Cosmic rays from active galactic nuclei

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I. Introduction

The overall origin of cosmic rays (CR) is steel unresolved problem in astrophysics. The understanding of CR origin requires determination of astrophysical objects, which are the CR sources, and appropriate acceleration process, which form CR spectrum in these objects. In this regard, during last several years considerable progress has been achieved in this field, both experimentally and theoretically. Recently the steepening of the CR spectrum above 3×10^{19} eV was established in the HiRes [1] and Auger [2] experiments. It presumably corresponds to the so-called Greizen-Zatsepin-Kuzmin (GZK) cutoff, caused by CR energy losses in their interactions with the microwave background radiation (CMB). This is evidence that the highest energy part of the CR spectrum is of extragalactic origin. It was also recently demonstrated [3] that the CRs with energies up to $\epsilon \sim 10^{17}$ eV can be produced in supernova remnants (SNRs) and that the observed CR energy spectrum can be well represented by two components [3]. The first one, dominated up to 10^{17} eV, consists of CRs, produced in galactic SNRs, whereas the second is produced in extragalactic sources. This so called dip scenario [4] requires relatively steep CR spectrum produced in extragalactic sources, $J^{\rm s} \propto \epsilon^{-\gamma}$ with $\gamma = 2.55 - 2.75$ at energies $\epsilon > 10^{18}$ eV.

Below we consider CR acceleration at the shock created by the expanding cocoon around active galactic nuclei (AGN) and demonstrate that it provides CR acceleration with an appropriate spectrum up to the energy 10^{20} eV.

II. CR energy spectrum

Astrophysical objects, which are considered as potential extragalactic sources of ultra high energy CRs, should fulfill a number of requirements. First, they should have sufficiently high energy output, not less than $L_{\rm p} \sim 2 \times 10^{45} - 3.5 \times 10^{46}$ erg Mpc^{-3}yr^{-1} depending on the form of CR spectrum, which they produce [4]. Given the energy requirements, AGNs [4] are considered as potential extragalactic sources of the ultra high energy CRs.

The second requirement to the extragalactic CR sources is their ability to produce power-law CR spectrum up to the maximal energy, which for protons should be at least as large as $\epsilon_{\max} = 10^{20}$ eV, that is well above GZK cutoff.

Relativistic jet in AGN is surrounded by the hot cocoon, which expands into the surrounding intergalactic medium with the supersonic speed [5]. Since the essential fraction of the jet energy is transformed into the internal energy of the background medium due to the outermost nonrelativistic shock, driven by the cocoon overpressure, it is natural to suppose that a good part of this energy is represented by effectively accelerated CRs like it takes place in SNRs. Since CR acceleration by nonrelativistic shocks is very well studied one can obtain reliable estimate of the expected spectrum of CRs. First of all the maximal energy of CRs, accelerated at the expanded shock of size $R(t)$ and speed $V = dR/dt$, is determined by the expression [6]

$$\epsilon_{\max} \approx ZeBRV/c, \qquad (1)$$

where B is the upstream magnetic field, c is the speed of light, e is the proton charge and Z is the charge number of CR nuclei.

Magnetic field near the shock front, as it was established for all young SNRs [7], [8], is strongly amplified nonlinearly by CRs up to the level

$$B^2/(8\pi) \approx 3 \times 10^{-3} \rho V^2, \qquad (2)$$

which is presumably also appropriate for extragalactic shocks. Here ρ is the external gas density.

The outer cocoon shock expands with the speed [5]

$$V \approx [L_{\rm j}/(\rho V_{\rm h})]^{1/4} t^{-1/2}, \qquad (3)$$

where $L_{\rm j}$ is the mechanical luminosity of the jet, $V_{\rm h}$ is the hot spot or the jet head speed. Substituting magnetic field value followed from the Eq.(2), the shock speed (3) and the shock size $R = 2Vt$ into the expression (1) we have

$$\epsilon_{\max} \approx 10^{20} Z \left(\frac{L_{\rm j}}{10^{46}\ \text{erg/s}}\right)^{3/4} \left(\frac{N_{\rm g}}{10^{-4}\ \text{cm}^{-3}}\right)^{-1/4} \times \left(\frac{V_{\rm h}}{10^{10}\ \text{cm/c}}\right)^{-1/4} \left(\frac{l_{\rm j}}{1\ \text{kpc}}\right)^{-1/2} \text{eV}, \qquad (4)$$

where $l_{\rm j} = V_{\rm h} t$ is the jet length. According to this expression during the evolutionary epochs corresponding to the jet length from $l_{\rm j} = 1$ kpc to $l_{\rm j} = 10$ Mpc the cocoon shock produces power-law proton spectrum which extends up to the maximal energy from $\epsilon_{\max} = 10^{18}$ eV to $\epsilon_{\max} = 10^{20}$ eV.

