Galactic anisotropy of Ultra-High Energy Cosmic Rays produced by CDM-related mechanisms

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Abstract

We briefly review current theoretical and experimental status of Ultra-High Energy Cosmic Rays. We show that "top-down" mechanisms of UHE CR which involve heavy relic particle-like objects predict Galactic anisotropy of highest energy cosmic rays at the level of minimum $\sim 20\%$. This anisotropy is large enough to be either observed or ruled out in the next generation of experiments.

This talk is devoted to a specific signature of CDM-related mechanisms of production of Ultra-High Energy Cosmic Rays (UHE CR) [1], connected to non-central position of the Earth in our Galaxy. We start by brief review of the current theoretical and experimental status of UHE CR. We then specify what we mean by CDM-related mechanisms and explain the origin of the anisotropy of the UHE CR produced by these mechanisms. Finally, we estimate the anisotropy and give our conclusions.

UHE CR consist of the most energetic particles available for physicists at present, with energies in excess of 10^{19} eV. At these energies the flux of cosmic rays which falls like E^{-3} is very small, roughly 1 event per km^2 per

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century. The number of events observed so far is well below hundred; the primary particle content is currently unknown.

The special interest in cosmic rays with energies higher than 10^{19} eV is related to the cutoff predicted in the spectrum in this energy range, the so-called GZK cutoff [2]. The origin of this effect is easy to understand assuming that primary particles are protons. At energies exceeding $E_{GZK} \sim 4 \times 10^{19}$ eV a proton propagating through cosmic microwave background rapidly loses its energy due to resonant pion photoproduction. The proton mean free path $R_{GZK} \sim 50$ Mpc is two orders of magnitude smaller than the size of the visible part of the Universe. Consequenly, the flux of cosmic rays (assuming they are protons) is expected to drop by two orders of magnitude at $E \sim E_{GZK}$. Similar cutoff is expected for photons [3].

There are several experiments capable of detecting the low flux of UHE CR, the largest being Akeno Giant Air Shower Array (AGASA), Fly's Eye I,II Experiments and Yakutsk Experiment. The common idea of these experiments is observation of showers of secondary particles which are produced in the collisions of primary UHE particles with atmosphere. Detecting such a shower and reconstructing the energy and arrival direction of a primary particle requires a large number of detectors on the total area of order several decades of square kilometers. AGASA, for example, consists of 111 scintillators, located on the area of 100 km^2.

The sensitivity of the experiments has just reached the energy range where the GZK cutoff is expected. About 20 events with energies higher than E_{GZK} were detected. There were 8 events observed with energy above 10^{20} eV. Two most reliable ones have the following energies: $2.1^{+0.5}_{-0.4} \times 10^{20}$ eV (AGASA, [4]) and $3.2^{+0.92}_{-0.94} \times 10^{20}$ eV (Fly's Eye, [5]). While the typical angular resolution in these experiments is rather high, of order 3°, the energy resolution is only about 30%. As a result of poor statistics and low energy resolution, current data are not enough to draw definite conclusion about the very existence of the GZK cutoff. They, however, indicate that the expected sharp cutoff is absent.

If confirmed, the absence of the cutoff would definitely be a hint for a new physics. There may be two possible explanations: either primary particles are some new particles (e.g. UHEcrons, [6]) which do not interact with cosmic microwave background, or the sources of UHE CR are relatively close to us (i.e., within ~ 50 Mpc). In what follows we concentrate on the latter possibility. On this way, the main problem is a *mechanism* of production of cosmic rays with such a huge energy.

Regardless of the location of the sources, possible mechanisms of production of UHE CR are naturally divided into two classes — the astrophysical and particle-physics ones. The astrophysical mechanisms employ acceleration of charged particles in strong magnetic fields. There are severe constraints on maximum energy to which a particle can be accelerated at a given value of magnetic field and the size of astrophysical object [7],

$$BL > \frac{E}{10^{15}\mathrm{eV}} \frac{1}{Z\beta} ,$$

where B is the magnetic field in μG, L is the size in parsecs, Z is the charge of the particle and β is the speed of the shock wave. There are very few astrophysical objects (for instance, active galactic nuclei [8, 9] or hot spots of radio galaxies [9]) which are believed to be able to accelerate particles to energies of order 10^{20} eV. If such an object located within 50 Mpc from us were source of UHE CR it would be identified. Thus, in order to reconcile the astrophysical mechanizm with the absence of the GZK cutoff one would have to consider 'exotic' primary particles.

