Cosmic ray spectrum and mass composition in the ultra-high energy region

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***Abstract*. In this work we present cosmic ray spectrum (CR) and mass composition data obtained from Cherenkov radiation measurements at the Yakutsk EAS array. Mass composition was determined from the maximum of shower development X_{max}. The energy dependence of X_{max} was compared to simulation results (EPOS and QGSjetII-03) for p and Fe primaries. Within the framework of these models and superimposition method, an estimation for mass composition of cosmic rays was made in energy region of $10^{17} - 5 \times 10^{19}$ eV. At $E_0 = 10^{17}$ eV, $\langle \log A \rangle$ value is 2.6 ± 0.4. Discrepancy in estimated values results as from precision of X_{max} measuring in various experiments, so from systematics arising from the chosen hadronic model. Two scenarios were considered for interpretation of the obtained result: 1)CR spectrum is generated by supernovae remnants (SNRs) and dominates at 10^{17} eV, at higher energies spectrum is formed by particles of metagalactic origin (*dip-scenario*); 2)Spectrum is composed of three components: CR from SNRs, galactic cosmic rays modulated by galactic star wind near 10^{18} eV and metagalactic CR with hard spectrum above 10^{18} eV (*ankle-scenario*). It is shown that energy dependence of CR mass composition better fits to the ankle-scenario, while spectrum is well-described by the dip-scenario. The unambiguous answer to this question requires more precise experimental data on mass composition and further theoretical research.**

***Keywords*: ultra-high energy cosmic rays, spectrum, mass composition**

I. INTRODUCTION

The origin of cosmic rays (CR) is steel unresolved problem in astrophysics. However, during last several years considerable progress has been achieved in this field experimentally and theoretically as well. Recently the steepening of CR spectrum above 3×10^{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 [3], [4], [5]. Therefore it becomes evident that the highest energy part of CR spectrum is of extragalactic origin.

It was also recently demonstrated [6] that CRs with energies up to $\epsilon \sim 10^{17}$ eV are presumably produced in supernova remnants (SNRs). Nonlinear kinetic theory of CR acceleration in SNRs [7] not only explains the existing measurements of CRs but also well reproduces the properties of nonthermal emission from young SNRs produced by CRs [6], [8], [9]. It was demonstrated, that observed CR spectrum can be well represented by two components [6]. 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 [10] requires relatively steep CR spectrum produced in extragalactic sources $J \propto \epsilon^{-2.7}$ at least at high energies $\epsilon > 10^{18}$ eV. Here J is CR differential intensity and ϵ is the total energy of CR particle.

According to energetic requirements active galactic nuclei (AGN) and gamma-ray bursts (GRB) [11], [12], [13] are considered as a potential extragalactic sources of ultra high energy CRs. However, as Berezinsky et al. [5] argued, the energy output of GRBs has a serious problem to be considered as a main source of extragalactic CRs. In addition, simulations of CR shock acceleration performed by Niemiec et al. [14] demonstrated low efficiency in the case of relativistic shocks, which are considered as a source of CRs in GRBs. At the same time AGNs have enough power to generate ultrahigh energy CRs and diffusive acceleration at the outer shock associated with AGN jet is presumably able to produce CR spectrum up to the sufficiently high energy $\epsilon \sim 10^{20}$ eV [15]. Since this shock is nonrelativistic the expected CR spectrum is close to the form J/ϵ^{-2}, eventhough much steeper spectrum $J/\epsilon^{-2.7}$, produced by the ensemble of AGNs is also possible. Note, that based on the data collected at the Auger EASA correlation between the arrival directions of CRs with energy above 6×10^{19} eV and the position of nearby AGNs has been find [16], that strongly supports AGNs as a prime candidate for the source of ultra high energy CRs. Note that recent analysis of the arrival directions of CRs with energies above 4×10^{19} eV detected at Yakutsk EASA gave the same conclusion [17].

If indeed the spectrum of extragalactic CRs is as hard as J/ϵ^{-2}, then in this so called ankle scenario extragalactic CRs dominate in the observed CR spectrum only above 10^{19} eV [10]. In this case except SNRs there is another galactic CR source (component B according to Hillas definition [18]) 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 pick up the most energetic CRs from SNRs and increases their energy up to a factor of 100.

It was already noted [6] that chemical CR composition is expected to be very different in these two cases at energies $10^{17} - 10^{19}$ eV. Therefore the experimental determination of CR composition at these energies is so important.

In this paper we analyze CR spectrum and composition measured by Cherenkov detectors of Yakutsk extensive air shower array (EASA) in order to find transition region between galactic and extragalactic CR components.

