Ultrahigh–energy cosmic ray spectrum from nearby active galactic nuclei

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Abstract. We present spectra of cosmic rays in the energy range \((0.5 - 2) \times 10^{20}\) eV. Particles with charge number \(Z\) are assumed to be accelerated at their sources to maximum energies \(ZE_p\), complying with a power law \(E^{-\gamma_0}\). The maximum energy \(E_p\) for protons and the injection index \(\gamma_0\) are determined from experimental data. Within this model we restrict distances to probable sources of ultrahigh–energy cosmic rays up to \(\sim 40\) Mpc. Cen A is discussed as a likely source of heavy nuclei.

1. Introduction

At present the experimental data reported by High Resolution Fly’s Eye (HiRes) and Telescope Array (TA) in the northern hemisphere and by Pierre Auger Observatory (Auger) in the southern one, have some differences in data relating to ultrahigh–energy cosmic rays (UHECRs). For instance, while the break point is clearly set at \(\approx 5.7 \times 10^{19}\) eV in the HiRes spectrum [1], one of the two approximations of the Auger spectrum has a smooth shape [2]. Though, of course, both results basically support the existence of suppression around the GZK energy [3, 4]. The shower maximum data obtained by HiRes [5] and TA [6] show the proton dominance in the UHECR composition, whereas the Auger team [7] points out a transition from protons to heavy nuclei. Besides, there is a contradiction in anisotropy of the UHECR arrival directions. A correlation with nearby active galactic nuclei (AGNs) within 75 Mpc and an excess in the flux of UHECRs around Cen A located at a distance of \(\approx 4\) Mpc are found in the Auger data [8]. On the contrary, the HiRes [9] and TA [10] experiments observe no significant correlations with nearby AGNs. One of the possible solutions of these discrepancies can be concealed in the existence of one or more sources in the southern hemisphere, which produce heavy particles (see, e.g., [11]).

In this work we attempt to find out at what distances the most probable sources of UHECRs are located and which acceleration regimes could explain the experimental data. It is demonstrated that Cen A could be a source of heavy particles, changing the UHECR flux strongly.

2. Model assumptions

In our model, particles with charge number \(Z\) are accelerated at their sources to maximum energies \(E_{\text{max}} = ZE_p\), where \(E_p\) is the maximum energy for protons. This rigidity acceleration
mechanism is commonly used (see, e.g., [12]). The particle composition is assumed to be mixed, similar to the Galactic composition. We consider the most abundant stable elements. Besides protons, these are nuclei of $^4\text{He}$, $^{12}\text{C}$, $^{14}\text{N}$, $^{16}\text{O}$, $^{20}\text{Ne}$, $^{23}\text{Na}$, $^{24}\text{Mg}$, $^{27}\text{Al}$, $^{28}\text{Si}$, $^{32}\text{S}$, $^{40}\text{Ar}$, $^{40}\text{Ca}$, $^{52}\text{Cr}$ and $^{56}\text{Fe}$. Their abundance ratios are taken from [13]. Another assumption is that injection spectra obey a broken inverse power law with indices $\gamma_0$ at energies below $E_{\text{max}}$ and $\gamma_0 + 4$ otherwise. Then the number of nuclei with mass number $A$ and energy in the range of $(E, E + dE)$ is proportional to $A^{\gamma_0 - 1}$ [14]. If the injection index is high enough, the fraction of heavy nuclei is essentially increased at a given energy. It is necessary to emphasize that at large values of $\gamma_0$ the broken power law should be used only in the vicinity of $E_{\text{max}}$ as its extrapolation to substantially lower energies may demand too high efficiency from the sources.

When constructing spectra, we divide nuclei under study into several groups depending on their mass number. Besides protons (p), these are the helium group (He) and the groups of light (L), mean (M), heavy (H) and very heavy (VH) nuclei. This assumption simplifies calculations and is quite justified as there exists some uncertainty in measuring energy and type of incoming particles.

As sources of UHECRs, two cases are discussed below: 1) uniformly distributed sources, and 2) AGNs from the catalog [15], located at distances of $\lesssim 40$ Mpc.

At energies in the range of $(0.5 - 2) \cdot 10^{20}$ eV, main processes by which an ultrahigh-energy particle can lose its energy in propagating through the space are 1) disintegration of nuclei due to interactions with infrared (IR) and cosmic microwave background (CMB) photons, and 2) pion production by protons on CMB radiation. In addition, to estimate the contribution of nuclei to secondary protons, we extend the energy range up to Lorentz factor of $2.1 \cdot 10^{11}$, so photopion production by the nuclei is also taken into account. The approximate conservation of Lorentz factor in photodisintegration and photopion production makes it possible to use a quite simple approach to the problem of nuclei propagation. A more detailed calculation scheme can be found in [16].

3. Calculation results and discussion

In order to estimate the radius of the sphere of probable UHECR sources, we adopt the following simplified model. The sources are identical in cosmic–ray intensity, composition and acceleration regimes. Consequently, the contribution from a single source at a distance $R$ to the total flux should be taken into account with weight $R^{-2}$. Our calculations show that optimal values of parameters to reproduce the break in the HiRes spectrum and light mass composition are $E_p = 5.7 \cdot 10^{19}$ eV and $\gamma_0 = 2.2$. As for the Auger data, the injection index $\gamma_0 = 4.6$ allows us to describe both heavy composition and spectrum shape at the same value of $E_p$. For the case of $\gamma_0 = 2.2$ and sources that are uniformly distributed within 400 Mpc, we obtain mean distances from which the groups of nuclei can reach our Galaxy (Figure 1). A variation of $E_p$ from $10^{19}$ eV to $10^{20}$ eV and $\gamma_0$ from 2.2 to 4.6 does not affect significantly these results. As can be seen, the mean distances for the groups of protons, heavy and very heavy nuclei decrease from $\sim 200$ Mpc at $5 \cdot 10^{19}$ eV to several tens of Mpc at energies $\gtrsim 1.4 \cdot 10^{20}$ eV. The HiRes and Auger data concerning the composition of cosmic rays have been measured only up to $\approx 5 \cdot 10^{19}$ eV because of insufficient statistics of experimental events at higher energies. But if the assumption that the CR composition is light (for the HiRes data) or grows heavy (for the Auger data) holds true above the GZK–cutoff energy, distances to the sources should be restricted by a few tens of Mpc.

