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Stochastic scattering in Cen A radio lobes

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The results of direct numerical modelling of the cosmic ray acceleration in strongly excited turbulence, where quasi-linear theory is non-applicable, are presented. We model turbulent plasma by a set of randomly propagated Alfvén waves with Kolmogorov spectrum of magnetic field fluctuations. The influence of stochastic scattering in Cen A radio lobes on correlation of the ultra high energy cosmic rays (UHECR) events registered by Auger observatory with Cen A is studied. Typical radio lobe regions, which UHECR of different chemical composition are supposed to come from, are estimated by applying numerical modelling of UHECR scattering with Fermi II mechanism in the turbulent regions.

Key words: acceleration, cosmic rays, turbulence

INTRODUCTION

One of the most topical problems of the high-energy astrophysics in the recent years are mechanisms of acceleration of cosmic rays (CR) — elementary particles and stable nuclei with energies up to 10^{20} eV. Their registered flux is about 1 event per $1\,\mathrm{km}^2$ in 100 years.

The analysis of CR flux, spectrum and anisotropy can assign valuable information about CR sources, as well as physical conditions and electromagnetic fields in the different regions of the Universe. Galactic Supernovae remnants are widely believed to be the main source of CR with energies below 10^{18} eV, while UHECR, i. e. those with the energies over 10^{18} eV, are supposed to originate from extragalactic sources such as active galactic nuclei (AGN), gamma-ray bursts, young magnetars etc. The distance to UHECR sources is believed not to exceed hundreds of Mpc due to the so-called GZK-cutoff [4, 14]. This problem is discussed more thoroughly in [1, 3, 5, 6].

In the present paper we develop a theory of stochastic acceleration of CR in AGN radio-lobes, initiated in our previous studies [12, 13]. Radio lobes are known as strongly turbulent media especially in the jet deceleration regions, where the level of turbulence $\frac{(\delta B)^2}{B_0^2}$ is sufficient for creating favourable conditions for CR acceleration up to ultra high energies.

The authors of [2] estimated the probability of stochastic acceleration of cosmic rays up to several TeV in molecular clouds which are located in the centre of the Galaxy. To solve this problem they performed a run of numerical simulations for the calculation of space-energy diffusion coefficients for the protons in molecular clouds. These data allowed estimating the highest possible energies that can be reached. In our simulations we use the similar mathematical technique but apply it to another model of astrophysical medium and another astrophysical object, namely Cen A. Besides, we lay stress not on the maximum cosmic rays' energy estimation, but on determining the location of real sources of CR of different chemical composition registered by Auger Observatory.

TURBULENT REGION MODELLING

Standard numerical analysis of ion dynamics in turbulent magnetic fields assumes that variable magnetic field $\delta\mathbf{B}$ is applied upon stationary field $\mathbf{B}_0$; $\delta\mathbf{B}$ is formed as the sum of a large number of randomly polarized transverse Alfvén waves with wavelengths $\lambda_A = \frac{2\pi}{k_A}$ logarithmically distributed between λ_{min} and λ_{max}.

As a rule there are no large scale electric fields in astrophysical plasma due to its high electroconductivity, though waves of different types which contribute to MHD turbulence can cause arrival of variable electric field which can accelerate charged particles [7, 8]. In the present paper we consider a simple model of MHD turbulence, proposed in [8] as a set of equally polarized (electric vectors of all random waves are coplanar) Alfvén waves with different wavelengths, amplitudes, frequencies and phases, applied upon uniform background field $\mathbf{B}_0$.

As it was pointed above variable magnetic field is given as a composition of N randomly directed plane waves which propagate along X-axis in different di-

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rections:

$$\delta\mathbf{B} = \sum_{n=1}^{N} \mathbf{A}_n e^{i(\mathbf{k}_n\cdot\mathbf{r}-\omega_n t+\varphi_n)}, \qquad (1)$$

where the direction of vector $\mathbf{k}_n$ and its phase φ_n are specified randomly [2] (for every single wave from the set), and A_n is the n-th wave amplitude. The total number of terms in the sum (1), i. e. the number of Alfvén waves (N), is a parameter which value can be chosen independently. For the simulations reported in the present paper it equals 500.