The particle-physics mechanisms typically involve decays of heavy particle-like objects, "X-particles", either primordial or recently produced in the process of the evolution of cosmological defects. The mechanisms of the former type we call "CDM-related". Their characteristic feature is that the sources of UHE CR are distributed in the Universe in the same way as Cold Dark Matter (CDM), i.e., they are concentrated in galactic halos as a result of gravitational clustering at the stage of galaxy formation[1] [10]. Numerically it means that the average densities of sources of UHE CR in the Galactic halo $\bar{n}_h$ and in the Universe $\bar{n}$ are related in the same way as the average densities of the matter in the Galaxy and in the Universe,

$$\frac{\bar{n}}{\bar{n}_h} \simeq \frac{\Omega_{CDM}\rho_{crit}}{\bar{\rho}_{halo}} \sim 10^{-5}. \tag{1}$$

According to this definition, any mechanism involving primordial massive particles which are non-relativistic at the time of galaxy formation, is CDM-related. On the contrary, mechanisms where X-particles are permanently

[1]Note that distribution of X-particles inside a halo does not need to follow that of CDM as it is determined by the interactions of particles with each other and with matter.

produced by topological defects like cosmic strings or 'cosmic necklaces' (for a review see Refs. [11]) are not CDM-related.

For the sake of completeness consider briefly some of the CDM-related mechanisms discussed in the literature. Simplest ones are based on decays of heavy long-living particles [12, 13, 14]. Regardless of their nature, the mass and lifetime of these particles must lie in a certain range. Indeed, the flux F of UHE CR resulting from decays of the relic X-particles is

$$\frac{dF}{d\log E} \sim \frac{n_X}{\tau_X} R_{GZK} N \ , \tag{2}$$

where n_X is the average number density of X-particles and τ_X is their lifetime. N is average multiplicity of UHE CR produced in one decay; it equals to the number of produced jets times the fragmentation function. The expected value of N lies in the range $N \sim 10 \div 1000$. Thus, the mass of X-particles should satisfy

$$m_X \gtrsim 10^{13}\text{GeV}.$$

Such heavy particles can be produced either during reheating (if the reheating tmperature was of order m_X) or directly from vacuum fluctuations during inflation [15, 16].

The lifetime of X-particles can be bounded from the requirements that they produce the observed flux of UHE CR and do not overclose the Universe. One gets [13]

$$10^{10}\text{yr} \lesssim \tau_X \lesssim 10^{22}\text{yr}.$$

It is difficult to explain naturally such a long but finite lifetime. One may speculate that decay of X-particles, which are otherwise stable, is due to instanton-type [13] or wormhole [14] effects. Detailed discussion of the hypothesis that the UHE cosmic rays result from decays of metastable massive relic dark matter particles in the Galactic halo can be found, e.g. in ref. [17].

Another potential mechanism of UHE CR production is monopole-antimonopole annihilation [18]. If monopoles exist in Nature, one may expect that some of them are in the form of monopole-antimonopole bound state (monopolonium). Certainly, the ground state of monopolonium is very unstable. For example, in the non-relativistic model the first Bohr radius of the monopolonium is much less than the size of the monopole and monopole-antimonopole pair should immediately annihilate. However, highly excited states of monopolonium can be rather long-living. Estimates of [18] give

$\tau_m \sim 40$ days for monopolonium of the size $r_m \sim 1$ fm and $\tau_m \sim 10^{11}$ yr for $r_m \sim 1$ nm.

The scenario of UHE CR production is the following. Monopolonium forms in highly excited state with $r_m \sim 1$ nm. Then it radiates light vector bosons and comes down to the ground state after a time comparable to the age of the Universe. Finally monopole and antimonopole annihilate and produce heavy gauge bosons. Primary UHE particles appear as the products of decays of these bosons. Estimates of [18] show, that the abundance of the monopolonium, required in order to produce the observable flux of UHE CR can in principle be consistent with experimental limits.

