Acceleration of cosmic rays

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Abstract. Cosmic ray (CR) origin problem is briefly discussed. It is argued that CRs with energies up to $10^{17}$ eV are produced in galactic supernova remnants, whereas ultra high energy CRs are extragalactic. CR composition strongly changes within the transition from galactic to extragalactic CR component, therefore precise measurements of CR composition at energies $10^{17} - 10^{19}$ eV are needed for the reliable determination of this transition. The possible sources of extragalactic CRs are briefly discussed. It is argued that CR acceleration at the shock created by the expanding cocoons around active galactic nuclei has to be considered as a prime candidate for the sources of extragalactic CRs.

1. Introduction

The origin of cosmic rays (CR) is still an unresolved problem in astrophysics. The understanding of CR origin requires determination of astrophysical objects, which are the CR sources, and appropriate acceleration processes, which form CR spectrum in these objects. In this regard, during the last several years considerable progress has been achieved experimentally and theoretically as well. Recently the steepening of CR spectrum above $3 \times 10^{19}$ eV was established in HiRes [1] and Auger [2] experiments. It is presumably Greizen-Zatsepin-Kuzmin (GZK) cutoff, caused by CR energy losses in their interactions with cosmic microwave background radiation. Therefore it becomes evident that the highest energy part of CR spectrum is of extragalactic origin. At the same time it was also recently demonstrated [3] that CRs with energies up to $\epsilon \sim 10^{17}$ eV are presumably produced in supernova remnants (SNRs).

Below we briefly discuss the most essential aspects of CR spectrum formation.

2. CR acceleration in SNRs

The main reason why SNRs are usually considered as the CR source is a simple argument about the energy required to sustain the galactic CR population against loss by escape, nuclear interactions and ionization energy loss. Supernovae have enough power to drive the CR acceleration if there exists a mechanism for channeling about 10% of the mechanical energy release into relativistic particles. The high velocity ejecta produced in the supernova explosion interacts with the ambient medium to produce a strong blast wave. This outer shock may accelerate a small suprathermal fraction of the ambient plasma to high energies (e.g. [4, 5, 6]).

The only theory of particle acceleration which at present is sufficiently well developed and specific to allow quantitative model calculations is diffusive acceleration [7, 8] applied to the strong outer shock associated with SNRs (e.g. see [4, 5, 6] for review). Considerable efforts have been made during the last years to empirically confirm the theoretical expectation that the main
part of CRs indeed originates in SNRs. Theoretically, progress in the solution of this problem has been due to the development of a kinetic nonlinear theory of diffusive shock acceleration (e.g. [9]). This theory includes all the most relevant physical factors, essential for the SNR evolution and CR acceleration in a SNR, at least in its early very energetic stages, and it is able to make quantitative predictions of the expected properties of CRs produced in young SNRs and their nonthermal radiation. The application of the theory to individual SNRs and their known synchrotron emission [5, 10, 6] has demonstrated its capability of explaining the observed SNR properties and in calculating new effects like the extent of magnetic field amplification which leads to the concentration of the highest-energy electrons in a very thin shell just behind the shock.

Nonlinear kinetic theory of CR acceleration in SNRs explains the existing measurements of CRs with energies up to $\epsilon \sim 10^{17}$ eV [3]. As it is seen in Fig.1, where CR differential intensity $J(\epsilon)$ as a function of total energy $\epsilon$ of CR particle is shown, the observed CR spectrum can be well represented by two components [3]. The first one $J^{g}(\epsilon)$, dominated up to $10^{17}$ eV, consists of CRs, produced in galactic SNRs, whereas the second, $J^{eg}(\epsilon)$, is produced in extragalactic sources. This so called dip scenario [11] requires relatively steep CR spectrum produced in extragalactic sources, $J^{eg}(\epsilon) \propto \epsilon^{-\gamma}$ with $\gamma \approx 2.7$ at energies $\epsilon > 10^{18}$ eV. Note that compared with the source spectrum $J^{eg}(\epsilon)$ the extragalactic component $J^{eg}(\epsilon)$, observed in the Galaxy, is modified by two factors. At energies $\epsilon > 10^{18}$ eV the shape of $J^{eg}(\epsilon)$ is influenced by the energy losses of CRs in intergalactic space as a result of their interaction with the cosmic microwave background that leads to the formation of a "dip" structure at $\epsilon \sim 10^{19}$ eV, and to a GZK-cutoff for $\epsilon > 3 \times 10^{19}$ eV [11]. At $\epsilon < 10^{18}$ eV the spectrum $J^{eg}(\epsilon)$ is determined by the character of CR propagation in intergalactic space, followed by adiabatic cooling [11]. Since a galactic wind is expected to exist, CRs penetrating into the Galaxy from outside are in addition subject to modulation by the wind [3].

