, the characteristic time of energy losses amounts to $\sim 10^8$ years, so these particles can reach the

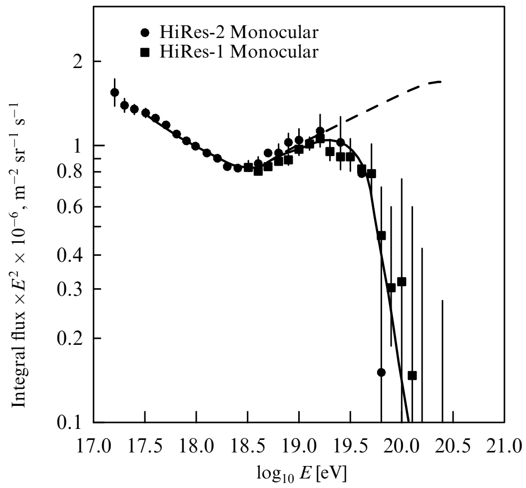

Figure 4. Spectrum of ultrahigh-energy cosmic rays according to the HiRes data [75]. The curves show the presence of the spectral cut-off at an energy of 6×10^{19} eV.

Earth from comparatively small cosmological distances. Possible sources of the ultrahigh energy particles could in principle include active galactic nuclei, interacting galaxies, gamma-ray bursts and some others (see review [78]).

When interpreting the observed spectrum of ultrahigh energy particles two main versions are considered. According to the first version, the flattening of the spectrum at an energy of 4×10^{18} eV (see Fig. 4) is explained as the passage from galactic to extragalactic cosmic rays (see Refs [79, 80] for more detail). Here, the spectrum of extragalactic sources is close to $E^{-2.3}$ and their composition is mixed; more precisely, in the extragalactic sources protons and heavy nuclei are presented in the normal proportion. In another version [81], the passage from galactic to extragalactic cosmic rays in the observed spectrum occurs at energy $\sim 10^{18}$ eV. In the last case, the spectrum of the sources is close to $E^{-2.7}$, and for a purely proton composition the feature at $E \sim 4\times10^{18}$ eV is explained as being due to the contribution to the total energy loss by the microwave background radiation from pair creation. The choice between these alternatives can be made after having measured more accurately the particle composition for energies $E \gtrsim 10^{18}$ eV (see a detailed discussion in Ref. [80]). In any case, it is required that galactic sources accelerate particles up to $E \sim 10^{18}-10^{19}$ eV, which significantly exceeds estimates made in Section 6. Perhaps this issue can be solved by taking into account the contribution from rare hypernovae with a huge energy release, $W \approx 3\times10^{52}$ erg [74]. Another possibility is related to a strong additional acceleration of particles by an ensemble of shocks in O-B star associations [82] or in the galactic wind [83]. The contribution from young neutron stars with a high magnetic field ($\geqslant 10^{13}$ G) and relativistic wind, in which ion acceleration up to $E \sim 10^{20}$ eV is principally possible, is not excluded, either [84].

In general, the main attention in present-day cosmic ray studies is focused on the high-energy region. Clearly understanding the nature of the knee in the particle spectrum at $E \approx 3\times10^{15}$ eV (notice that this feature was experimentally discovered almost 50 years ago [85]), determining the particle acceleration limit in the Galaxy, and analyzing ultrahigh-energy particle acceleration in extragalactic sources are required.

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Ginzburg – Landau equations for high-temperature superconductors

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The phenomenological theory of superconductivity [1] formulated by V L Ginzburg and L D Landau in 1950 (long before the appearance of the Bardeen – Cooper – Schrieffer