The third requirement to CR sources is related with the form of CR spectrum. 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 into the outer space. The existence of the CR escape phenomenon, makes it possible to estimate the shape of spectrum of the most energetic CRs, produced during the source evolution. As it was demonstrated analytically [9], [6] and confirmed numerically [10], since the maximal energy $\epsilon_{\max}(t)$ of CRs accelerated by the expanding shock on its the most active phase decreases with time t due to the shock deceleration, the most energetic particles with energy $\epsilon \sim \epsilon_{\max}(t)$ undergo diffusive escape from the shock vicinity into the surrounding space. To estimate the spectrum of escaped CRs one can use the simple relation [9]

$$N(\epsilon)\epsilon d\epsilon \propto \rho V^2 R^{2-\beta} dR, \qquad (5)$$

which determines at any given phase t the overall number of CRs $N(\epsilon)$ with highest energy $\epsilon \sim \epsilon_{\max}(t)$. Due to the hard selfconsistent spectrum of CRs, produced by the strong shock, the main contribution to the CR energy content is given by the particles with highest energy $\epsilon \sim \epsilon_{\max}(t)$ [10]. Therefore their energy content scales as the shock ram pressure ρV^2 times the shock volume, as it is given by Eq.(5). Factor $R^{-\beta}$ describes the progressive slow decrease of CR acceleration efficiency due to the shock weakening. For the shock expansion law $R \propto t^{-\nu}$ relation (5) gives

$$N(\epsilon) \propto \epsilon^{-\gamma} \quad \text{with} \quad \gamma = 1 + (2-\beta)/(2/\nu - 3). \qquad (6)$$

In our case $\nu = 1/2$ that gives $\gamma = 3 - \beta$. For the constant acceleration efficiency we have $\beta = 0$ that gives $\gamma = 3$. 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 $\sigma \propto V^{3/8}$ [10]. 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 $\epsilon > 10^{18}$ eV very well corresponds to the experiment [4].

Particles with energies $\epsilon \leq \epsilon_{\max}(t)$ 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 will 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 $\epsilon < 10^{18}$ eV [4].

III. CR COMPOSITION

The composition of CRs is determined if we know not only their all-particle spectrum, $J(\epsilon) = \sum_A J_{\rm A}(\epsilon)$, that is the differential intensity $J(\epsilon)$ with respect to particle energy ϵ, but also the spectra $J_{\rm A}(\epsilon)$ of all relevant elements with atomic number A. Since the shock-accelerated CRs come originally from the thermal background plasma, one has to expect that the flux of each CR element in/near the source, is proportional to the number density of this element $N_{\rm A}$ in the background plasma: $J^{\rm s}_{\rm A}(\epsilon) \propto N_{\rm A}$. Therefore it is useful to represent the spectrum of each CR element in the form

$$J^{\rm s}_{\rm A}(\epsilon) = e_{\rm A}(\epsilon) a_{\rm A} J^{\rm s}_{\rm H}(\epsilon), \qquad (7)$$

where $a_{\rm A} = N_{\rm A}/N_{\rm H}$ is the abundance of element A relative to the hydrogen abundance and $e_{\rm A}(\epsilon)$ is an enrichment factor which describes the preferential production of element A relative to the production of protons (marked by the subscript H).

Direct measurements of CR fluxes at energies $\epsilon < 10^{14}$ eV show that the factor $e_{\rm A} > 1$ considerably exceeds unity and that it progressively increases with the increase of A [11]. This means a considerable enrichment of CRs in heavy elements compared with the interstellar abundance.

According to Eq.(5) the spectra of ultrahigh energy CRs produced by nonrelativistic cocoon shocks can be represented in the form

$$J^{\rm s}_{\rm A}(\epsilon) = C_{\rm A}\epsilon^{-\gamma}, \qquad (8)$$

where $\gamma \approx 2.6$ and $C_{\rm A} \propto e_{\rm A} N_{\rm A}$. Since the injection/acceleration of CRs at cocoon and supernova shocks are expected to be very similar, the values of the enrichment factors $e_{\rm A}$ in the former case can be extracted from the experimentally measured fluxes of the Galactic CR component $J_{\rm A}(\epsilon)$ at some fixed energy, say $\epsilon = 1$ TeV [3], according to the expression

$$e_{\rm A} = J_{\rm A}(1 \text{ TeV})/J_{\rm H}(1 \text{ TeV})(N_{\rm H}/N_{\rm A})_{\odot}. \qquad (9)$$

Here $(N_{\rm A}/N_{\rm H})_{\odot}$ is the solar system relative abundance of elements with atomic number A.