II. EXPERIMENT

Yakutsk EASA is the ground based experiment for the detection of CRs with energies $10^{15} - 10^{19}$ eV (see [19], for details). Its detectors cover the area of 12 km^2. The measurements of light-integrating Cherenkov detectors can be analyzed separately from the measurements of other detectors of Yakutsk EASA [20]. Cherenkov detectors are array of photomultiplier tubes with light collection cones looking upwards in the night sky, measuring the lateral distribution of Cherenkov light at the ground level. The energy of CR primary particle initiating extensive shower is determined in almost model independent way using Cherenkov detectors measurements together with charged particle detectors data [21], [22]. The depth of the shower maximum X_{max} is derived from observations of lateral distribution of Cherenkov light [23], [24], [25], [26].

Knowing the average depth of the shower maximum for protons X pmax and for iron nuclei $X^{\text{Fe}}_{\text{max}}$ from simulations, the mean logarithmic mass can be derived from the measured X_{max} according to the relation [27], [28]

$$\langle \ln A \rangle = \frac{X_{\text{max}} - X^{\text{p}}_{\text{max}}}{X^{\text{Fe}}_{\text{max}} - X^{\text{p}}_{\text{max}}} \cdot \langle \ln A^{\text{Fe}} \rangle \qquad (1)$$

This conversion requires to chose a particle interaction model. Here we use the model `QGSJET01` to determine $\langle \ln A \rangle$.

Compared with earlier considerations we present here the most complete set of events detected at the Yakutsk EASA. At highest energies $\epsilon > 10^{17}$ eV it includes about 75000 events.

III. MODELS

We analyze below experimental data within two, dip and ankle, scenarios. In both cases low energy part of CR spectrum $J(\epsilon)$ is represented by particles produced in SNRs. Their spectrum $J^{\text{g}}(\epsilon)$ and composition are calculated within kinetic nonlinear theory (see [6] for a details).

Within the dip scenario the second CR component $J^{\text{eg}}(\epsilon)$ is represented by extragalactic sources, assuming that they produce CR spectrum $J^{\text{eg}}_{\text{s}}/\epsilon^{-2.7}$ at $\epsilon > 10^{18}$ eV and taking into account the modification of this spectrum due to the propagation effects in the intergalactic space according to Aloisio et al [10]. Extragalactic CRs are assumed to consist of 90% of protons and 10% of helium nuclei.

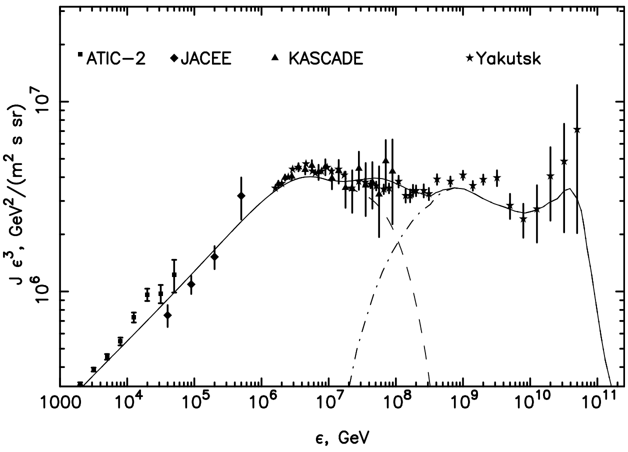

Fig. 1. CR intensity as a function of energy. The dashed line represents the Galactic component, which consists of CRs produced in SNRs [6]. The dash-dotted line represents the assumed extragalactic component, which corresponds to the source spectrum $J^{\text{eg}}_{\text{s}}(\epsilon)/\epsilon^{-2.7}$ [10]. Experimental data obtained in the ATIC-2 [32], JACEE [33], KASCADE [34] and Yakutsk EASA experiments are shown as well.