Figure 1. CR intensity as a function of energy [3]. The dashed and dash-dotted lines represent galactic and extragalactic components respectively. Data obtained in the ATIC-2 [12], JACEE [13], KASCADE [14], Akeno - AGASA [15], HiRes [16] and Yakutsk [17] experiments are shown as well.

3. Reacceleration of galactic CRs
If the spectrum of extragalactic CRs is as hard as $J^{eg} \propto \epsilon^{-2}$, then in this so called ankle scenario extragalactic CRs dominate in the observed CR spectrum only above $10^{19}$ eV [11, 18]. In this case except SNRs there is another galactic CR source (component B according to Hillas’s [19] definition), which significantly contributes in the energy interval $10^{17} - 10^{19}$ eV. The most natural way to produce a smooth extension of the spectrum of CRs created in SNRs towards the higher energies is some kind of reacceleration process which picks up the most energetic CRs from SNRs and increases their energy up to a factor of 100. Such a process can be modeled in a following
way. Instead of \( J_i^g(\epsilon) \) as in the dip scenario we use for every CR element \( i \) the spectrum \( J_i^g(\epsilon) \), which coincides with \( J_i^g(\epsilon) \) at \( \epsilon < \epsilon_{\text{max}1}^i \) and has a power-law form with exponential cutoff

\[
J_i^g(\epsilon) = J_i^g(\epsilon_{\text{max}1}^i)(\epsilon/\epsilon_{\text{max}1}^i)^{-\gamma}\exp(-\epsilon/\epsilon_{\text{max}2}^i)
\]

at \( \epsilon > \epsilon_{\text{max}1}^i \). Here \( \epsilon_{\text{max}1}^i \) is minimal energy of particles involved into reacceleration and \( \epsilon_{\text{max}2}^i \) is maximal particle energy achieved during reacceleration. It is natural to assume that these energies are proportional to the particle rigidity \( \epsilon_{\text{max}}^i = Z_i e_{\text{max}}^p \). Here \( Z_i \) is charge number of CR element \( i \) and subscript \( p \) denotes protons. Quantities \( e_{\text{max}}^p, e_{\text{max}}^p \) and \( \gamma \) are treated as a free parameters, which values are determined as a result of best fit. CR acceleration by spiral shocks in the galactic wind [20] or CR acceleration in the pulsar vicinity [21, 22] could play a role of reacceleration mechanism.

According to Fig.2 the CR spectrum calculated within the ankle scenario with \( e_{\text{max}}^p = 5 \times 10^{15} \text{ eV}, e_{\text{max}}^p = 1.5 \times 10^{17} \text{ eV} \) and \( \gamma = 3 \) is also in reasonable agreement with the experiment. Note, however that such a well-known peculiarity in CR spectrum as a knee at \( \epsilon \approx 3 \times 10^{15} \text{ eV} \) is much less pronounced in the theoretical CR spectrum. This can be considered as indication against the ankle scenario.

4. Transition from galactic to extragalactic CRs

It was noted [3, 23] that CR chemical composition is expected to be very different in these two cases - dip and ankle scenario - at energies \( 10^{17} - 10^{19} \text{ eV} \). It is indeed very clearly seen in Fig.3, where the mean logarithm of CR atomic number as a function of CR kinetic energy \( \epsilon_k \) is presented, for these two scenarios [23]. Since maximal energy of CRs produced in SNRs scales as \( \epsilon_{\text{max}}^i = 3Z_i \times 10^{15} \text{ eV} \) CR composition progressively changes from proton-dominated to iron-dominated as the energy increases from \( \epsilon = 3 \times 10^{15} \text{ eV} \) to \( \epsilon = 3 \times 10^{17} \text{ eV} \). Within the dip scenario after reaching the peak value at \( \epsilon \approx 3 \times 10^{17} \text{ eV} \) the quantity \( \ln A > \) goes down at higher energies \( \epsilon > 3 \times 10^{17} \text{ eV} \) towards the value \( \ln A > \approx 0.3 \), which corresponds to extragalactic CRs (see Fig.3).

