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The origin of cosmic rays

V S Ptuskin

1. Introduction

Cosmic ray studies constitute an important part of Sergei Ivanovich Syrovatskii's scientific heritage. The famous book published in 1963 by Ginzburg and Syrovatskii, *The Origin of Cosmic Rays* [1], has become a 'Bible' for scientists working in high-energy astrophysics. Already in this book, which was written before the discovery of quasars, cosmic background radiation, and pulsars, during the days when information on cosmic rays beyond the Solar System was based primarily on radio astronomy data, the foundations of the cosmic ray origin model were formulated, which remain firm up to this day. The model developed in Ref. [1] is based on the following assumptions: the main component of cosmic rays is of galactic origin, the cosmic rays diffuse in interstellar magnetic fields and fill a vast halo, the cosmic ray sources are supernova explosions, and the highest-energy particles (according to the modern nomenclature, cosmic rays with energies above $10^{18}-10^{19}$ eV) have an extragalactic origin. In 1979, shortly after Syrovatskii's death, Ginzburg suggested to several colleagues working in this field to jointly write a book on this topic. The book *Astrophysics of Comic Rays*, edited by Ginzburg, was published in 1984, and a second edition appeared in 1990. It included new chapters such as gamma-ray and neutrino astronomy, and a kinetic description of cosmic ray acceleration and propagation processes. In a certain sense, that book was a comprehensive summary of many years of collaborative work of Ginzburg, Syrovatskii, and their colleagues in the field of cosmic ray astrophysics.

In this brief communication, we describe, some recent results of research into the origin of cosmic rays.

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2. Galactic cosmic rays: acceleration in supernovae and propagation in galactic magnetic fields

Because of their energy characteristics, supernovae and their remnants are the most suitable galactic cosmic ray sources [1]. To obtain the observed energy density of cosmic rays, ≈ 1.5 eV cm^{-3}, approximately 10–20% of the kinetic energy of a supernova burst should be converted into the energy of relativistic particles. It is assumed that the kinetic energy of a supernova explosion is 10^{51} erg and that galactic supernova outbursts occur every 30 years on average. Direct evidence of the presence of relativistic particles in supernova remnants follow from nonthermal radiation observations in the radio, X-ray, and gamma-ray ranges. Synchrotron radio emission data indicate that there are electrons with energies 50 MeV–30 GeV in supernova remnants such as Cas A, IC 433, Cygnus Loop, and many others [3]. In the case of Cas A, the synchrotron radiation was detected in the infrared range, which indicates that there are electrons with energies up to 200 GeV. The nonthermal X-ray radiation with a characteristic power-law spectrum and energy up to a few dozen keV detected from bright rims in approximately ten young galactic supernova remnants, including SN1006, Cas A, RXJ 1713.7-3946, RX J08852-46/Vela Jr, RCW86, and G266.2-1.2 can be explained by synchrotron emission of very-high-energy electrons, up to 10–100 TeV (see review [4]). The inverse Compton scattering of background photons by such high-energy electrons, and gamma-ray emission via π^0-meson production and decays in interaction processes of protons and nuclei with energies up to ~ 100 TeV with gas nuclei, explain the presence of TeV gamma emissions detected from a number of young shell-type supernova remnants [5]. Spatial distribution of nonthermal emission in all frequency ranges demonstrates that particle acceleration occurs directly on the shock wave produced by the supernova explosion.

Cosmic ray composition data also confirm that particle acceleration occurs on a shock wave propagating in the interstellar medium or presupernova wind (see [6] for the details). In particular, it turns out that after accounting for the atomic properties such as the first ionization potential or volatility (the composition of matter deposited on the interstellar dust is volatility dependent), the chemical composition of cosmic ray sources is close to the typical composition of the local interstellar medium or solar photosphere. The ion and dust acceleration probably occurs in the partially ionized interstellar gas and/or hot interstellar gas bubbles with a high rate of supernova outbursts. The relatively high abundance ratio of ^{59}Co/^{56}Fe isotopes in the material of cosmic ray sources shows that most ^{59}Ni isotopes synthesized in a supernova explosion have time to decay into ^{59}Co isotopes due to orbital electron capture before the particle acceleration begins. It therefore follows that the acceleration occurs no less than 10^5 years after the nucleosynthesis process.