Now let us turn to the main topic of this talk, the specific signature of the CDM-related mechanisms. We argue that, regardless of their nature, all CDM-related mechanisms predict anisotropic flux of UHE CR with the excess of at least 20% towards the center of our Galaxy [1].

The observed flux of UHE CR can be divided into Galactic and extragalactic parts,

$$j = j_{\rm ext} + j_h,$$

where

$$j_h = C \int_{\rm halo} \frac{d^3x}{x^2} n(x) \tag{3}$$

is the contribution of our Galaxy and

$$j_{\rm ext} = C\, 4\pi R_{\rm ext} \bar{n}$$

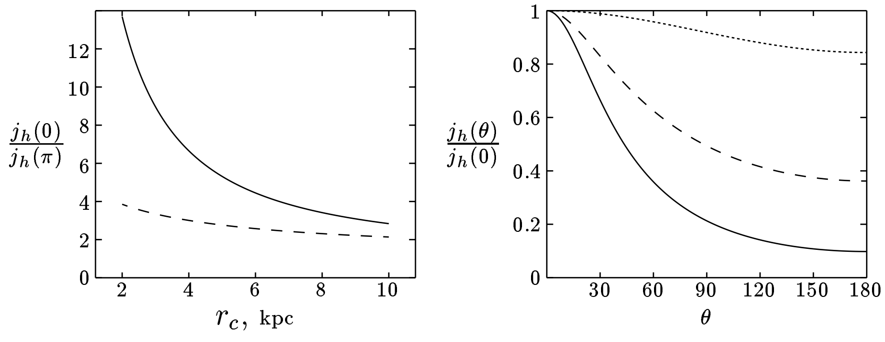
has extragalactic origin. Here $R_{ext} = R_{\rm Universe} \sim 4$ Gpc for energies below $E_{\rm GZK}$ and $R_{\rm ext} \sim 50$ Mpc for energies above $E_{\rm GZK}$. Note that the constant C is the same in both equations.

The Galactic part of the total UHE CR flux, j_h, is anisotropic due to our position at 8.5 kpc from the center of the Galaxy. The anisotropy can be obtained from eq.(3),

$$j_h(\theta) \propto \int dx\, n(r(x,\theta)).$$

Fig.1a shows the anisotropy $j_h(0)/j_h(\pi)$ as a function of the core radius for the trial distributions

$$n(r) \propto \frac{1}{(r_c^2 + r^2)} \tag{4}$$



a) b)

Figure 1: a) The anisotropy $j_h(0)/j_h(\pi)$ as a function of the core size r_c for the density profiles (4) (solid line) and (5) (dashed line). b) The corresponding angular distributions at $r_c = 5$ kpc. The dotted line shows the angular distribution for $n(x) = \text{const}$ (i.e., when the anisotropy is minimum).

and

$$n(r) \propto \frac{1}{\sqrt{(r_c^2 + r^2)(R_h + r)^2}}, \tag{5}$$

where R_h is the halo size. First of these distributions describes isothermal halo model [19] while the second one is more realistic distribution of ref. [20]. We have arbitrarily regularized it at $r = 0$ by introducing the core size r_c. For $n(x) = \text{const} \times \Theta(R_h - r)$ the anisotropy is minimum and constitutes about 20%. Fig.1b shows corresponding angular dependencies of $j_h(\theta)$ at $r_c = 5$ kpc. As can be seen from the picture, the anisotropy of the galactic contribution is at least $\sim 20\%$ and can be much larger if $n(x)$ is concentrated around the galactic center. Also, it should be noted that the anisotropy depends exclusively on $n(x)$ and does not depend on energy since cosmic rays with energy $E \sim E_{\rm GZK}$ are deflected by the Galactic magnetic field by only $\sim 3^\circ$ [21].

