SN 1987A as a possible source of cosmic rays up to energy $10^{18}$ eV by Yakutsk EAS array data

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Abstract. Yakutsk extensive air shower array experiment is the only one which is in operation since 1974, it has the best exposure around $10^{18}$ eV. It is believed that the bulk of cosmic rays up to $\sim 10^{17}$ eV originated in supernova remnants [1]. Under certain conditions they can accelerate cosmic rays up to $\sim 10^{18}$ eV or even higher [2]. However, there is a lack of an undoubted observational evidence for such idea. Here we show that Yakutsk experiment probably has observed cosmic rays from SN 1987A. We found that before 1996 the intensity of cosmic rays in energy range $10^{17}$-$10^{18}$ eV fluctuate near some average value, then it start to increase. The increase of intensity total $45\pm5\%$. It is also accompanied by significant changes in cosmic ray composition; it became heavier – iron dominated. In the last 3-4 years it is a trend to return to the initial state. This peculiarities can be explained by the appearance of SN 1987A. If so, then our results demonstrate that supernova remnants can indeed accelerate cosmic rays up to $\sim 10^{18}$ eV. This is an important step in understanding the cosmic ray origin problem and reveal the great importance of long-term and multicomponent observations of ultra-high energy cosmic rays.

Yakutsk extensive air shower (EAS) array is a ground based experiment for the detection of cosmic rays (CRs) with energies between $10^{15}$ and $10^{20}$ eV [3,4]. It is located near Yakutsk, Russia 61.661°N, 129.367°E, 100 m above a sea level (1020 g cm$^{-2}$). In 1974 the first stage of array from 35 similar stations on area more than 17 km$^2$ put into operation. Each station included two scintillation detectors of size $2\times2$ m$^2$, which operate in the coincidence mode, and registering electronics. In 1978-1979 two muon scintillation detectors with the total area 72 m$^2$ and threshold energy $1.0 \times \sec \theta$ GeV($\theta$ – zenith angle) was build at 350-530 m from the center of array. In 1986 three more muon detectors with area 20 m$^2$ each and the same threshold was added in the central circle of array with radius 1 km. During the reconstruction in 1990-1992 most far stations (>3 km) was disassembled and the total area decreased to 11 km$^2$. At present 49 stations located in a circle with radius 2 km$^2$ takes part in an events selection. On most part of array the distance between stations is 500 m.

Here we analyze EAS with energy of primary particle $E_0 \geq 10^{17}$ eV and $\theta \leq 45^\circ$ registered with Yakutsk array during 1978-2012. In contrast to previous considerations [5,6,7,8,9] we analyze the obtained data year by year separately using the same method [8,9] for all years (see also Supplementary information). We select only showers whose axes hit the central circle of array with a radius $R \leq 500$ m. That part of array was in stable operation during all years (see Supplementary information). The electronic logic of EAS selection has not changed. The showers registration efficiency was about 1. This is ensured by the requirement that at least one master triangle comprised 3 stations with the number of registered particles $\geq 8$. The total number of such equilateral triangles is six. The accuracy of determining the coordinates of the axis was not worse than 20 m. Showers were recorded from September 5-10 to June 15-20. In summer time the array turned off because of the risk of damage from thunderstorms, and for maintenance works.
The CR intensity was not the constant in time (see Figure 1a). Before 1996 it roughly remained at the same level, and then it started to increase. In 2003-2004 the intensity reaches its peak value \(\approx 45\pm 5\%\). Then it starts to decrease and at present it returns to its initial level. This is developed on the background of significant variations in the CR intensity with intervals 1-3 years, which could be generated by turbulent fluctuations of Galactic magnetic field. This is not due to the technical side of Yakutsk array or some other experimental errors. Detectors are continuously calibrated with the background cosmic rays spectrum (see Supplementary information). Electronics regularly checked with test signals. There is a significant difference between the spectra combined over two different period of time (see Figure 1b). In the energy range below \(10^{18}\) eV there is a striking discrepancy, reaching \(25\pm 4\%\) at \(E_0=10^{17}\) eV. However at higher energies the spectra are almost the same. The measured excess of the number of particles with \(E_0 \geq 10^{17}\) eV during 12 years (1998-2011) is about 0.05 particle per m\(^2\).