In the ankle scenario the extragalactic source spectrum is assumed to be much harder $J^{\text{eg}}_{\text{s}}/\epsilon^{-2}$. In this case extragalactic component $J^{\text{eg}}(\epsilon)$ becomes dominant above the energy $\epsilon = 10^{19}$ eV and therefore to fit the observed CR spectrum one needs the third component. Since it is presumably due to reacceleration we represent it in a following way. Instead of $J^{\text{g}}_{Z}(\epsilon)$ for every element with the nuclear charge number Z as in the dip scenario we use the spectrum $J'^{\text{g}}_{Z}(\epsilon)$, which coincides with $J^{\text{g}}_{Z}(\epsilon)$ at $(\epsilon) < \epsilon^{Z}_{\text{max1}}$ and has a power-law form with exponential cutoff

$$J'^{\text{g}}_{Z}(\epsilon) = J^{\text{g}}_{Z}(\epsilon^{Z}_{\text{max1}}) \cdot \left(\frac{\epsilon}{\epsilon^{Z}_{\text{max1}}}\right)^{-\gamma} \cdot \exp\left\{\frac{-\epsilon}{\epsilon^{Z}_{\text{max2}}}\right\} \qquad (2)$$

at $\epsilon > \epsilon^{Z}_{\text{max1}}$. Here $\epsilon^{Z}_{\text{max1}}$ is minimum energy of particles involved into reacceleration and $\epsilon^{Z}_{\text{max2}}$ is maximum particle energy achieved during reacceleration. It is natural to assume that these energies scale proportional to the rigidity $\epsilon^{Z}_{\text{max}} = Z\epsilon^{\text{p}}_{\text{max}}$. Here subscript p denotes protons. Quantities $\epsilon^{\text{p}}_{\text{max1}}$, $\epsilon^{\text{p}}_{\text{max2}}$ and γ 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 [29] or in the pulsar vicinity [30], [31] could play a role of the reacceleration mechanism.

IV. RESULTS AND DISCUSSION

CR spectrum measured at Yakutsk EASA by Cherenkov detectors is compared with the theoretical spectrum for dip and ankle scenarios in Fig. 1 and 2 respectively, where the data obtained in the ATIC-2 [32], JACEE [33] and KASCADE [34] experiments are shown as well. It is clearly seen that Yakutsk data are very well consistent with the KASCADE data.

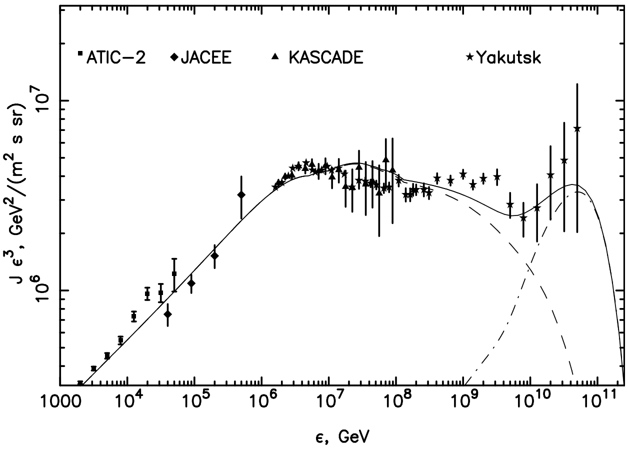

Fig. 2. The same as in Fig. 1 but for the ankle scenario. Dashed line represents galactic component, which includes CRs produced in SNRs and reaccelerated CRs. Dash-dotted line represents extragalactic component, which corresponds to the source spectrum J_s^{eg}/ϵ^{-2} [10].

It is also seen in Fig. 1 that the experimental CR spectrum in a satisfactory way is consistent with the theoretically expected spectrum within the dip scenario [6]. Note that compared with the source spectrum $J_s^{eg}(\epsilon)$ the component $Jeg(\epsilon)$, 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 [10]. At $\epsilon < 10^{18}$ eV the spectrum $J(\epsilon)$ is determined by the character of CR propagation in intergalactic space, followed by adiabatic cooling [10]. Since a Galactic Wind is expected to exist [29], CRs penetrating into the Galaxy from outside are in addition subject to modulation by the wind. This effect is described by the modulation factor $f = \exp(-\epsilon_m/\epsilon)$, where the maximum CR energy modulated by the Galactic Wind is about $\epsilon_m = 10^{17}$ eV.

According to Fig. 2 and 3 CR spectrum calculated within the ankle scenario with $\epsilon^p_{max1} = 5 \times 10^{15}$ eV, $\epsilon^p_{max2} = 1.5 \times 10^{17}$ eV and $\gamma = 3$ is less consistent with the experiment. For instance, such a well-known peculiarity in CR spectrum as a knee at $\epsilon \simeq 3 \times 10^{15}$ eV is much less pronounced in the theoretical CR spectrum. This can be considered as indication against the ankle scenario.