Values of k_n are uniformly distributed over logarithmic scale between $k_{min} = 2\pi/\lambda_{max}$ and $k_{max} = 2\pi/\lambda_{min}$: $k_n = k_1(\Delta k)^{N-1}$, where $\Delta k = \left(\dfrac{k_{max}}{k_{min}}\right)^{1/(N-1)}$. The expected spectrum is set up by choosing the spectral index Γ while calculating random field amplitudes:

$$A_n^2 = A_1^2 \left[\frac{k_n}{k_1}\right]^{-\Gamma+1},$$

where $\Gamma = 5/3$ in the case of Kolmogorov spectrum. The value of A_1 depends on the parameter ξ which defines the mean energy density of turbulent magnetic field $\langle\delta B^2\rangle = A_1^2 \sum_n \left[\dfrac{k_n}{k_1}\right]^{-\Gamma+1} = \xi B_0^2$ [2].

Alfvén waves do not compress the medium they propagate in but impose velocity which satisfies the condition $\mathbf{k}\cdot\mathbf{v} = 0$ to it. The total velocity of the medium can be written as the sum:

$$\delta\mathbf{v} = \sum_{n=1}^{N} \delta\mathbf{v}_n.$$

Thus the equation for the overall electric field will be written as

$$\delta\mathbf{E} = -\frac{\delta\mathbf{v}}{c} \times \mathbf{B},$$

where $\mathbf{B} = B_0\hat{x} + \delta\mathbf{B}$.

Motion of a particle with charge q, rest mass m_0, velocity $v = \beta c$, Lorentz-factor $\gamma = \left(1-\beta^2\right)^{-1/2}$ and momentum $p = mv = \gamma m_0 v$ in electric and magnetic fields $\mathbf{E}$ and $\mathbf{B}$ are described as:

$$\frac{d\mathbf{p}}{dt} = q\mathbf{E} + \frac{q}{c}\left[\mathbf{v}\times\mathbf{B}\right], \qquad (2)$$

where c is the speed of light, and

$$\frac{d\mathbf{r}}{dt} = \mathbf{v}. \qquad (3)$$

For a chosen combination of main uniform and turbulent magnetic fields we solve numerically (Runge-Kutta method of the 4th order) equations (2)–(3) for a set of 1000 particles, injected in turbulent region, each of them with randomly generated direction and time of injection (each particle interacts with different realization of MHD turbulence).

POSSIBLE UHECRS CLUSTERIZATION AROUND CEN A: THE ROLE OF STOCHASTIC SCATTERING IN RADIO LOBES

Relativistic jets as well as giant radio lobes of radiogalaxies are plausible sources of UHECR. Studying physical conditions in these regions one can obtain important information on mechanisms of particle acceleration up to 10^{20} eV.

Centaurus A (Cen A or NGC 5128) is the nearest (3.8 ± 0.1 Mpc) active galaxy, and a Fanaroff-Riley Class I (FR-I) radio galaxy. Due to its proximity Cen A can be regarded as a laboratory for investigation of cosmic rays' acceleration mechanisms.

Observations of Cen A in X-ray, radio and gamma wavebands give evidences of CR acceleration to energies of several EeV. UHECR are likely accelerated in Cen A relativistic jets [9] and are injected out of them into the radio lobes — regions of turbulent plasma generated due to the jet interaction with near-nuclear and intergalactic medium. After injection UHECRs can be additionally accelerated via stochastic processes of scattering on turbulent fluctuations. Though the value of extra acceleration can be small, stochastic scattering will be substantial for spread-out of the initial UHECR flux, collimated in the jet direction. If the jet is directed at an angle ψ to the line of sight the UHECR will arrive to the observer only after scattering through the angles larger than ψ. This effect is important for estimation of the correlations of UHECR arrival directions with astrophysical objects such as Cen A. Observational data by Auger which show some correlation of CR arrival directions with Cen A are presented in Fig. 1 and are also discussed in [11] where the authors investigated the influence of magnetic field on trajectories of UHECR propagation, and determined locations of the real sources of the registered UHECR events. The map is presented in the galactic coordinate system where the galactic longitude l or l_G is the angular distance of an object eastward from the galactic centre along the galactic equator and the galactic latitude b or b_G is the angular distance of an object from the galactic equator. For the distance to the Cen A, 3.8 Mpc, the angular size 1° corresponds to 66 kpc.

