Composition of cosmic rays at ultra high energies

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Abstract: We present measurements of the cosmic ray (CR) composition above 10^{15} eV, performed with the Yakutsk extensive air shower array. Almost forty four thousand events above 10^{17} eV observed by Cherenkov detectors are selected for the analysis of the depth of maximum of the longitudinal development of air showers induced by CRs. The interpretation of these results in terms of CR mass composition is given. It is shown that mean logarithm of the CR atomic number $\langle A(\epsilon)\rangle$ is characterized by the peak value $\langle \ln A\rangle \approx 2.5$ achieved at $\epsilon \sim 10^{17}$ eV and its substantial decrease within the energy interval $10^{17}-10^{18}$ eV to $\langle \ln A\rangle \approx 1$ at $\epsilon > 10^{18}$ eV. Such a behavior has to be considered as indication for the transition from galactic CR component, which is produced in galactic supernova remnants, to extragalactic CR component at $\epsilon = 10^{17} - 10^{18}$ eV.

Keywords: instrumentation: detectors — methods: data analysis — acceleration of particles — cosmic rays — shock waves — ISM: supernova remnants

1 Introduction

The overall origin of cosmic rays (CR), in particular at ultra high energies, above 10^{18} eV, is still an unresolved problem in astrophysics. Understanding this origin requires the determination of the astrophysical objects, that are the CR sources, and of the appropriate acceleration processes, that form the CR spectrum in these objects.

During the last several years considerable progress has been achieved in this field, both experimentally and theoretically. Recently the sharp 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 energy losses of the CRs in their interactions with the microwave background radiation. 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) as a result of diffusive shock acceleration [4], and that the observed CR energy spectrum can be well represented by two components: the first, dominant up to 10^{17} eV, consists of CRs produced in Galactic SNRs; the second, dominant at energies above 10^{18} eV, is of extragalactic origin. The latter component can be produced at the shock that is formed by the expanding cocoon around active galactic nuclei (AGNs): above the energy 10^{18} eV the overall energy spectrum of CRs, produced during the AGN evolution and released into intergalactic space extends at least up to the energy $\epsilon_{\max} \sim 10^{20}$ eV, well above the GZK cutoff [5]. This is the "dip scenario" of the overall CR spectrum formation [6].

Within the alternative "ankle scenario", extragalactic CRs are expected to dominate only above the energy 10^{19} eV [6]. In this case one needs some kind of process which provides the extension of the Galactic CR component up to about 2×10^{18} eV. The possible solution of this problem is 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 [7]. Here we study the alternative possibility where the second component of Galactic CRs is due supernovae (SNe) which explodes into the dense wind of presupernova star.

It was already noted [3, 7] that the chemical CR composition is expected to be very different at energies 10^{17} to 10^{19} eV in these two cases. Therefore the experimental determination of CR composition at these energies is so important.

2 Experiment

The Yakutsk EASA is a ground based experiment for the detection of CRs with energies between 10^{15} and 10^{19} eV [8]. It is located near Yakutsk, Russia (61.661°N, 129.367°E), 100 m above the sea level (1020 g cm^{-2}). The total area covered by the detectors is 12 km^2. The main aspects of the Yakutsk experiment as well as its latest results are discussed in detail by [9, 10, 11].

The depth of shower maximum $X_{\max}$ is derived from observations of the lateral distribution of the Cherenkov light [12]. Knowing the average depth of the shower maximum for protons $X^{\rm p}_{\max}$ and for iron nuclei $X^{\rm Fe}_{\max}$ from simulations, the mean logarithmic mass can be derived from the measured $X_{\max}$ according to the relation [13]

$$\langle \ln A \rangle = (X_{\max} - X^{\rm p}_{\max})/(X^{\rm Fe}_{\max} - X^{\rm p}_{\max}) \left\langle \ln A^{\rm Fe} \right\rangle . \quad (1)$$

We use the result of calculations of $X^{\rm p}_{\max}(\epsilon)$ and $X^{\rm Fe}_{\max}(\epsilon)$ performed within two different hadronic interaction models: QGSJET and SIBYLL. Compared with earlier considerations [12, 14, 15] we present here the most complete set of events detected with the Cherenkov detectors of Yakutsk EASA. At the highest energies $\epsilon > 10^{17}$ eV it comprises about 25000 events detected during 2000-2009 together with previously analyzed 16800 events detected during 1994-2000.