In order to calculate the spectra of extragalactic CRs inside the Galaxy one needs to take into account the modification of the CR spectra due to their interaction with the cosmic microwave background and due to their modulation in the Galactic wind. This can be done by representing the observed extragalactic CR spectrum in the form

$$J_{\rm A}(\epsilon) = P_{\rm l} P_{\rm h} J^{\rm s}_{\rm A}(\epsilon), \qquad (10)$$

where factors $P_{\rm l}$ and $P_{\rm h}$ describe CR flux modification due to Galactic wind and CMB respectively. Since the diffusive mobility of the CRs is inversely proportional to the particle charge number Z, the first factor can be represented in the form

$$P_{\rm l} = \exp(-Z\epsilon_{\rm l}/\epsilon), \qquad (11)$$

where $\epsilon_{\rm l} \sim 10^{17}$ eV [3].

We use a simple analytical form of the factor $P_{\rm h}$

$$P_{\rm h} = \exp[-(A\epsilon/\epsilon_{\rm h})^2]. \qquad (12)$$

At $\epsilon_{\rm h} = 1.3 \times 10^{18}$ eV for the case of helium and iron nuclei it satisfactorily fits the results of detailed calculations [4]. In the case of protons, instead of the modification factor $P_{\rm h}$ we directly use their modified spectrum calculated by [4].

The cocoon shock propagates initially through the interstellar medium (ISM) of the host galaxy and later through the intergalactic medium (IGM). The IGM is less abundant in heavy elements than the ISM: the median metallicity of the IGM is $(N_{\rm A}/N_{\rm H}) = 0.2(N_{\rm A}/N_{\rm H})_\odot$ for all relevant elements heavier than helium [12]. Since the maximal CR energy produced by the expanding cocoon shock decreases with time, the local metallicity at the shock front changes from the ISM value $(N_{\rm A}/N_{\rm H}) \approx (N_{\rm A}/N_{\rm H})_\odot$ at early phases, when the shock produces CRs up to $\epsilon_{\rm max} \sim Z \times 10^{20}$ eV, to the IGM value at late phases, when $\epsilon_{\rm max} \sim Z \times 10^{18}$ eV. To describe this effect we use a metallicity $(N_{\rm A}/N_{\rm H}) = 0.2[\epsilon/(Z \times 10^{18}\ {\rm eV})]^{0.35}(N_{\rm A}/N_{\rm H})_\odot$. For helium we use the cosmological value $N_{\rm He} = 0.08 N_{\rm H}$. Using these number densities one can calculate the relative values of the coefficients $C_{\rm A}/C_{\rm H}$ for all elements except protons. The proton coefficient $C_{\rm H}$ is determined by the fit of the expected all-particle CR flux $J(\epsilon)$ to the existing measurements of the CR intensity at energies $\epsilon > 10^{18}$ eV.

Secondary protons appearing as a result of photodesintegration of helium nuclei are also included in an approximate way: it is assumed that the secondary protons (whose total number equals four times the number of helium nuclei in the source spectrum with energy above 2×10^{18} eV) have the normal energy distribution around $\epsilon_0 = 5 \times 10^{17}$ eV within the interval $\Delta\epsilon = \epsilon_0$.

In Fig.1 we present the all-particle spectrum which includes two components: CRs produced in SNRs [3] and extragalactic CRs, which consist of protons (H), helium (He) and three groups of heavier nuclei, produced in AGNs. The calculated overall CR spectrum is in a satisfactory way consistent with the experimental data, except in the energy interval $10^{17} < \epsilon < 10^{18}$ eV in the transition region, where, contrary to the experiment, the calculated spectrum has a small dip.