Relativistic jets of Cen A are directed at the angle $\psi \geq 50°$ to the line of sight, so one can detect CR only from the region where the beam of particles accelerated along the jet defocuses from the initial direction through the angles more than 50°.

Therefore we expect to detect CR from those regions of jet, where considerable part of initially collimated beam of CRs is scattered into the angles, larger than misalignment of Cen A jet. Since the CR scattering (pith-angle diffusion in our case) strongly depends on the chemical composition (the mass number) for given energy of CR, different nuclei will satisfy the demand for considerable scattering at different distances from Cen A nucleus. This distance L is of order of displacement of CR during the scattering time t ($L \sim c \cdot t$) while the trajectory in not completely diffusive and longitudinal (in jet direction) component of CR velocity is still of order of the speed of light c. Therefore, light nuclei (p, He) with smaller diffusion coefficient are expected to be observed at larger distances (region 1 in Fig. 3), whereas for heavy nuclei (Fe) we expect the shortest distances (region 3 in Fig. 3).

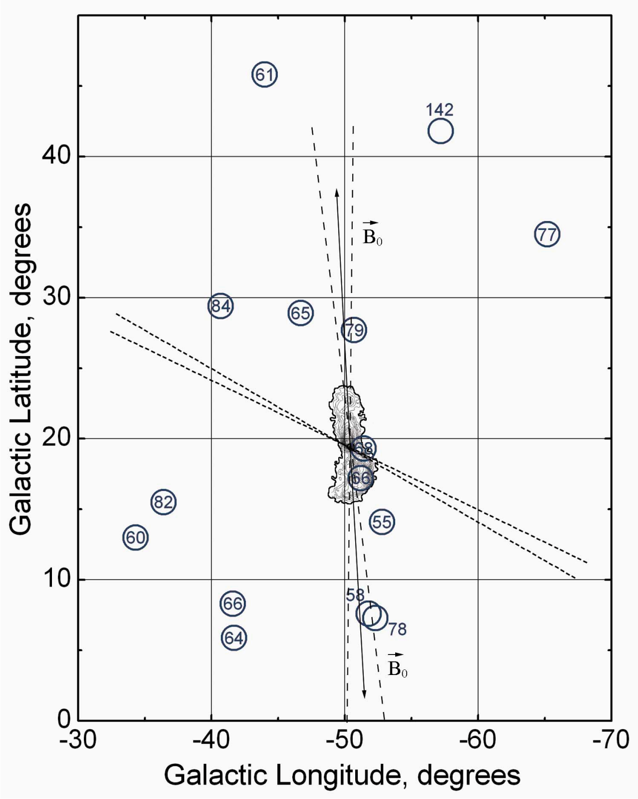

Fig. 1: Model of Cen A galaxy, which is used in our simulations: the active jets are denoted with dotted lines; the direction of the jets which are associated with the giant lobe production is denoted with dashed lines. The positions of UHECR events registered by Auger Observatory in Cen A region are denoted with circles and numbers in them show the event energy in EeV.

For this reason one needs to compare CR arrival directions with the scattering regions inside the radio lobes for the given CR chemical composition (protons, helium, carbon, oxygen and iron) to estimate possible correlation of UHECR with Cen A correctly.

We have calculated spreading-out process in Cen A case by injection of 1000 monoenergetic particles (He, C, O, Fe with atom number $A = 4$, 12, 16 and 56, respectively) with the initial Lorentz-factor of $7 \cdot 10^{10}/A$, along the jet direction into the turbulent region. According to the results of [10] the turbulent region was modelled by superposition of 500 Alfvén waves with the Kolmogorov spectrum in the wavelength interval ($\lambda_{min} = 7.101$ kpc, $\lambda_{max} = 100$ kpc) and the background field $B_0 = 1\,\mu$G directed along the jet, with turbulence level $\dfrac{(\delta B)^2}{B_0^2} = 1.0$, plasma density $n = 10^{-4}\,\mathrm{cm}^{-3}$ and Alfvén velocity $v_A = 2 \cdot 10^7$ cm/s.

The typical scattering time (i. e. lifetime of a particle in a turbulent medium before it scatters on the angle over 50°) t and the distance L for UHECR with typical Auger energy $E = 7 \cdot 10^{20}$ eV but with different chemical composition are presented in Fig. 2 and 3, respectively: helium nuclei (He), which are deflected from the initial direction through the angles $\psi > 50°$ will be observed at typical distance from Cen A nucleus $L \geq 100$ kpc, carbon and oxygen — at $L \geq 30$ kpc, and iron nuclei at $L \geq 10$ kpc.

