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On Ultra-High Energy Cosmic Rays Produced by AGN Jets

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Abstract: The cosmic ray source spectrum produced by AGN (Active Galactic Nucleus) jets is evaluated. A distinctive feature of this evaluation is the account for the jet distribution on kinetic energy. The expected cosmic ray spectrum at the Earth is calculated.

Keywords: ultra-high energy cosmic rays, active galactic nuclei

1 Introduction

Estimates [23, 7] show that from the viewpoint of energetics the AGN jets can be the sources of ultra-high energy cosmic rays. Different aspects of particle acceleration in AGN jets were considered by [9, 18, 10, 19], see also references below. It is assumed in the present work that the AGN jets are the main extragalactic sources of ultra-high energy cosmic rays. The kinetic energy of an individual jet determines the maximum particle energy and the cosmic-ray power it produces. The cases of power-law and delta-shaped spectra of cosmic rays produced by an individual jet are considered. The distribution of AGN jets over the kinetic energy shapes the average source spectrum of accelerated particles. A simple numerical code is used to calculate the expected intensity of cosmic rays at the Earth.

2 Spectrum of ultra-high energy cosmic rays accelerated in AGN jets

To maintain the cosmic ray intensity observed in the Auger experiment at energies above 10^{19} eV, the power of extragalactic sources of the order of 3×10^{36} erg s^{-1} Mpc^{-3} is required. This value increases if the contribution of cosmic rays with smaller energies is taken into account. At the same time the AGN jets release kinetic energy at the level of 3×10^{40} erg s^{-1} Mpc^{-3} and approximately 6% of this energy is contained in the jets with a power $L_{jet} = 10^{44} - 10^{46}$ erg s^{-1} characteristic of FRI-I (Fanaroff-Riley II) radiogalaxies and radio loud quasars. We shall use the notation FII for this population of jets. The numerous and less powerful jets of low-luminosty AGN have power $L_{jet} = 10^{40} - 10^{44}$ erg s^{-1}. We shall denote them as FI sources.

Without specifying the mechanism of particle acceleration in jets, one can use the Hillas criterion $E_{max} = Ze\beta Bl$ for the estimate of maximum energy which the particles with charge Ze in the acceleration region of size l, magnetic field strength B, and the velocity of magnetic field transport $u = \beta c$ can gain ([13], see also [20]).

Let us consider the "optimistic" estimate and assume that the energy flux of a statistically isotropic magnetic field frozen in the jet is related to the kinetic energy flux by the relation $L_{jet} = \beta c \frac{B^2}{6\pi} \pi R^2$. The equality $R = l/2$ is accepted here for the jet radius; the jet velocity is βc. As a result, the following estimate of the maximum energy of accelerated particles can be obtained:

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

where $L_{jet,45} = L_{jet}(10^{45}\text{erg s}^{-1})^{-1}$, see [17, 11, 3, 24, 12] and references therein for the derivation of similar formulas.

The expression for E_{max} can be also derived based on the well studied case of the diffusive shock acceleration in young supernova remnants. Let us consider a jet which consists of the proton-electron plasma with the mass density ρ and the power $L_{jet} = 0.5\rho u^3 \pi R^2$. The cosmic rays are accelerated at the jet termination shock and their energy density is $w_{cr} = \eta_{cr} \rho u^2$, where $\eta_{cr} \approx 0.1$. The magnetic field at the site of acceleration can reach the value of the order $B = (4\pi\beta w_{cr})^{1/2}$ if the field is amplified by the strong cosmic-ray streaming instability [6]. The maximum energy of accelerated particles is $E_{max} = Ze\beta BR$ if the Bohm diffusion near the shock is assumed (note that this E_{max} satisfies the Hillas criterium). It finally gives $E_{max} \approx Ze\beta\left(8\eta_{cr} c^{-1} L_{jet}\right)^{1/2}$ that is close to the esti-

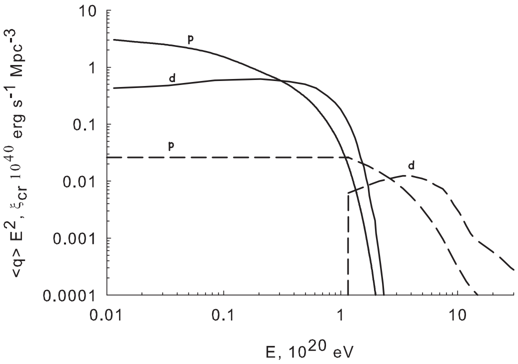

Figure 1: Calculated average source spectra of jet populations FI (solid lines) and FII (dash lines) for delta-function (*d*) and power law E^{-2} (*p*) cosmic ray spectra generated in individual jets. Eq. (1) was used for calculations of $E_{max}(L_{jet})$