The mean logarithm of CR atomic number is represented in Fig.2 as a function of energy. The CR mass energy dependence $< \ln A(\epsilon) >$ has two peaks. The first one at the energy $\epsilon \approx 10^{17}$ eV corresponds to the very end of the galactic CR component [3], whereas the second, at the energy $\epsilon \approx 10^{19}$ eV, is at the beginning of the GZK cutoff. Note that at high energies $\epsilon > 10^{15}$ eV information about CR composition is obtained from the mean values of the shower maxima $X_{\rm max}$, determined by the ground based detectors. Knowing the average depth of the shower maximum for protons, $X^{\rm H}_{\rm max}$, and for iron nuclei, $X^{\rm Fe}_{\rm max}$, from simulations, the mean logarithmic mass can be estimated from the measured $X_{\rm max}$ according to the relation [13]

$$< \ln A >= (X_{\rm max} - X^{\rm H}_{\rm max})/(X^{\rm Fe}_{\rm max} - X^{\rm H}_{\rm max}) < \ln 56 > . \quad (13)$$

It is seen from Fig.2 that the HiRes data are very well consistent with the expected sharp decrease of $< \ln A >$ within the energy interval $10^{17} - 10^{18}$ eV. At higher energies, between 10^{18} and 10^{19} eV, the experimental values of $< \ln A(\epsilon) >$ have a quite irregular behavior. Nevertheless, the experiment reveals a trend of progressive increase of the mean CR mass so that the expected peak value $< \ln A > \approx 1.7$ at the energy $\epsilon \sim 10^{19}$ eV is consistent with the existing HiRes data.

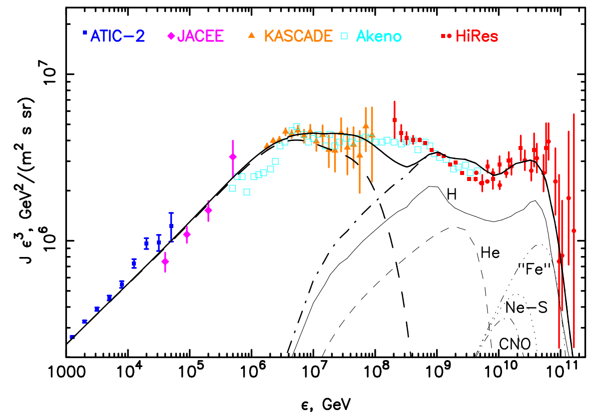

Fig. 1. Overall CR intensity as a function of energy (thick solid line), Galactic CR component produced in SNRs (thick dashed line) and extragalactic component produced in the IGM (thick dash-dotted line). The spectra of different extragalactic components are shown by thin lines. Experimental data obtained in the ATIC-2 [14], JACEE[15], KASCADE [16], Akeno [17], and HiRes [1] experiments are shown as well.

IV. Alternative scenario

The alternative scenario for the overall CR spectrum is the "ankle scenario" [4]. In this case the extragalactic source spectrum, as compared with the dip-scenario, is assumed to be much harder $J^{\rm s}_{\rm A} \propto \epsilon^{-2}$ so that it becomes dominant above an energy of $\epsilon = 10^{19}$ eV [4]. Therefore, to fit the observed overall CR spectrum one needs a third component to fill the gap between the Galactic CR spectrum, produced by SNRs, and the hard extragalactic spectrum. The appropriate solution of this problem is the existence of some kind of reacceleration process which picks up the most energetic CRs from SNRs and substantially increases their energy, resulting in a smooth extension of the first CR component towards the higher energies.

We model the spectra of reaccelerated CRs in the following way, without specifying the reacceleration mechanism. For every element with the nuclear charge number Z, as in the dip scenario, we use the spectrum, which coincides with $J_{\rm A}(\epsilon)$ for $\epsilon < \epsilon^{\rm Z}_{\rm max1}$ and has a form

$$J_{\rm A}(\epsilon) = J_{\rm A}(\epsilon^{\rm Z}_{\rm max1})(\epsilon/\epsilon^{\rm Z}_{\rm max1})^{-\gamma} \exp(-\epsilon/\epsilon^{\rm Z}_{\rm max2}) \quad (14)$$

at $\epsilon > \epsilon^{\rm Z}_{\rm max1}$. Here $\epsilon^{\rm Z}_{\rm max1}$ is the minimum energy of particles involved in reacceleration, and $\epsilon^{\rm Z}_{\rm max2}$ is the maximum particle energy achieved during reacceleration. It is natural to assume that these energies scale proportional to the rigidity $\epsilon^{\rm Z}_{\rm max} = Z\epsilon^{\rm p}_{\rm max}$. Here the superscript p denotes protons. The quantities $\epsilon^{\rm p}_{\rm max1}$, $\epsilon^{\rm p}_{\rm max2}$ and γ are treated as free parameters whose values are determined as a result of the best fit.