For the proton case the values of typical scattering time are about $t \geq 10^{14}$ s. The estimated size of the regions protons can arrive from is $L \geq 250$ kpc, i. e., greater than the radio lobes' size and thus no conclusions on their possible correlation with Cen A can be made.

As one can see from Fig. 3, where we present also the escaping positions of detected UHECRs calculated in [11] for different atom numbers with taking into account the deflection in regular Galactic magnetic field, stochastic scattering in the radio lobes is important for finding out correlation of CR with Cen A.

CONCLUSIONS

AGN are considered as the most promising candidate on UHECR sources. Relativistic jets can generate shock waves which effectively accelerate the charged particles via the 1st order Fermi mechanism. But FR II galaxies with the powerful shock wave features are located too far to provide the registered UHECR flux. Therefore great efforts are applied towards studying CR acceleration in FR I galaxies which are situated close enough to the Earth but have less powerful jets which decelerate gradually. Deceleration region has to be strongly turbulent and fulfil conditions favourable for CR acceleration via the 2nd order Fermi mechanism with turbulent fluctuations and MHD waves as centres of scatter. The results of direct numerical modelling of stochastic scattering of CR in strongly excited relativistic turbulence, which is typical for Cen A, were analysed in the present paper. We estimated characteristic sizes

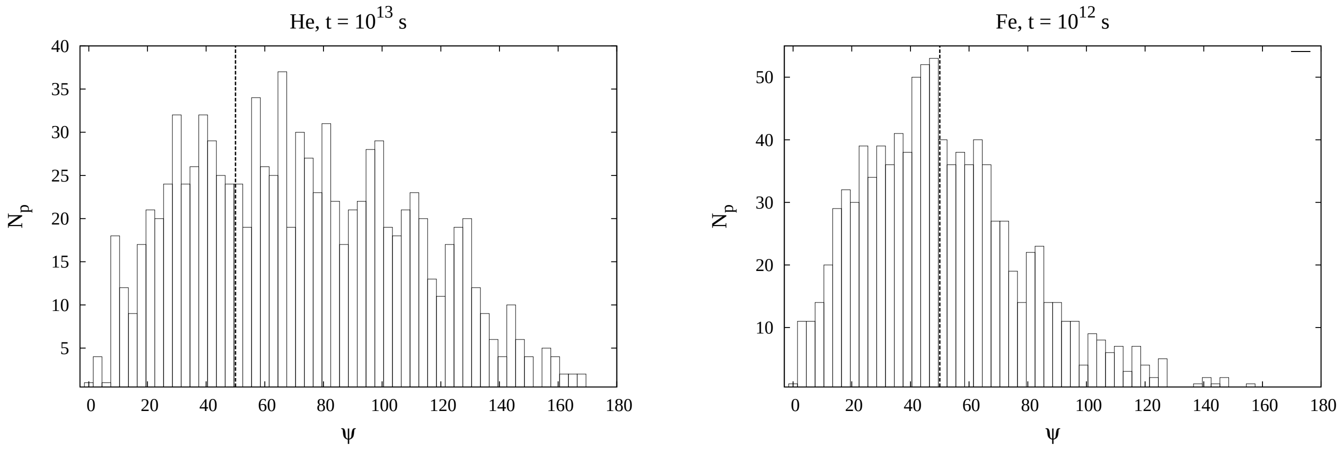

Fig. 2: Particles' directional distribution (over the angles of deflection from the initial direction): for helium nuclei (He) at $t = 10^{13}$ s (left); for iron nuclei (Fe) at $t = 10^{12}$ s (right). The particles which are deflected from the initial direction on the angles $\psi \geq 50^0$ and thus can be registered on the Earth are presented to the right from the dashed line. All the particles are thrown along the jet at initial time ($\psi = 0^0$).

of regions of radio lobes for CR of different chemical composition using direct numerical modelling of UHECR scattering and acceleration by Fermi II mechanism in the turbulent regions.