The mean logarithm of CR atomic number $\langle \ln A \rangle$ as a function of CR kinetic energy ϵ_k is presented in Fig. 4. Due to the dependence of maximal (cutoff) energy of CRs produced in SNRs $\epsilon_{max} \simeq 3\,Z\,10^{15}$ eV on the atomic charge number Z CRs become progressively heavier as the energy increases from $\epsilon \sim 10^{15}$ eV to $\epsilon \simeq \times 10^{16}$ eV, where iron nuclei contribution is dominant. At higher energies within the dip scenario the contribution of extragalactic CRs becomes essential, therefore $\langle \ln A \rangle$ goes down with the increase of the energy towards the value $\langle \ln A \rangle \simeq 1.5$.

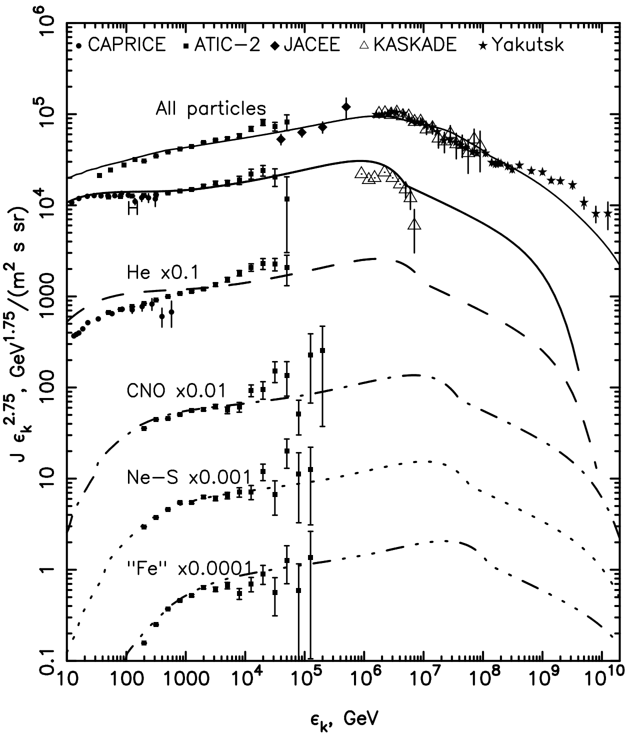

Fig. 3. Galactic component of CR spectrum, which consists of CRs accelerated in SNRs and reaccelerated CRs, which spectrum starts above the energy $\epsilon_{max1} = 5\,Z\,10^{15}$ eV. Experimental data obtained in CAPRICE [35], ATIC-2, JACEE, KASCADE and Yakutsk experiments are shown as well.

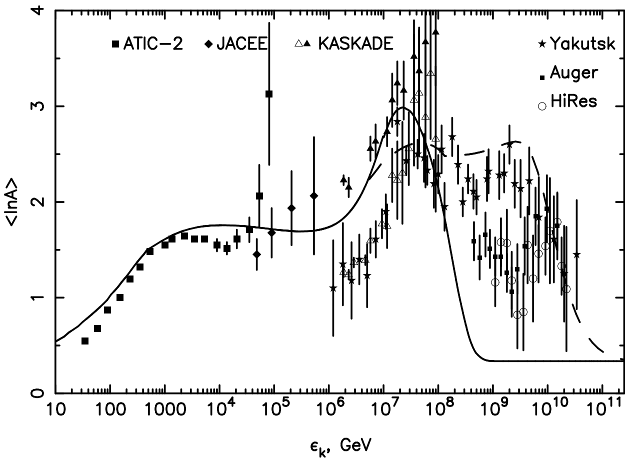

Fig. 4. Mean logarithm of the CR nucleus atomic number as a function of kinetic energy calculated within the dip and ankle scenario are represented by solid and dashed lines respectively. Experimental data obtained in the ATIC-2, JACEE, KASCADE (QGSJET and SYBYLL [27], HiRes [36], Auger [37] and Yakutsk EASA experiments are shown as well.

Essentially different CR composition is expected at energies $\epsilon > 10^{16}$ eV within the ankle scenario. In this case due to reacceleration heavy CR composition with the dominant iron contribution extends from $\epsilon \sim 10^{16}$ eV to about $\epsilon \simeq 10^{19}$ eV (see Fig. 3), as it is seen in Fig. 4. In this case the transition to the light extragalactic component takes place at $\epsilon \sim 10^{19}$ eV.

Yakutsk EASA data as it is seen in Fig. 4 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 [36] and Auger [37] data reveals constant or even progressively heavier CR composition as energy increases from 3×10^{17} eV to 2×10^{19} eV.