In order to see the significance of galactic part, it is neccessary to compare the galactic component j_h of the total flux with the isotropic extragalactic contribution j_{ext}. By making use of eq.(1), one obtains

$$\frac{j_{\rm ext}}{j_h} = \alpha \frac{R_{\rm ext}}{R_h} \frac{\bar{n}}{\bar{n}_h} \sim \alpha \frac{R_{\rm ext}}{R_h} \times 10^{-5}, \tag{6}$$

where $R_h \sim 100$ kpc is the size of the Galactic halo and α is the constant of purely geometrical origin,

$$\alpha = \frac{3 \int_{r<R_h} d^3x n(x)}{R_h^2 \int_{r<R_h} \frac{d^3x}{x^2} n(x)}. \tag{7}$$

Here $r(x,\theta) = (x^2 + r_0^2 - 2xr_0 \cos\theta)^{1/2}$ is the distance between current point and the Galactic center while $r_0 = 8.5$ kpc is the distance to the Galactic center. The numerical value of α is $\alpha \simeq 0.15$ and $\alpha \simeq 0.5$ for distributions (4) and (5), respectively, with no strong dependence on r_c in the range $r_c = 2-10$ kpc, while for homogeneous distribution $n(x) = \text{const} \times \Theta(R_h - r)$ α is close to 1.

From eq.(6) we find

$$\begin{aligned} \frac{j_{\rm ext}}{j_h} &\sim \alpha & &\text{for } E < E_{\rm GZK}, \\ \frac{j_{\rm ext}}{j_h} &\sim 10^{-2} \times \alpha & &\text{for } E > E_{\rm GZK}. \end{aligned} \tag{8}$$

Therefore, at $E < E_{\rm GZK}$ the Galactic and extragalactic contributions can be comparable (although the Galactic one is probably somewhat larger), while at $E > E_{\rm GZK}$ the extragalactic part is suppressed by a factor $\sim 10^{-2}$. In either case a substantial fraction of the observed UHE CR should come from the halo of our Galaxy. In this respect our conclusions agree with that of ref.[14].

Since at energies above the GZK cutoff the extragalactic contribution is negligible, non-observation of the anisotropy at the level of $\sim 20\%$ would rule out the CDM-related mechanisms of UHE CR. The observation of the Galactic anisotropy would allow to reconstruct the density profile $n(x)$ and, possibly, the distribution of CDM in the Galactic halo.

At energies below the GZK cutoff, the anisotropy is smaller due to the relative enhancement of the isotropic extragalactic part. The latter should have narrow peaks in the direction of nearby galaxies and custers. The contribution of such a peak, $\delta j_{\rm ext}$, equals

$$\frac{\delta j_{\rm ext}}{j_h} = \alpha \frac{R_h^2}{3R^2}\frac{M}{M_G},$$

where R is the distance to the astronomical object, M is its mass, and M_G is the mass of our Galaxy including halo. For instance, contributions from Andromeda Nebula and Virgo Cluster are comparable and close to $10^{-2} \times \alpha$, in agreement with eq.(8) and ref.[14].

Since anisotropy does not depend on energy and can be measured at $E > E_{\rm GZK}$, it is possible, in principle, to determine the magnitude of the extragalactic contribution. Provided the CDM-related mechanisms are dominant at $E \lesssim E_{\rm GZK}$ and the coefficient α is known, the ratio $j_h/j_{\rm ext}$ could give, in view of eqs.(1) and (6), an important information about the distribution of matter in the Universe.

Current data is not enough to draw definite conclusions about the angular distribution of highest energy cosmic rays both because of very limited statistics and the absence of data in the South hemisphere where the Galactic center is situated. However, since the anisotropy predicted by the CDM-related mechanisms is large, it will be either observed or excluded already in the next generation of experiments [22]. Among these the Pierre Auger Project has the best potential due to large number of expected events (600–1000 events with $E > 10^{20}$ eV in 10 years) and the ability to see both hemispheres.

In conclusion, it is worth noting that there are mechanisms in which smaller but still observable galactic anisotropy is expected. As an example, consider a model based on annihilation of high energy neutrinos on massive relic neutrinos [23]. Relic neutrinos with mass $m_\nu \sim 1$ eV are non-relativistic at present and may be expected to cluster in galactic halos similar to CDM. From the Pauli exclusion principle, the maximum number density of neutrinos in the Galactic halo scales with neutrini mass as $(m_\nu)^3$. At $m_\nu \sim 10$ eV corresponding flux from the halo of our Galaxy is 10 times bigger than the extragalactic one, which may lead to observable anisotropy.

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