Since reacceleration produces a power law tail of CR iron spectrum originally produced in SNRs up to the energy \( \epsilon \approx 4 \times 10^{18} \text{ eV} \), within the ankle scenario CR spectrum is expected to be dominated by the iron contribution at energies \( 10^{17} < \epsilon < 10^{19} \text{ eV} \). As it is seen in Fig.3 CR atomic number is indeed almost constant \( \ln A > \approx 2.5 \) at these energies, that is very much different from what is expected within the dip model.

Yakutsk data as it is seen in Fig.3 better agree with the ankle scenario. Note however that CR composition determined on the basis of measurements accomplished by different instruments are not in agreement with each other. Contrary to the Yakutsk data, HiRes [16]
and Auger [30] data reveals considerably lighter CR composition with $<\ln A > \approx 1.5$ at energies $3 \times 10^{17} < \epsilon < 2 \times 10^{19} \text{ eV}$.

5. Extragalactic CR sources

Astrophysical objects, which can be considered as potential extragalactic sources of ultra high energy CRs, should fulfill a number of conditions (e.g. [18]). First, they should have sufficiently high energy output, not less than $L_p \sim 2 \times 10^{45} - 3.5 \times 10^{46} \text{ erg Mpc}^{-3}\text{yr}^{-1}$ depending on the form of CR spectrum, which they produce. According to this energetic requirements active galactic nuclei (AGN) (e.g. [18]) and gamma-ray bursts (GRBs) [25, 27, 26] are considered as a potential extragalactic sources of ultra high energy CRs. However, as it was argued [18], the energy output of GRBs has a serious problem to be considered as a main source of extragalactic CRs.

The second requirement to extragalactic CR sources is their ability to produce power-law CR spectrum up to the maximal energy, not less than $\epsilon_{\text{max}} = 10^{20} \text{ eV}$, that is well above GZK-cutoff. Particle acceleration at relativistic shocks in AGNs [31] and GRBs [25, 27, 26] and frictional acceleration at the sides of AGN jets [32] are discussed as an appropriate acceleration processes. Particles are effectively accelerated at the relativistic shock under the condition of their nearly isotropic scattering in the downstream region [33]. However, simulations of CR shock acceleration performed for realistic parameters of the upstream medium [34] demonstrated insufficient CR scattering in downstream region leading to low efficiency of CR acceleration.

Since many aspects of CR acceleration by nonrelativistic shocks are very well studied one can obtain the most reliable estimate of the expected spectrum of CRs produced by nonrelativistic shocks in extragalactic objects [35]. In this case the maximal energy of CRs, accelerated at the expanded shock of size $R(t)$ and speed $V = dR/dt$, is determined by the expression [36]

$$\epsilon_{\text{max}} \approx ZeBRV/c, \quad (2)$$

where $B$ is the upstream magnetic field, $c$ is the speed of light, $e$ is the proton charge. Magnetic field near the shock front, as it was established for all young SNRs [5, 6], is strongly amplified up to the level

$$B^2/(8\pi) \sim 10^{-3}\rho V^2, \quad (3)$$

which is presumably also appropriate for extragalactic shocks. Here $\rho$ is the external gas density. If the shock is produced due to the prompt energy release $E$, like the supernova shock, then the CRs with maximal energy are produced at the beginning of the Sedov evolutionary phase $t = t_0$, where $t_0 = R_0/V_0$ $R_0 = [3M_{ej}/(4\pi \rho)]^{1/3}$, $V_0 = \sqrt{2E/M_{ej}}$, $M_{ej}$ is the ejected mass.
In the case of GRBs we have $M_{ej} = E/(\Gamma c^2)$, where $\Gamma \approx 100$ is fireball Lorenz factor. Then Eq.(2) gives

$$\epsilon_{max} = 10^{18} Z(E/10^{51} \text{ erg})^{1/3}(N_g/1 \text{ cm}^{-3})^{1/6},$$

(4)

where $N_g = \rho/m_p$ is the ambient gas number density, $m_p$ is the proton mass. This is too small value to consider GRBs as a main sources of extragalactic CRs, if energy release in the GRBs is not essentially higher than $10^{51} \text{ erg}$.