V. SUMMARY

Chemical CR composition determined at Yakutsk array is characterized by CR mean atomic number which increases with energy at $\epsilon < 3 \times 10^{16}$ eV, has maximum 2.6 ± 0.4 at $\sim 10^{17}$ eV, in the region $3\times10^{17}-3\times10^{18}$ eV some irregularities can be seen and progressively decreases with energy at $\epsilon > 4 \times 10^{18}$ 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. On the other hand CR spectrum measured with Cherenkov detectors of Yakutsk array better agrees with the theoretical spectrum, expected in the dip scenario. However CR composition deduced from HiRes and Auger experiments is significantly different: at energies $\epsilon > 3 \times 10^{17}$ eV it reveals almost constant relatively light CR composition with $\langle \ln A \rangle \simeq 1.5$. Estimated value of $\langle \ln A \rangle$ depends on chosen hadron interaction model and hence, may change. 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 $10^{16} < \epsilon < 10^{19}$ eV is needed to determine this transition.

REFERENCES

[1] D. R. Bergman et al. 2007, Nuclear Phys. B (Proc. Supl.), 165, 19
[2] T. Yamamoto et al. 2007, arXiv:0707.2638v3[astro-ph]
[3] K. Greisen. 1966, Phys. Rev. Let. 16, (17): 748-750
[4] G. Zatsepin, V. Kuzmin. 1966, JETPl 4, 78-80
[5] V. S. Berezinsky et al. 2006, Phys. Rev. D, 74, 043005
[6] E. G. Berezhko, H. J. Völk. 2007, ApJ, 661, L175
[7] E. G. Berezhko, V. K. Elshin, L. T. Ksenofontov. 1996, JETPh, 82, 1
[8] E. G. Berezhko. 2005, Adv. Space Res., 35, 1031
[9] E. G. Berezhko. 2005, Adv. Space Res., 41, 429
[10] R. Aloisio. et al. 2007, Astropart. Phys., 27, 76
[11] M. Milgrom, V. Usov. 1995, ApJ, 449, L37
[12] E. Waxman. 1995, Phys. Rev. Let., 75, 386
[13] M. Vietri. 1995, ApJ, 453, 883
[14] J. Niemiec, M. Ostrowski, M. Pohl. 2006, ApJ, 650, 1020
[15] C. A. Norman, D. B. Melrose, A. Achterberg. 1995, ApJ, 454, 60
[16] J. Abraham (Pier Auger Collaboration). 2007, Science, 318, 938
[17] A. A. Ivanov et al. 2008, JETPh Lett., 87, 185
[18] A. M. Hillas. 2006, J. Phys.: Conf. Ser., 47, 168
[19] V. P. Egorova et al. 2004, Nucl. Phys. B (Proc.Suppl.), 136, 3
[20] A. A. Ivanov, S. P. Knurenko, I. Ye. Sleptsov. 2003, Nucl. Phys. B (Proc.Suppl.), 122, 226
[21] S. P. Knurenko et al. 2006, Nucl. Phys. B (Proc. Suppl.), 151, 92
[22] A. A. Ivanov, S. P. Knurenko, I. Ye. Sleptsov. 2007, JETPh, 104, 870
[23] S. P. Knurenko et al. 2005, Int. J. Mod. Phys. A (Proc. Suppl.), 20, 6894
[24] S. P. Knurenko et al. 2005, Int. J. Mod. Phys. A. (Proc. Suppl.), 20, 6897
[25] S. P. Knurenko et al. 2005, Int. J. Mod. Phys. A (Proc. Suppl.), 20, 6900
[26] S. P. Knurenko et al. 2008, Nucl. Phys. B (Proc.Suppl.), 201, 175
[27] J. R. Höandel. 2005, Nuovo Cim. B., 120, 825
[28] S. P. Knurenko, A. A. Ivanov, A. V. Saburov. 2007, JETPh Lett., 86, 621
[29] H. J. Völk, V. N. Zirakashvili. 2004, A&A, 417, 807
[30] A. R. Bell. 1992, Mon. Not. R. Astron. Soc. 257, 493
[31] E. G. Berezhko. 1994, Astronom. Let., 20, 75
[32] A. D. Panov et al. 2006, astro-ph/0612377
[33] K. Asakimori. et al. 2003, ApJ, 502, 278
[34] T. Antoni et al. 2005, Astropart. Phys., 24, 1
[35] M. Boezio et al. 2003, Astropart. Phys., 19, 583
[36] R. U. Abbasi et al. 2005, ApJ, 622, 910
[37] M. Unger et al. 2007, arXiv:0706.1495v1[astro-ph]