In this context, great interest is the ratio of muons number to total number of charged particles at the observation level, which contain the information about CR composition. Continuous registration of EAS muon component on Yakutsk array during a long time allows us to analyze it simultaneously with the above results. We determine the muons fraction at the distance \(R=300\) m from EAS axis, where there are enough statistics. The values of \(\rho_m(300)\) are derived from the mean muons lateral distribution function (see Supplementary information). The changes of muons fraction in average correlates with the CRs intensity behavior (see Figure 2). The rapid increase of muons fraction after 1996 indicates the domination of heavier nuclei in CR composition. Indeed, EAS simulations show that the mean

Figure 1. The integral intensity of CRs. On top panel the yearly values are presented for \(E_0 \geq 10^{17}\) eV as function of years. Each point include from 1700 to 2500 events. Error bars includes events statistics and errors of flux determination \(\Delta J(\geq E_0)\) due to errors of energy determination \(E_0\) in each shower. The anomaly after 1996 has the probability that it is by chance less than \(10^{-7}\). Solid curve represents smoothed values. On lower panel the combined integral spectra as function of energy before (1983-1994) and after (2000-2011) increase of intensity are shown by solid and open circles respectively. Error bars are same as on top panel.
logarithmic mass $\ln A$ connected with the parameter $d = \ln (\rho_p(300)/\rho_s(300))$ by linear relation $\langle \ln A \rangle = \ln(56) \left[ (d_{\exp} - d_p) / (d_{\text{Fe}} - d_p) \right]$, where $d$ is the calculated for primary proton (p) and iron (Fe) and measured in the experiment (exp) muons fraction. Simultaneous changes of CR intensity and muons ratio measured with similar detectors is the evidence that the discussed phenomenon is real.

Indeed, if we assume for a moment that the changes of CR intensity are due to some error in energy estimation, than this error would be same for both components of EAS and will not lead to changes of muon ratio.

KASCADE experiment first measured an increase of $\langle \ln A \rangle$ from 1.5 to 3.4 in the energy range $10^{15}$-$1.6 \times 10^{17}$ eV [10]. These measurements were carried out from May 1998 to December 1999. Before this no experiment observe such increase. This is in agreement with our result on Fig. 2, where $\langle \rho_p(300)/\rho_s(300) \rangle \approx 0.23$ and 0.28 which according to QGSJET model [11] of EAS development corresponds to $\langle \ln A \rangle \approx 1.87$ and 3.34 before and after the composition change in 1996, respectively. Recently the observation of a steepening in the cosmic ray spectrum at $E_0 \approx 8 \times 10^6$ eV is reported [12]. This result is based on independent measurements of the charged particle and muon components of the secondary particles of EAS in the energy range $E_0 \approx 10^{16}$-$10^{18}$ eV. The reconstructed electron-poor energy spectrum (enriched by heavy primary nuclei) at $E_0 \approx 10^{17}$ eV exceed electron-rich energy spectrum (enriched by light primary nuclei) on $63 \pm 25\%$. As far as our data suggest that the increase of flux after 1996 on 45% was due to additional flux of high energy heavy nuclei, this is in rough agreement with KASCADE result.

The most prominent event in last decades is the appearance of supernova SN 1987A. SN 1987A was a supernova in the Large Magellanic Cloud, a nearby dwarf galaxy. It occurred approximately 50 kpc from Earth, close enough that it was visible to the naked eye. The direction to supernova is 30° below Galactic plane. It could be seen only from the Southern hemisphere. SN 1987A has been extensively studied in all wavelengths from the radio to the $\gamma$-ray range [13,14].