Relativistic jet in AGN is surrounded by the hot cocoon, which expands with the speed (e.g. [37])

$$V_h \approx [L_j/(\rho V_h)]^{1/4} t^{-1/2},$$

(5)

where $L_j$ is the mechanical luminosity of the jet, $V_h$ is the hot spot speed. In this case Eq.(2) gives

$$\epsilon_{max} \approx 10^{20} Z \left(\frac{L_j}{10^{47} \text{ erg/s}}\right)^{3/4} \left(\frac{N_g}{10^{-4} \text{ cm}^{-3}}\right)^{-1/4} \left(\frac{V_h}{10^{10} \text{ cm}/\text{c}}\right)^{-1/4} \left(\frac{l_j}{1 \text{ kpc}}\right)^{-1/2} \text{ eV},$$

(6)

where $l_j = V_h t$ is the jet length. According to this expression proton maximal energy decreases from $\epsilon_{max} = 10^{20}$ eV to $\epsilon_{max} = 10^{18}$ eV when jet length increases from $l_j = 1$ kpc to $l_j = 10$ Mpc. Thus we conclude, that AGNs fulfill also the second requirement for extragalactic CR sources.

Note, that the above expression is based on the amplified magnetic field value (3) and therefore does not depends on the assumed value of intergalactic magnetic field opposite to earlier estimate for $\epsilon_{max}$ [29].

The third requirement to CR sources is related with the form of CR spectrum. Thus for two considered cases one needs power law CR spectrum $J_\epsilon \propto \epsilon^{-\gamma}$ with $\gamma \approx 2.7$ and $\gamma \approx 2$ for dip and ankle scenarios respectively. The form of resultant CR spectrum produced during the whole evolution of the expanding shock is determined by three physical factors: i) nonlinear shock modification due to the CR backreaction; ii) adiabatic energy losses in downstream region; iii) diffusive CR escape from the shock vicinity in the outer space. The existence of CR escape, makes it possible to estimate the shape of spectrum of the most energetic CRs, produced during the source evolution. As it was demonstrated analytically [4, 36] and confirmed numerically [9], particles accelerated by the expanding shock which produces decreasing maximal energy $\epsilon_{max}(t)$ undergo diffusive escape from the shock vicinity into the surrounding space. If such a behavior happens during the period from $t_1$ to $t_2$, then at any given epoch $t_1 < t < t_2$ all accelerated particles with energies $\epsilon > \epsilon_{max}(t)$ are already escaped and inside the source there are only particles with $\epsilon \leq \epsilon_{max}(t)$.

Note, that this phenomenon, particle escape, has two important aspects. First, escaped CRs reach the outer observer with the same energy without any influence of adiabatic cooling inside the parent expanding source. Second, the spectrum of the escaped CRs can be essentially different from the canonical spectrum $N \propto \epsilon^{-2}$, produced by strong nonrelativistic shock. To estimate the spectrum of escaped CRs one can use the simple relation [4, 35]

$$N(\epsilon)\epsilon d\epsilon \propto \rho V^2 R^{2-\beta} dR,$$

(7)

which determines at any given phase $t$ the overall number of CRs $N(\epsilon)$ with highest energy $\epsilon \sim \epsilon_{max}(t)$. Due to hard selfconsistent spectrum of CRs, produced by the strong shock, the main contribution to CR energy content is given by these particles with highest energy $\epsilon \sim \epsilon_{max}(t)$. Therefore their energy content scales as the shock ram pressure $\rho V^2$ times the shock volume, as it is given by Eq.(7). Factor $R^{-\beta}$ describes the progressive decrease of the acceleration efficiency due to the shock weakening. For the expansion law $R \propto t^{-\nu}$ relation (7) gives

$$N(\epsilon) \propto \epsilon^{-\gamma} \quad \text{with} \quad \gamma = 1 + (2-\beta)/(2/\nu - 3).$$

(8)
In our case \( \nu = 1/2 \) that gives \( \gamma = 3 - \beta \). For the constant acceleration efficiency \( \beta = 0 \) and we have \( \gamma = 3 \). However, the shock deceleration accompanies by the decrease of the acceleration efficiency. This effect is described by the amount of shock modification, which is characterized by the shock compression ratio, which for the case of strong shock depends on the shock speed as \( \sigma \propto V^{3/8} \) [9]. Since in our case \( V \propto 1/R \) we have \( \beta = 3/8 \) that gives \( \gamma \approx 2.6 \). Such a spectrum of extragalactic CRs at energies \( \epsilon > 10^{18} \text{ eV} \) very well corresponds to observations [18].