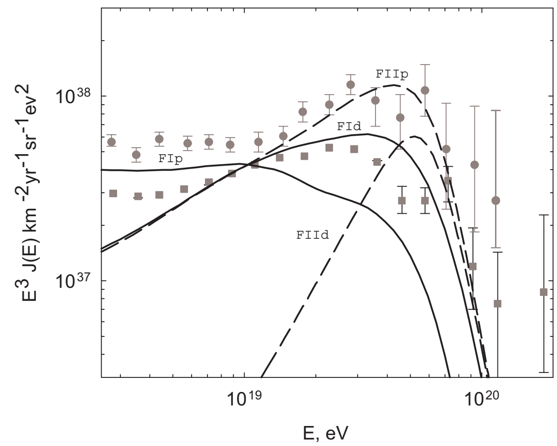

Figure 2: Calculated spectra of extragalactic cosmic rays for sources $< q_d >$ and $< q_p >$ averaged over the AGN jet population FI (solid lines FId and FIp) and FII (dash lines FIId and FIIp). The spectra (except FIId) are normalized to the intensity observed at 10^{19} eV in the Auger experiment. Data are from HiRes experiment [1] (circles) and Auger experiment [2] (squares).

mate (1). We shall use Eq. (1) and set $\beta = 1$ in the calculations below.

We consider two types of cosmic-ray source spectrum ejected into the intergalactic space. The first type is a delta function spectrum and the corresponding source power is $q_d = \xi_{cr} n_{jet} L_{jet} {E_{max}}^{-1} \delta(E - E_{max})$, where the coefficient ξ_{cr} characterizes the fraction of jet kinetic energy that goes to the accelerated particles; n_{jet} is the jet number density in the intergalactic space. The second type of sources has a power law spectrum $\propto E^{-2}$ and the corresponding source power is $q_p = \xi_{cr} n_{jet} L_{jet} E^{-2} \mathrm{H}(E_{max} - E)$, where $\mathrm{H}(x)$ is the step function. (Strictly speaking, the additional logarithmic normalization factor $(\ln(E_{max}/E_{min}))^{-1}$ should by included in the last expression for q_p. We omit it because of uncertain value of the minimal energy E_{min} for particles ejected from the accelerator.)

It can be recalled as an example that both spectrum shapes of ejected particles arise in the consideration of diffusive shock acceleration in supernova remnants, see [21]. The runaway particles have close to the delta function energy spectrum $\sim \delta(E - E_{max})$ where E_{max} is the maximum energy of accelerated particles that is achieved at the given stage of a supernova shock evolution. The energetic particles that remains confined inside the remnant may have close to a power law spectrum and leave out into the interstellar medium at some stage of SNR evolution when the shock breaks up. It should be stressed that we do not assume that two discussed injection spectra work at the same time and analyze them separately.

The source functions $q_d(E)$ and $q_p(E)$ should be averaged over the distribution of jet luminosity $n_{jet}(L_{jet})$ to obtain the average source function of extragalactic cosmic rays. The results are shown in Fig. (1) for the functions $n_{jet}(L_{jet})$ presented by [16] in their Figure (8) for the kinetic luminosity function of jets. Four source functions in Fig. (1) correspond to the combination of two populations of jets, FI and FII, and two types of jet spectra, *d* and *p*. These four source functions are considered here as representing four different scenarios of cosmic ray acceleration in jets.

We solved numerically the set of transport equations for protons and nuclei from He to Fe moving through the microwave, infrared and optical background radiation in the expanding Universe. The described types of the average source spectrum were used. Fig. (2) illustrates the results. It was assumed that the source chemical composition coincides with the composition of Galactic cosmic ray sources. The spectra were normalized at 10^{19} eV to the observed by Auger intensity. It requires very different efficiency of particle acceleration $\xi_{cr,FII}/\xi_{cr,FI} \sim 20$ in the FII and FI jets. These efficiencies are $\xi_{cr,FII} \sim 0.1$ and $\xi_{cr,FI} \sim 0.005$ if the source spectra are extrapolated down to 1 GeV. No cosmological evolution was assumed in our calculations ($m = 0$). The evolution is different for different morphological types of AGN, see e.g. [8], but it does not significantly affect the calculated spectra at energies $> 3 \times 10^{18}$ eV since these particles may come from the distances not larger than about 2×10^{3} Mpc.

Of four spectra shown in Fig. (2), two reproduce cosmic ray observations with reasonable accuracy. They correspond to the AGN jet population FI with delta-function source spectra and the AGN jet population FII with power-law spectra E^{-2}.