The mechanism of cosmic ray acceleration in supernova remnants is a version of the first-order Fermi acceleration. Acceleration of fast particles occurs in a gas flow that is compressed on the shock wave owing to multiple shock wave front crossings by diffusing fast particles [7, 8] (see also reviews [6, 9]). The particle diffusion is due to their scattering on magnetic field inhomogeneities. This scattering has a resonant character, and therefore a particle with a gyroradius r_g mostly interacts with inhomogeneities with the wavenumber $k \sim 1/r_g$. The particle diffusion coefficient can be estimated as $D \approx v r_g B^2 (3B_{\rm res}^2)^{-1}$, where v is the particle velocity, B is the total magnetic field, and $B_{\rm res}$ is the random magnetic field at the resonant scale $1/k \sim r_g$. The momentum distribution function of accelerated particles has a power-law character, $f(p) \propto p^{-3r/(r-1)}$, where r is the gas compression ratio on the shock wave (the function $f(p)$ is related to the cosmic ray intensity $I(E)$ as $p^2 f(p) = I(E)$, where E is the particle energy). The ultimate gas compression in a strong shock wave propagating in a monatomic gas without luminescence is $r = 4$, which for ultrarelativistic energies results in the accelerated particle spectrum $I(E) \sim E^{-2}$. This applies to the test-particle acceleration. For effective acceleration on a shock wave produced by a supernova explosion, the relativistic particle pressure becomes so strong that the shock wave profile is modified and the emerging self-consistent spectrum of accelerated particles essentially differs from that of test particles: it steepens for nonrelativistic energies and can flatten to $\sim E^{-3/2}$ in the highest energy range.

The necessary condition for acceleration is the inequality $D \leqslant 0.1 u_{\rm sh} R_{\rm sh}$, where $u_{\rm sh}$ and $R_{\rm sh}$ are the shock wave velocity and radius, and the numerical factor 0.1 is calculated approximately. The expression in the right-hand side of this inequality reaches the maximum value $\sim 10^{27}(W_{51}/n)^{2/5}$ [cm^2 s^{-1}] at the beginning of the Sedov phase of supernova remnant evolution; here, the supernova explosion energy is $W_{\rm sn} = 10^{51} W_{51}$ [erg], and n is the interstellar gas number density in cm^{-3}. But the typical value of the galactic cosmic ray diffusion coefficient is $D_{\rm G} \sim 10^{28}$ cm^2 s^{-1} for the particle energy 1 GeV per nucleon, increasing as the energy increases; this becomes too large to ensure the relativistic particle acceleration. Therefore, an anomalously low diffusion is necessary near the shock wave front, including the region directly before the front. This is ensured by the accelerated particles themselves that leave the acceleration region and create an enhanced level of magnetohydrodynamic (MHD) turbulence owing to the streaming instability. The weak turbulence theory predicts a significant amplification of the random magnetic field δB for shock waves with a large Mach number; but the theory cannot adequately describe the field increase up to a value comparable with the background interstellar magnetic field $B_0 = 5$ μG. Assuming that $\delta B = B_0$, we can obtain the so-called Bohm diffusion coefficient $D_{\rm B0} = v r_g/3 \sim 6 \times 10^{21} \beta R_{\rm m}$ [cm^2 s^{-1}] that is the low limit for the particle diffusion coefficient along the magnetic field (here, $\beta = v/c$, and $R_{\rm m} = pc/Z$ is the magnetic rigidity for a particle with the charge Z). The Bohm diffusion coefficient can accelerate particles up to the maximum energy $E_{\max} \sim 2 \times 10^{14} Z (W_{51}/n)^{2/5}$ [eV], which is reached at the beginning of the Sedov phase of supernova remnant evolution. Until recently, the assumption of the Bohm diffusion coefficient $D_{\rm B0}$ near the shock wave in a supernova remnant was common in the analysis of cosmic ray acceleration (see Ref. [10]).

Recent advances [11–14] in the theory of the strong streaming instability of cosmic rays in a shock wave precursor demonstrate that it is incorrect to use the Bohm acceleration limit in the interstellar field. In particular, it turns out that the stochastic field increases to $\delta B \gg B_0$ for $u_{\rm sh} \geqslant 10^3$ km s^{-1}, while it rapidly decreases to $\delta B < B_0$ for $u_{\rm sh} < 10^3$ km s^{-1} with the supernova remnant age, due to the dissipation of turbulence. Under extreme conditions, which can apparently occur at the initial phase of supernova shell expansion, the random field can reach the value $\delta B_{\max} \sim 10^3 (u_{\rm sh}/3 \times 10^4$ [km s^{-1}]$)\, n^{1/2}$ [μG], and the maximum energy of accelerated particles can reach the value $E_{\max} \sim 10^{17} Z (u_{\rm sh}/3 \times 10^4$ [km s^{-1}]$)^2 M_{\rm ej}^{1/3} n^{1/6}$ [eV] (here, $M_{\rm ej}$ is the discarded shell mass in units of solar masses). The presence of a strong magnetic field is confirmed by observations of nonthermal X-ray emission from young supernova remnants. A large field increase in the young remnants is indirect evidence of proton acceleration accompanied by a strong streaming instability. The dependence $E_{\max}(t)$ predicted by the streaming instability theory is stronger than the dependence $E_{\max} \sim t^{-1/5}$ obtained under the Bohm diffusion assumption with the coefficient $D_{\rm B0}$, which allows understanding why the TeV gamma emission is only observed from relatively young supernova remnants. Another consequence of the strong magnetic field is the steepening of the accelerated particle spectrum because of the Alfvén particle drift effect behind the shock wave front (particle drift is caused by Alfvén waves propagating mostly away from the shock wave front), which seems to reconcile the galactic cosmic ray spectrum and the empirical model of cosmic ray origin.