3 Model

To describe the acceleration CRs in galactic SNRs we use here a nonlinear kinetic theory. It couples the particle acceleration process with the hydrodynamics of the thermal gas [16, 17]. It was already demonstrated [3] that the CRs with energies up to $\epsilon \sim 10^{17}$ eV can be produced in SNRs, exploded into the uniform interstellar medium.

It was also proposed [18], that galactic SNRs generate CR spectrum up to about $\epsilon \sim 10^{18}$ eV due to fact that some fraction of CRs are produced by SN shock exploded into the dense presupernova star wind. We consider here this possibility.

In the case of type IIb SN which explodes into the dense red supergiant (RSG) wind SN shock propagating through this wind is able to produce power law CR spectrum up to the maximal energy $\epsilon_{\max} \gg 10^{17}$ eV which is considerably larger than in the case of uniform medium. When magnetic field amplification due to accelerated CRs is not taken into account maximal energy of protons produced in RSG wind region is about $\epsilon_{\max} \approx 2 \times 10^{14}$ eV [17]. According to plasma physical considerations [19], the existing upstream wind magnetic field is expected to be significantly amplified at a strong shock by CR streaming instabilities up to the level

$$B_0 = \sqrt{2\pi \times 10^{-2} \rho_0 V_s^2}, \quad (2)$$

that is consistent with all thoroughly studied young SNRs [20]. Here ρ_0 is the upstream medium density, V_s is the shock speed. This amplified magnetic field provides the value of Alfven speed $c_A = 0.07 V_s$. Since the shock speed during the initial phase of SNR evolution as high as $V_s \approx 1.2 \times 10^4$ km s^{-1} it gives $c_A = 800$ km s^{-1}. This is by a factor of 100 larger than in the case of unamplified magnetic field, considered by [17]. Since the maximal energy of CRs, produced by the expanding shock, scales as $\epsilon_{\max} \propto Z B_0 V_s$ the field amplification is expected to provide acceleration of protons up to the energy $\epsilon_{\max} \approx 5 \times 10^{16}$ eV, whereas iron nuclei maximal energy is about $\epsilon_{\max} \approx 10^{18}$ eV. This is consistent with the consideration of [18].

We use the values of relevant physical parameters of type IIb SNe: kinetic energy of the ejecta $E_{\rm SN} = 3 \times 10^{51}$ erg, ejecta mass $M_{\rm ej} = 2 M_\odot$, the mass loss rate $\dot{M} = 2 \times 10^{-5} M_\odot$ yr^{-1}, duration of RSG phase of the presupernova star 10^5 yr. We apply kinetic nonlinear theory of CR acceleration in SNRs and calculate the spectrum of CRs, produced during the SN shock propagation through the RSG wind. The essential difference compared with the previous consideration [17] is much higher maximal CR energy due to the amplified magnetic field given by equation (2). The other difference is that besides protons we include into consideration helium nuclei and three groups of other elements which significantly contribute composite CR spectrum produced in RSG wind (see below). Then we add this second Galactic CR component to the main first Galactic CR component, produced in the standard SNR evolving in the uniform interstellar medium [3].

4 Results and discussion

In figure 1 we present the intensities $J(\epsilon) \times \epsilon^{2.75}$ of protons (H), Helium, three groups of heavier nuclei, and "All particles" as a function of kinetic energy, as solutions of the nonlinear equations. CR overall spectrum produced by SNRs expanding in the uniform interstellar medium with the standard explosion energy $E_{\rm SN} = 10^{51}$ erg extends up to the energy 10^{17} eV, which corresponds to the maximal energy of accelerated iron nuclei [3]. In the second case the overall CR spectrum is a sum of the previous one plus relatively small fraction of CRs with about 16 times larger maximal energy produced by SN shock within the RSG wind regions. Normalization of the spectra of these second CR component was made so to get the smooth power law extension of the overall CR spectrum above 10^{17} eV up to about 2×10^{18} eV.This was achieved under the assumption that the second CR component contains 0.02 protons, 0.05 of helium nuclei and 0.3 of heavier nuclei relative to the first CR component. As a result second component contains about 10% of the energy contained in the overall CR spectrum. We have used the escape time of CRs from the Galaxy $\tau_{\rm esc} \propto R^{-\mu}$ as a function of CR rigidity R, with $\mu = 0.75$.

According to figure 1 the knee in the observed all-particle GCR spectrum has to be attributed to the maximum energy of protons, produced in SNRs, expanding in the uniform interstellar medium. The steepening of the all particle GCR spectrum above the knee energy 3×10^{15} eV is a result of the progressively decreasing contribution of light CR nuclei with increasing energy. Such a scenario is confirmed by the KASCADE experiment which shows relatively sharp cutoffs of the spectra of various GCR species at energies $\epsilon_{\max} \approx 3\ Z \times 10^{15}$ eV [21], so that at energy $\epsilon \sim 10^{17}$ eV the GCR spectrum is expected to be dominated by the contribution from the iron nuclei.