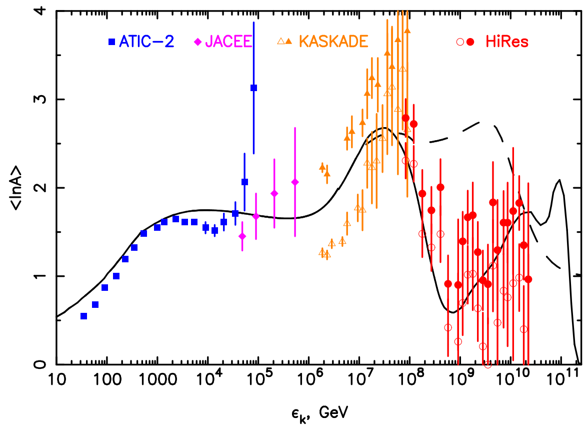

Fig. 2. Mean logarithm of the CR nucleus atomic number as a function of energy. Experimental data obtained in the ATIC-2, JACEE, KASCADE (QGSJET and SYBYLL;[13]), and HiRes (QGSJET and SYBYLL; [18]) experiments are shown.

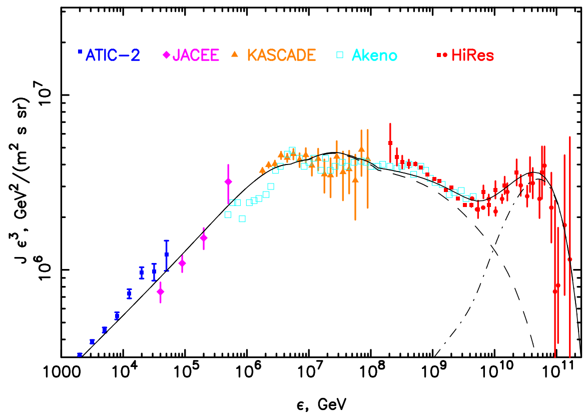

Fig. 3. The same as in Fig.1, but for the ankle scenario. The dashed line represents the Galactic component, which includes CRs produced in SNRs and reaccelerated CRs. The dash-dotted line represents the extragalactic component; it corresponds to the source spectrum $J_A^s \propto \epsilon^{-2}$ [4].

We present in Fig.3 the CR spectrum calculated within the ankle scenario, with the adopted values $\epsilon^{\rm p}_{\rm max1} = 5\times10^{15}$ eV, $\epsilon^{\rm p}_{\rm max2} = 1.5\times10^{17}$ eV and $\gamma = 3$. Following [4] we use the extragalactic CR source spectrum in the form $J_A^s \propto \epsilon^{-2}$ and assume the composition of these CRs with $< A(\epsilon) >= 1$.

It is seen that at $\epsilon > 10^{17}$ eV it is well consistent with the data. However, such a well-known peculiarity in CR spectrum as the knee at $\epsilon \approx 3\times10^{15}$ eV is much less pronounced in the theoretical CR spectrum than in the experiment. This may be considered as an indication against the ankle scenario.

As it is seen in Fig.2, the CR composition corresponding to the ankle scenario is considerably heavier at energies $10^{17}\epsilon < 10^{19}$ eV than in the dip scenario and is inconsistent with the HiRes measurements. Note, that CR composition of the reaccelerated CRs is a direct consequence of the heavy CR composition at the energy $\epsilon > \epsilon^{\rm Z}_{\rm max1}$, where the reacceleration is assumed to start, and it is not sensitive to the details of reacceleration process.

V. Summary

The composition of ultra high energy CRs produced by nonrelativistic cocoon shocks around AGNs is characterised by well pronounced peculiarities which are two peaks in the energy dependence of the mean CR atomic number $< A(\epsilon) >$. The first peak at the energy $\epsilon \approx 10^{17}$ eV corresponds to the very end of the Galactic CR component, produced in SNRs [3], whereas the second, at the energy $\epsilon \approx 10^{19}$ eV, is expected at the beginning of the GZK cutoff. The strong energy dependence of the CR composition within the energy interval from 10^{17} to 10^{18} eV is expected as a signature of the transition from heavy Galactic to light extragalactic CRs, whereas the detection of a heavy CR composition at $\epsilon \approx 10^{19}$ eV has to be considered as the signature of CR production by the nonrelativistic cocoon shocks.

The existing measurements of CR composition are consistent with the dip scenario with a formation of the CR spectrum in SNRs and AGNs and are inconsistent with the ankle scenario, which includes reacceleration of CR produced in SNRs as a third CR component. Additional peculiarity in the overall CR spectrum – the dip in the transition region $10^{17} < \epsilon < 10^{18}$ eV – is expected within the dip scenario. Since it is not seen in the existing data it is a real difficulty for the dip scenario. It is therefore clear that a more precise measurements of CR spectrum and composition at energies above 10^{17} eV are needed for a strict determination of CR origin.

VI. Acknowledgments

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