Figure 1 shows the spectrum of cosmic rays in the interstellar medium calculated in Ref. [15]. The proton, helium, and iron spectra are given in the kinetic energy range from 1 GeV per nucleon to 10^3 GeV per nucleon, where reliable data for particular ion types exist, and total spectra of protons and all ions up to iron ions for the energy $E \geqslant 10^3$ GeV per particle. The absolute normalization of various ion sources is done by matching with observed cosmic ray intensities and compositions at the same particle energy 10^3 GeV. The simulations were done using a numerical code that allows modeling the evolution of a spherical shock wave generated by a supernova explosion, and particle acceleration accounting for back reaction of the particle pressure on the hydrodynamic flow. The cosmic ray acceleration is taken into account in type-Ia, IIP, Ib/c, and IIb supernova remnants. Conversion of the supernova explosive kinetic energy into the energy of accelerated cosmic rays becomes efficient at the beginning of the Sedov (adiabatic) phase of the shock wave evolution, i.e., when the supernova outburst mass equals the gas mass 'grabbed' by the shock wave. As a result, a characteristic break — a 'knee' — appears in the particle spectrum averaged over the total time of acceleration by the evolving shock wave. The knee energy is approximately estimated as $p_{\rm knee} c/Z \sim 1 \times 10^{15} W_{51} n^{1/6} M_{\rm ej}^{-2/3}$ [eV]. The calculated spectra agree well with observations up to energies $\sim 5 \times 10^{18}$ eV (this is the maximum energy of iron nuclei accelerated in type-IIb supernova remnants). Owing to summation over all supernova types and various nuclei, the knee is reproduced in the spectra of all particles at the energy 3×10^{15} eV. Overall, approximately 1/3 of the supernova explosion kinetic energy is converted into cosmic rays.

It is assumed in the above calculations that the ultrarelativistic particle diffusion coefficient in the interstellar medium outside the source area depends on the momentum as $D \propto (p/Z)^{0.54}$ in the entire energy range considered [17]. This dependence can actually be established only up to energies of the order of several hundred GeV per nucleon,

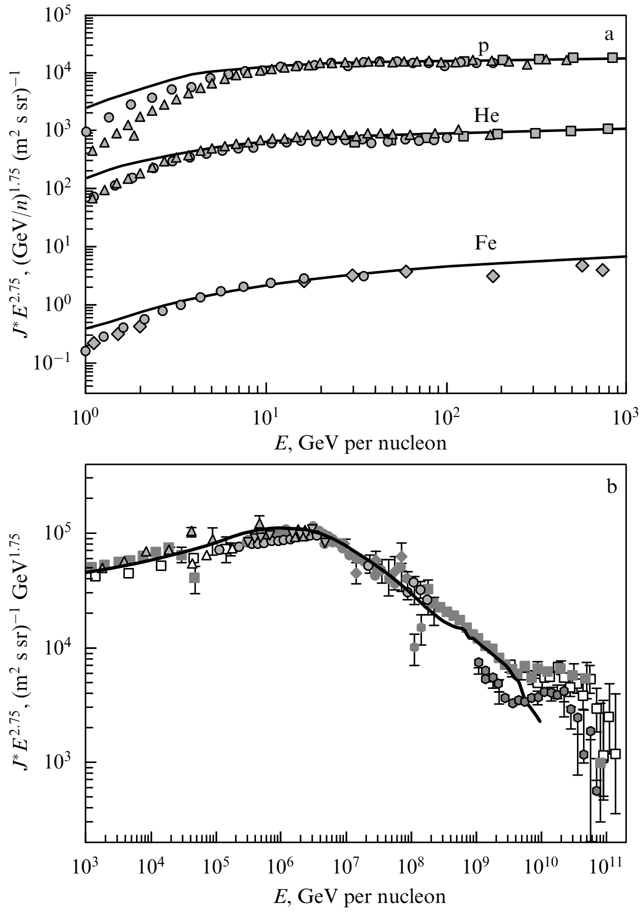

Figure 1. (a) The calculated proton, helium, and iron spectra in the interstellar medium (without the solar wind modulation effect at small energies). Observation data are taken from Ref. [15]. (b) The calculated total spectrum for all particles with energies higher than 10^3 GeV. Observation data are taken from Ref. [16].

for which there are data on the content of secondary nuclei in the cosmic ray composition. (Secondary nuclei such as deuterium, tritium, beryllium, boron, and a number of others are rare in nature; in cosmic rays, they appear as a result of nuclear fragmentation of heavier primary nuclei that traverse the thickness of interstellar matter $\sim 10\ \text{g cm}^{-2}$ before leaving the Galaxy.) Physical reasons based on examining particle diffusion in the galactic magnetic fields suggest that the required power-law momentum dependence of the diffusion coefficient extends to energy values of the order of $E/Z \sim 10^{17}$ eV [2]. Refining the cosmic ray propagation features at higher energies requires additional trajectory simulations with various assumptions on the structure of the galactic magnetic field, including the possible presence of the galactic wind with a frozen-in magnetic field and with typical scales of a few hundred kiloparsecs.