Diffusive shock acceleration theory [15] recently have made a significant progress, specifically, it is demonstrated that magnetic field in supernova remnants can be amplified non-linearly by the accelerated CRs to many times the pre-shock value, thus substantially decreasing the acceleration time and facilitating acceleration up to $10^{18}$ eV if they expand into a pre-existing stellar wind [2] with a magnetic field much higher than interstellar one. The maximum energy of accelerated nuclei is proportional to square of shock velocity [2] and can be attained during several tens of days [16]. Within the first 1200 days after explosion of SN 1987A the remnant's expansion velocity was extremely high, about 35000 km s$^{-1}$. During the subsequent period of 1500-3000 days the shock velocity dropped by an order of magnitude, to 3000 km s$^{-1}$, explained by the shock entering a region of
dense wind from a red giant which the SN progenitor have been \(\sim 10^4\) years before the explosion [17]. By that time the total energy of accelerated particles was about \(10^{34} E_{\text{SN}}\), where \(E_{\text{SN}}=1.5\times10^{51}\) erg is the kinetic energy of explosion [16,18]. This led to the fact that at 4-8 years after explosion the highest energy tail of already accelerated particles can’t retained anymore by the remnant and freely escaped from the remnant and lit up our Galaxy. If we assume that accelerated particles in the energy range \(10^{17}-10^{18}\) eV contain 1/10 of CR energy, we can estimate the total number of released particles as \(10^{52}\), which at Earth distance for isotropic approximation gives about 0.03 particle per m\(^2\). Even such simplified rough estimation gives comparable excess. A time delay of iron nuclei with \(E_0=2\times10^{17}\) eV propagating directly from SN 1987A to the Earth compared to the light photon is only about 0.18 s. Further delay will associated with the elongation of path due to curving in the Galactic magnetic field. Since SN 1987A is out of Yakutsk array field of observation, to be observable particles should deviate in the Galactic magnetic field at least on \(86^\circ\). For example, the iron nuclei with \(E_0=3\times10^{17}\) eV in magnetic field 3 \(\mu\)G, which is typical to Galactic arm, have gyroradius 4.2 pc and the time to deviate on \(86^\circ\) is about 2 years; protons with the same energy in the same magnetic field have gyroradius 108 pc and corresponding time 52 years. In other words, some fraction of iron nuclei flux from SN 1987A could reach Yakutsk array field of observation, but protons can’t yet. However, for more detailed comparison one should take into account possibility of anisotropic jet-like escape [19] and, of course, the fraction of particles flux which should deviate enough in Galactic magnetic field to reach Yakutsk array field of observation. This will be a subject for subsequent investigations.

In terms of measured flux and composition of ultra-high energy CR and time factor the presented data obtained on Yakutsk EAS array are in agreement with the scenario that SN 1987A is a source of CRs up to \(10^{18}\) eV. This could be a crucial evidence of CR acceleration in supernova remnants.

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References
[1] Berezhko E G and Völk H J 2007 Astrophys. J. 661 L175
[2] Bell A R and Lucek S G 2001 Mon.Not.R.Astron.Soc. 321 433
[3] Egorova V P et al 2001 J. Phys. Soc. Japan. (Suppl. B) 70 9
[4] Ivanov A A, Knurenko S P and Sleptsov I Y 2003 Nucl. Phys. B (Proc. Suppl.) 122 226
[5] Ivanov A A 2010 Astrophys. J. 712 746
[6] Ivanov A A, Knurenko S P and Sleptsov I E 2009 New J. Phys. 11 065008
[7] Ivanov A A et al 2010 Moscow Univ. Phys. Bull. 65 292
[8] Glushkov A V et al 2000 Phys. of Atomic Nuclei 63 1477
[9] Glushkov A V and Pravdin M I 2005 J. Exp. Theor. Phys. 101 88
[10] Ulrich, H et al 2001 Proc. 27th ICRC 2 97
[11] Kalmykov N N, Ostapchenko S S and Pavlov A I 1997 Nucl. Phys. B (Proc. Suppl.) 52 17
[12] Apel W D et al 2011 Phys. Rev. Lett. 107 id. 171104
[13] Chevalier R A 1992 Nature 355 691
[14] McCray R 1993 Ann.Rev.Astron.Astrophys., 31 175
[15] Malkov M A and Drury L O C 2001 Rep. Prog. Phys. 64 429
[16] Berezhko E G and Ksenofontov L T 2000 Astronomy Letters 26 639
[17] Gaensler B M et al 1997 Astrophys. J. 479 845
[18] Berezhko E G and Ksenofontov L T 2006 Astrophys. J. 650 L59
[19] Bell A R 2008 Mon.Not.R.Astron.Soc. 385 1884