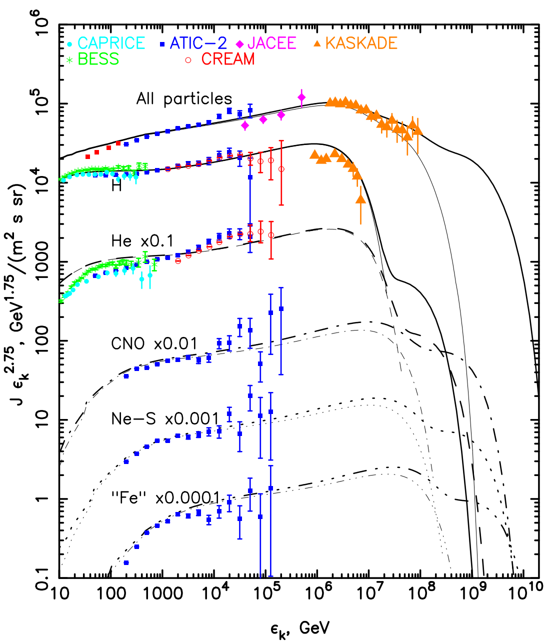

Figure 1: CR intensities at the Solar system as a function of kinetic energy. Experimental data obtained in the CAPRICE [22], BESS [23], ATIC-2 [24], CREAM [25], JACEE [26] and KASCADE [21] experiments are shown as well.

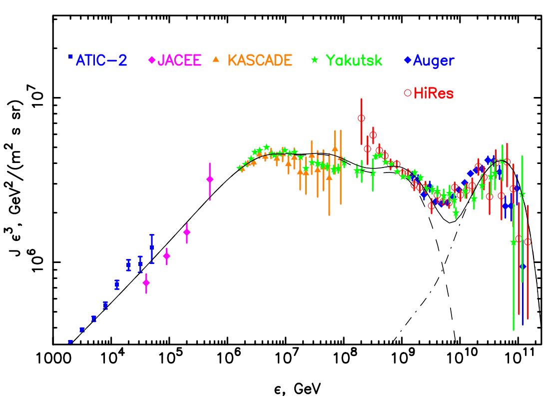

Figure 2: Overall CR intensity as a function of energy (thick solid line), Galactic CR component produced in SNRs (thick dashed line) and extragalactic component (thick dash-dotted line). Experimental data obtained in the ATIC-2 [24], JACEE[26], KASCADE [21], Auger [27], HiRes [1] and Yakutsk at $\epsilon < 3\times10^{17}$ eV [9] and Yakutsk at $\epsilon > 3\times10^{17}$ eV [8] experiments are shown as well.

The same is true for the second galactic CR component: it becomes progressively heavier within the energy interval 10^{17}–2×10^{18} eV so that at $\epsilon_{\max} \sim 10^{18}$ eV it is dominated by the iron group elements.

In order to reproduce the observed overall CR spectrum extragalactic CR component should be steep in the first case (dip scenario) $J_{\rm EG} \propto \epsilon^{-2.7}$ and flat in the ankle scenario

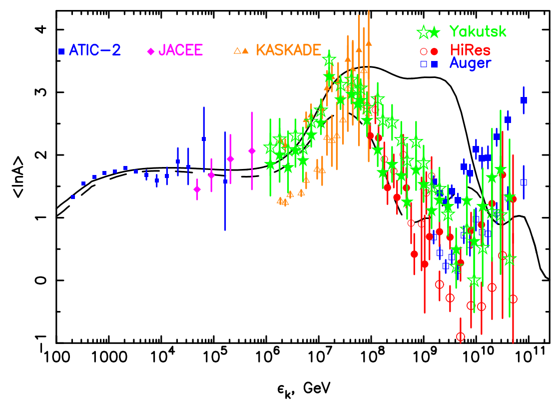

Figure 3: Mean logarithm of the CR nucleus atomic number as a function of energy. Experimental data obtained in the ATIC-2 [29], JACEE, KASCADE [13], Auger [30], HiRes at $\epsilon < 10^{18}$ eV [31], HiRes at $\epsilon > 10^{18}$ eV [32] and Yakutsk experiments are shown. Open and solid symbols corresponds to QGSJET and SYBYLL models respectively.