The finite distance z_{min} to the closest to an observer source was taken into account in the calculations. This distance is

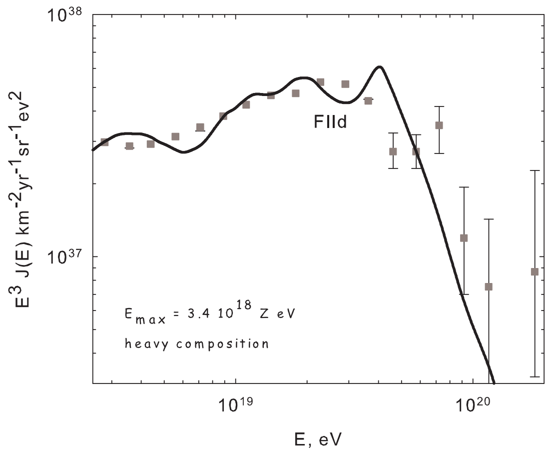

Figure 3: Calculated spectrum of extragalactic cosmic rays for sources $< q_d >$ averaged over the AGN jet population FIId with heavy composition; E_{max} is decreased by 80 compared to Eq. (1). Data are from Auger experiment [2] (squares).

a function of particle energy and charge and is different for the source populations FI and FII. The absence of sources at distances < 90 Mpc in our model resulted in a steeply sloping down spectrum of cosmic rays at the highest energies 10^{20} eV for the FII source distribution.

The dependence $n_{jet}(L_{jet})$ together with Eq. (1) for $E_{max}(L_{jet})$ leads to the dependence of cosmic-ray source number density on particle energy $n_s(E)$. For FI population of sources with delta shaped spectra, the source density is $n_s = 10^{-4}$ Mpc^{-3} at $E = 6 \times 10^{19}$ eV and $n_s = 2 \times 10^{-3}$ Mpc^{-3} at $E = 10^{19}$ eV that coincides with the results of [22] derived from the analysis of cosmic-ray arrival direction distribution.

Protons dominate in the calculated composition of cosmic rays that is in strong disagreement with the Auger data. To get out of a difficulty one can take anomalously high abundance of heavy nuclei and reduce the maximum particle energy at the source [5, 15]. We show in Fig. (3) only one example of calculations where the shape of source spectrum corresponds to the FIId sources with the maximum particle energy E_{max} decreased by a factor of 80 compared to the "optimistic" estimate (1) (this relieves the extreme assumptions used in the derivations of Eq. (1)) and the Iron abundance at the source comprises $1/3$ of all nuclei. The calculated cosmic-ray spectrum only roughly reproduce the observed spectrum. The cosmic-ray composition can be characterized by the mean logarithmic atomic number $< \ln(A) >$. Its calculated value rises approximately linearly from about 0.25 at 5×10^{18} eV to 3.7 at 5×10^{19} eV in a qualitative agreement with the Auger data on the shower maximum dependence on energy.

3 Conclusions

It is believed that the particle acceleration by jets in active galactic nuclei is the most efficient source of cosmic rays with the highest energies, $E > 10^{19}$ eV. In the present work we distinguish two populations of jets: FI produced by the low luminosity AGN populations with jet power 2×10^{40} to 3×10^{44} erg s$^{=1}$, and FII produced by high luminosity AGN with jet power larger than 2×10^{44}. The corresponding jet distributions on power were given by [16].

The typical power law spectrum of nonthermal jet radiation implies the power law particle spectrum of the form close to E^{-2}. One may expect that the spectrum of particles released into the extragalactic space, the source spectrum of extragalactic cosmic rays, has the same shape. Another possibility is that accelerated particles remains confined inside the source and only particles with maximum energies run away into intergalactic space so that the source spectrum is of a delta-shaped form. The average source spectrum of extragalactic cosmic rays is determined as the convolution of one of these source functions of an individual jet with the jet distribution on power. Based on the Hillas criterion, we accepted an optimistic estimate for the maximum energy of accelerated particles (1) with its characteristic scaling $E_{max} \propto L_{jet}^{1/2}$ and used it in our calculations. The computations of cosmic ray propagation in the expanding Universe filled with the background electromagnetic radiation were fulfilled for energetic protons and nuclei from He to Fe. The calculations were made under the approximation of continuous energy losses by e^-, e^+ and pion production and the "catastrophic" losses through photodisintegration and corresponding production of secondary nuclei.

The results of our calculations are illustrated in Fig. (2). The observed spectrum of ultra-high energy cosmic rays can in principle be explained in the frameworks of two scenarios - the acceleration by the FI sources with individual jet spectra of the delta-shaped form or the acceleration by the FII sources with individual jet spectra close to E^{-2} form. However, the presence of events with energies $\geq 10^{20}$ eV is difficult to explain - powerful FII sources are not sufficiently close to us, whereas numerous FI sources are not sufficiently powerful. The transition from Galactic to extragalactic component in the observed at the Earth spectrum occurs at about $(3...5) \times 10^{18}$eV.

The calculated spectra are normalized to the observed by Auger intensity at 10^{19} eV. It requires very different efficiencies of transformation of the jet kinetic energy to the energy of cosmic rays in the FII and FI sources: $\xi_{cr,FII}/\xi_{cr,FI} \sim 20$. It was assumed that the elemental composition of accelerated particles is the same as in the Galactic cosmic-ray sources. This results in the predominantly proton composition of ultra high energy extragalactic cosmic rays that is compatible with the HiRes data but not with the Auger data. One needs to significantly increase the abundance of heavy nuclei at the source and drastically decrease the value of E_{max} to fit the Auger data [5, 15].

This procedure was discussed at the end of Section 3 and illustrated by Fig. 3.

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