Supernova remnants are the main but by no means the only relativistic particle source in the interstellar medium. In particular, pulsars generating high-energy electron–positron pairs can be responsible for the positrons observed in cosmic rays. The measured flux of positrons with energies higher than 10 GeV [18] is stronger than the expected flux of secondary positrons produced in cosmic ray interactions with interstellar gas atoms, and the pulsar contribution explains this contradiction in principal. It is very important to finally clarify the nature of such a high positron flux in cosmic rays because an alternative explanation suggests that these positrons are products of dark matter decay (see the discussion in Refs [19, 20]).

3. Ultrahigh-energy cosmic rays

The core problem for the astrophysics of cosmic rays remains the issue of the origin of particles with ultrahigh energy $E > 10^{19}$ eV. The observed sharp decrease in the particle flux for energies higher than 5×10^{19} eV [21, 22] indicates that these particles interact with the cosmic background radiation photons for more than 3×10^9 years and are of extragalactic origin. Such ultrahigh-energy protons lose energy through electron–positron pair production and pion production (the Greisen–Zatsepin–Kuzmin effect [23, 24]), and the nuclei, in addition, undergo photodecay. Cosmic rays with energies less than 10^{17} eV observed near Earth are of galactic origin and were accelerated in supernova remnants. The characteristic energy value E_c in the range $10^{17}\ \text{eV} < E_c < 10^{19}$ eV, corresponding to the galactic component being changed by the extragalactic one, is debatable [25].

Simple estimates [16, 26, 17] show that from the standpoint of energy balance, jets of active galactic nuclei can be the sources of observed ultrahigh-energy cosmic rays. To maintain the cosmic ray intensity observed at energies higher than 10^{19} eV in the interstellar medium, the source power about $3 \times 10^{36}\ \text{erg s}^{-1}\ \text{Mpc}^{-3}$ is necessary. This value apparently increases by at least an order in magnitude when the contribution of less energetic particles is taken into account. At the same time, jets of active galactic nuclei release kinetic energy of the order of $10^{40}\ \text{erg s}^{-1}\ \text{Mpc}^{-3}$, and approximately 2% of this energy is in jets with the power $L_{\text{jet}} = 10^{44} - 10^{46}\ \text{erg s}^{-1}$, which is typical for radio galaxies and quasars with large radio luminosity. The value $L_{\text{jet}} = 10^{40} - 10^{44}\ \text{erg s}^{-1}$ is characteristic for numerous less powerful jets.

Without detailing the cosmic ray acceleration mechanism in jets, the Hillas criterion [28] can be used to estimate the maximum energy $E_{\max}$ that particles with the charge Ze can acquire in an acceleration region of size l, with the magnetic field B, and the magnetic field transfer velocity $u = \beta c$: $E_{\max} = Ze\beta Bl$. We note that this estimate is valid up to a numerical factor, for example, in the case of particle diffusion acceleration on a shock wave front in a supernova remnant by assuming the Bohm diffusion in the field B for energetic particles near the shock wave front. To estimate the magnetic field, we assume that the energy flux of the frozen statistically isotropic magnetic field in the jet is related to the kinetic energy flux as $L_{\text{jet}} = \beta c (B^2/6\pi)\pi R^2$, where $R = l/2$ is the jet cross section and βc is its velocity. As a result, we obtain the following estimate for the maximum possible energy of accelerated particles [29–32]:

$$E_{\max} = Ze\left(\frac{6\beta}{c}\,L_{\text{jet}}\right)^{1/2} \approx 2.7 \times 10^{20} Z\beta^{1/2} L_{\text{jet},\,45}^{1/2}\ [\text{eV}]\,,$$

where the notation $L_{\text{jet},45} = L_{\text{jet}}[(10^{45}\ \text{erg s}^{-1})^{-1}]$ is used. The maximum detected energy of cosmic ray events is approximately 2×10^{20} eV.

The above estimates demonstrate that according to general energy characteristics and the maximum possible energy value of accelerated particles, jets of galaxies with active nuclei can be the main sources of the highest-energy cosmic rays observed. More detailed discussions can be found in reviews [16, 27].

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