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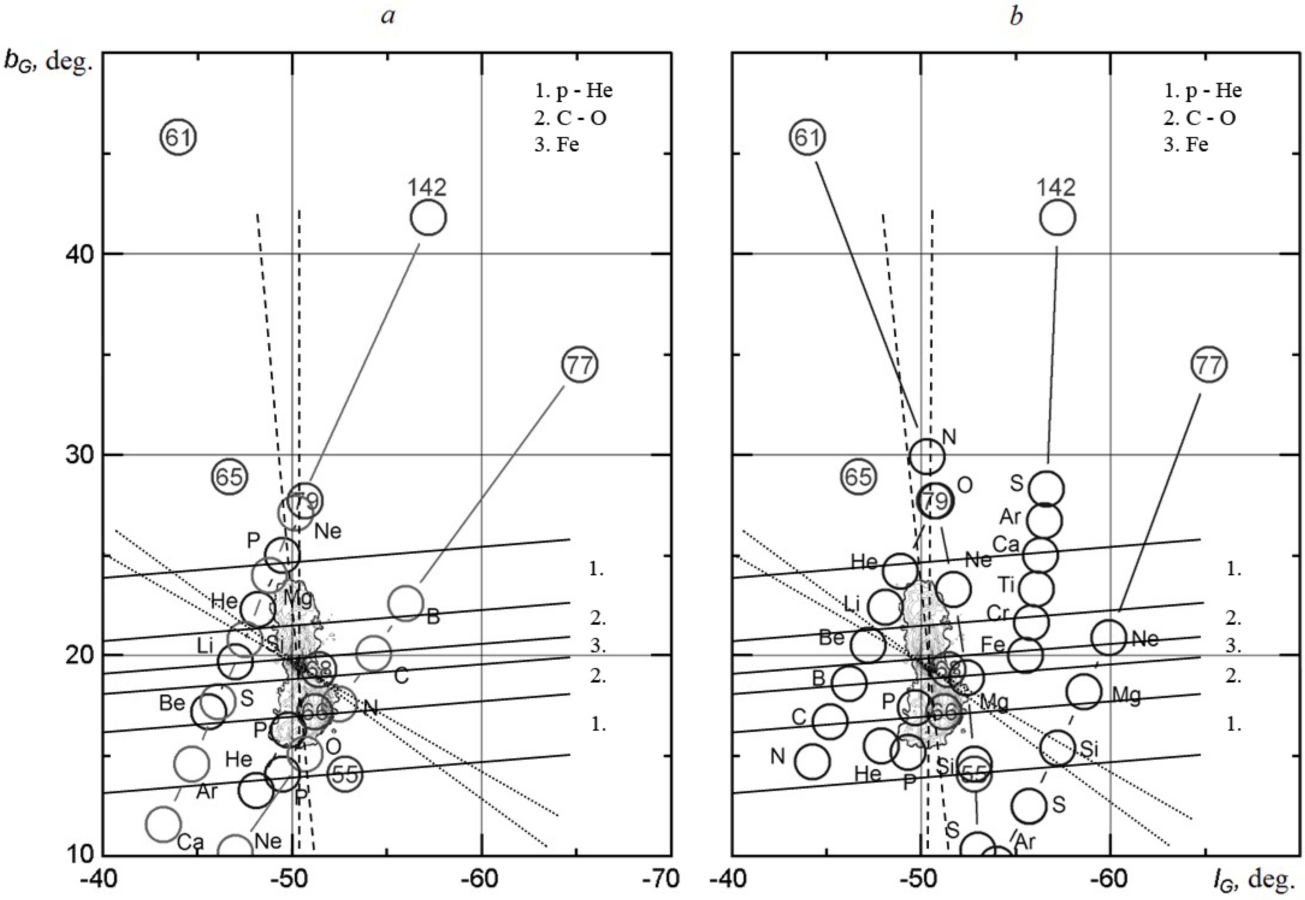

Fig. 3: Cen A with calculated regions UHECR can be expected to arrive from (in the case of p, He, C, O, Fe) — regions 1–3. The numbers in the circles show the energy of the CR particle, registered by Auger Observatory in Cen A region, given in EeV. The numbers with chemical elements' legends denote the calculated positions (according to Prouza M. & Smida R. model – a, and Kachelriess M. model – b) of the real sources of UHECR of the corresponding chemical composition, taking into account the influence of magnetic field from [11].