Particles with energies \( \epsilon \leq \epsilon_{\text{max}}(t) \) at any given epoch are contained inside the source and have the spectrum close to \( N \propto \epsilon^{-2} \). At very late epoch when the outer shock becomes weak these particles leave the source. Note however, that this is already not important for the Galaxy, because the contribution of extragalactic CRs expected to be low at energies \( \epsilon < 10^{18} \text{ eV} \) [18].

Note, that based on the data collected at the Auger experiment, correlation between the arrival directions of CRs with energy above \( 6 \times 10^{19} \text{ eV} \) and the position of nearby AGNs has been find [38], that strongly supports AGNs as a prime candidate for the source of ultra high energy CRs.

6. Summary

Magnetic field amplification due to shock accelerated CRs leads to a considerable increase of the maximal energy of CRs produced in SNRs. Calculations performed within nonlinear kinetic theory demonstrate that the expected CR spectrum, produced in SNRs, fits the existing CR data in a satisfactory way up to the energy \( 10^{17} \text{ eV} \) [3]. The first knee in the observed all-particle CR spectrum is attributed to the maximum energy of protons that are produced in SNRs. The steepening of the all-particle CR spectrum above the knee energy \( 3 \times 10^{15} \text{ eV} \) is then the result of a progressive depression of the contribution of light CR nuclei with increasing energy. Such a scenario is confirmed by the KASCADE experiment which shows relatively sharp cutoff spectra of CR species at energies \( \epsilon_{\text{max}} \approx 3Z \times 10^{15} \text{ eV} \) [14].

If the extragalactic CR source spectrum is rather steep, \( J_{eg}^{\gamma} \propto \epsilon^{-\gamma} \) with \( \gamma = 2.5 - 2.7 \), so that it dominates the observed CR spectrum already at \( \epsilon \geq 10^{18} \text{ eV} \), then CRs at lower energies are produced in SNRs without significant contribution from other Galactic CR sources. The CR spectrum up to the energy \( \epsilon = 10^{17} \text{ eV} \) is dominated by the contribution of SNRs, whereas at \( \epsilon > 10^{18} \text{ eV} \) CRs are predominantly extragalactic. If the extragalactic source spectrum is much harder \( J_{s}^{\gamma} \propto \epsilon^{-2} \), then the transition from the galactic to the extragalactic component is expected at higher energy \( \epsilon \sim 10^{19} \text{ eV} \). Since the expected CR chemical composition at \( 10^{17} - 10^{18} \text{ eV} \) is very well consistent with observations [18], such a spectrum is needed to discriminate them.

Chemical CR composition determined at Yakutsk experiment is characterized by CR mean atomic number which increases with energy at \( \epsilon < 3 \times 10^{16} \text{ eV} \), it remains nearly constant \( < \ln A \approx 2.3 \) at \( 3 \times 10^{16} < \epsilon < 4 \times 10^{18} \text{ eV} \) and progressively decreases with energy at \( \epsilon > 4 \times 10^{18} \text{ eV} \). Such a behavior is well consistent with ankle scenario in which CR spectrum consists of three components: CRs produced in SNRs; reaccelerated galactic CRs and extragalactic CRs with hard spectrum. However CR composition deduced from HiRes and Auger experiments is significantly different: at energies \( \epsilon > 3 \times 10^{17} \text{ eV} \) it reveals almost constant relatively light CR composition with \( < \ln A \approx 1.5 \). Such a rather controversial situation does not allow to make any reliable conclusion about the transition from galactic to extragalactic CR component. More precise determination of CR composition at \( 10^{16} < \epsilon < 10^{19} \text{ eV} \) is needed to determine this transition.

The outer shock created by the expanding cocoon around AGNs is expected to produce CR spectrum \( N \propto \epsilon^{-7} \) with \( \gamma \approx 2.6 \) at energies \( \epsilon > 10^{18} \text{ eV} \) up to \( \epsilon_{\text{max}} \sim 10^{20} \text{ eV} \) [35], that very well fulfill the requirements to extragalactic CR sources. Therefore AGNs have to be considered as a prime candidate for the sources of extragalactic CRs.
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