To check this hypothesis, we calculate total spectra of UHECR particles, produced by sources that are uniformly distributed within radii of 40, 100 and 400 Mpc (Figure 2). Given the scarce statistics of events at ultrahigh energies, it is difficult to determine the true shape of the UHECR spectrum. However, fits of measurements have been obtained by both HiRes and Auger teams and discussed in literature. Therefore we compare our results with these approximations. As
follows from Figure 2, the spectra produced by remote sources undergo suppression too fast. Such a suppression at long distances should be more pronounced if the absorption due to pair production would be taken into account. The best accord of the calculated total spectra with the HiRes and Auger fits appears in the case of sources that are uniformly distributed within a radius of 40 Mpc. In Figure 2 we also present spectra of the groups of nuclei, produced by AGNs at distances $\lesssim 40$ Mpc, taking into account the fields of view of the HiRes and Auger facilities. The total spectra are also in line with the fits, which confirms our restriction on distances to likely UHECR sources. It is worth mentioning that Seyfert galaxies located at distances $\lesssim 40$ Mpc have been identified in [17, 18] as probable sources of UHECRs.

Thus our calculations show that experimental data provided by both facilities could be explained by different acceleration regimes. But this idea seems a bit strange, as it results in fundamental differences between the sources observed by HiRes and Auger. A more likely situation is that one or more extragalactic objects in the southern hemisphere produce heavy particles. Here we apply this idea to the nearest active radio galaxy Cen A that is widely mentioned as a probable source of UHECR particles. Figure 3 demonstrates spectra of the groups of nuclei, calculated under the condition that an analog of Cen A (i.e. located at ~ 4 Mpc) with $\gamma_0 = 4.6$ makes an approximately 50 % contribution to the CR flux. Another half of the flux is produced by AGNs with $\gamma_0 = 2.2$, located at distances $\lesssim 40$ Mpc. The calculated results are in a good accord with the Auger smooth fit. However, the problem of which sources can contribute to the flux of heavy particles, certainly requires a deeper study, including the propagation of UHECR particles in galactic and extragalactic magnetic fields.
4. Conclusions
On the basis of the model adopted we have obtained spectra of UHECRs in the energy range of $(0.5–2) \times 10^{20}$ eV. A comparison with experimental results shows that probable sources of UHECR particles are located within $\sim 40$ Mpc. An attempt to reconcile data provided by HiRes and Auger with our model calculations leads to essentially different values of the injection index. But this discrepancy may be eliminated if the HiRes facility really does not observe sources producing heavy nuclei.

References
[1] Sokolsky P (The HiRes Collaboration) 2009 Nucl. Phys. B Proc. Sup. 196 67
[2] Salamida F (The Pierre Auger Collaboration) 2011 Proc. 32th Int. Cosmic Ray Conf. (Beijing, China) [arXiv:1107.4809]
[3] Abbasi R U et al. (The HiRes Collaboration) 2008 Phys. Rev. Lett. 100 101101 [arXiv:astro-ph/0703099]
[4] Abraham J et al. (The Pierre Auger Collaboration) 2008 it Phys. Rev. Lett. 101 061101 [arXiv:0806.4302]
[5] Abbasi R U et al. (The HiRes Collaboration) 2010 Phys. Rev. Lett. 104 161101 [arXiv:0910.4184]
[6] Jui C C H (The Telescope Array Collaboration) 2011 Proc. APS Division of Particle and Fields Conf. (Brown University, Providence, RI, USA) [arXiv:1110.0133]
[7] Abraham J et al. (The Pierre Auger Collaboration) 2010 Phys. Rev. Lett. 104 091101 [arXiv:1002.0699]
[8] Abreu P et al. (The Pierre Auger Collaboration) 2010 Astropart. Phys. 34 314 [arXiv:1009.1855]
[9] Abbasi R U et al. (The HiRes Collaboration) 2008 Astropart. Phys. 30 175 [arXiv:0804.0382]
[10] Tsunesada Y (The Pierre Auger Collaboration) 2011 Proc. 32th Int. Cosmic Ray Conf. (Beijing, China) [arXiv:1111.2507]
[11] Schwarzschild B 2010 Physics Today May 15
[12] Aloisio R, Berezinsky V, Gazizov A 2011 Astropart. Phys. 34 620 [arXiv:0907.5194]
[13] Allen C W 1973 Astrophysical Quantities (London: The Athlone Press)
[14] Ginzburg V L, Syrovatskii S I 1964 The Origin of Cosmic Rays (Oxford: Pergamon Press)
[15] Veron-Cetty M P, Veron P 2010 Astron. Astrophys. 518 A10
[16] Kalmykov N N, Shustova O P, Uryson A V 2011 Spectra and mass composition of ultrahigh-energy cosmic rays from point sources [arXiv:1112.5523]
[17] Uryson A V 1996 J. Exp. Theor. Phys. Lett. 64 77
[18] Uryson A V 2001 Astron. Rep. 45 591