$J_{\rm EG} \propto \epsilon^{-2}$. The overall CR spectrum in the dip scenario, calculated under the assumption, that extragalactic CRs are produced by nonrelativistic shocks, was analyzed in the previous paper [7].

The overall CR spectrum, corresponding to the ankle scenario is presented in figure 2. Compared with the source spectrum $J_s(\epsilon) \propto \epsilon^{-2}$, the component $J(\epsilon)$, observed in the Galaxy, is modified by two factors. At energies $\epsilon > 10^{18}$ eV the shape of $J(\epsilon)$ 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 black body cutoff for $\epsilon > 3\times10^{19}$ eV [6].

For $\epsilon < 10^{18}$ eV the spectrum $J(\epsilon)$ is determined by the character of CR propagation in intergalactic space. Since we assume the existence of a Galactic Wind, CRs penetrating into the Galaxy from outside are in addition subject to modulation by the wind. We describe this effect 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 [28].

Cf. [6], presenting data of Auger, Yakutsk (at energies ($\epsilon > 3\times10^{17}$ eV) and HiRes detectors in figures 2 and 3, we shift the energies by a factor of $\lambda = 1.35$, 0.83 and 1.15 respectively. At energies ($\epsilon < 3\times10^{17}$ eV) Yakutsk data which are obtained on small Cherenkov subarray [9] the shifting factor is $\lambda = 1.02$.

According to figure 2 the calculated overall CR spectrum is in reasonable agreement with the existing data.

The mean logarithm of CR atomic number corresponding to two considered scenarios are represented in figure 3 as a function of energy. As already discussed [7], within the dip scenario the CR mass energy dependence $\langle \ln A(\epsilon)\rangle$ 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 black body cutoff.

As it is seen from figure 3 energy dependence of the mean logarithm of CR atomic number corresponding to the ankle scenario is considerably different. In this case $\langle \ln A(\epsilon) \rangle$ remains large $\langle \ln A(\epsilon) \rangle \approx 3$ at energies $10^{17} - 10^{19}$ eV and only at energies above 10^{19} eV it goes down sharply toward the value $\langle \ln A(\epsilon) \rangle = 0$. This energy dependence of $\langle \ln A \rangle$ is similar to the prediction of the model which suggests as a second galactic component CRs from galactic SNRs reaccelerated up to the energy $\epsilon \sim 10^{18}$ eV [7].

The results of calculations are compared in figure 3 with the existing data. One can see that Yakutsk and HiRes data are consistent with the expected sharp decrease of $\langle \ln A \rangle$ within the dip scenario in the energy interval $10^{17} - 10^{18}$ eV. At higher energies, above 10^{18} eV, the experimental values of $\langle \ln A(\epsilon) \rangle$, corresponding to different experiments, are distributed over a wide range of values and do not quantitatively agree with each others. At the same time all experiments reveal a trend of progressive increase of the mean CR mass with the increase of CR energy. One can see that Yakutsk data are roughly consistent with the prediction of the dip scenario. HiRes experiment at energies $\epsilon > 10^{18}$ eV assumes considerably lighter CR composition, whereas Auger data at $\epsilon > 10^{19}$ eV correspond to heavier composition compared with the dip model prediction. All existing experiments are clearly inconsistent with the ankle model as it is seen from figure 3.

5 Summary

Composition of ultra high energy CRs measured by Yakutsk EASA is characterized by the peak value of mean logarithm of the CR atomic number $\langle \ln A \rangle \approx 2.5$ achieved at $\epsilon \sim 10^{17}$ eV and its substantial decrease within the energy interval $10^{17} - 10^{18}$ eV to $\langle \ln A \rangle \approx 1$ at $\epsilon > 10^{18}$ eV. Such a behavior is consistent with the HiRes data that has to be considered as indication for the transition from galactic CR component, which is produced in galactic supernova remnants, to extragalactic component at $\epsilon = 10^{17} - 10^{18}$ eV. Ankle scenario which predict this transition at $\epsilon = 3 \times 10^{18} - 10^{19}$ eV is clearly inconsistent with Yakutsk and HiRes data.

At higher energies $\epsilon = 10^{18} - 10^{20}$ eV Yakutsk data are also consistent with the dip scenario, which predicts relatively small variation of the mean CR atomic number near the value $\langle \ln A \rangle = 1$. However the existing data are quite contradictory at these energies: $\langle \ln A \rangle \approx 0$ according to HiRes data and $\langle \ln A \rangle \approx 2$ according to AUGER data. This very uncertain experimental situation does not allow to make any strict conclusion about CR composition at $\epsilon > 10^{19}$ eV.

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