Anisotropy of Ultra High Energy Cosmic Rays in the Dark
Matter Halo Model

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Abstract

The harmonic analysis of anisotropy of Ultra High Energy Cosmic Rays is performed for the Dark Matter halo model. In this model the relic superheavy particles comprise part of the Dark Matter and are concentrated in the Galactic halo. The Ultra High Energy Cosmic Rays are produced by the decays of these particles. Anisotropy is caused by the non-central position of the Sun in the Galactic halo. The calculated anisotropy is in reasonable agreement with the AGASA data. For more precise test of the model a comparison of fluxes in the directions of the Galactic Center and Anticenter is needed.

The spectrum of Ultra High Energy Cosmic Rays (UHECR) is measured now up to a maximum energy of $(2-3) \times 10^{20} \text{ eV}$ [1,2]. More than 1000 particles are detected at energies higher than $1 \times 10^{19} \text{ eV}$ [3,4,5,6]. The detailed energy spectrum was recently presented in [6]. No steepening of the spectrum has been observed in the energy range between $10^{18}$ and $2 \times 10^{20} \text{ eV}$. If extragalactic, the UHE protons must have the Greisen-Zatsepin-Kuzmin (GZK) cutoff [7] at energy $E_{1/2} = 6 \cdot 10^{19} \text{ eV}$ [8]. A similar cutoff should exist if primaries are extragalactic nuclei [4,8,9] or photons [10].
Recently it was suggested that UHECR can be generated by the decay of superheavy relic particles \[13, 14\]. These particles can be effectively produced in the post-inflationary Universe \[14, 17, 18\] and can constitute now a small or large part of Cold Dark Matter (DM). As any other form of Cold DM these relic particles are concentrated in the halo of our galaxy, and thus UHECR produced by their decays do not exhibit the GZK cutoff \[14\]. Realistic particle candidates for this scenario and possible mechanisms to provide the long lifetime for superheavy particles are discussed in Ref. \[13, 14, 19, 20\].

The halo model discussed above has three signatures \[14, 21, 22\]: the excess of high energy photons in the primary radiation, direct signal from a nearby clump of DM (e.g. Virgo Cluster), and anisotropy caused by the asymmetric position of the Sun in the Galactic halo. These signatures allow to confirm or to reject the DM halo hypothesis by the data of existing arrays.

As calculations show \[22, 23\], anisotropy reveals itself very strongly in the direction of the Galactic Center. This prediction can be reliably examined by the Pierre Auger detector in the southern hemisphere \[24\]. At present there is no detector which can observe this direction. In this article we present the calculations of anisotropy for the arrays in the northern hemisphere, taking as an example the geographical position of the Yakutsk and AGASA arrays.

We shall assume that primary photons dominate in the decays of SH particles as QCD calculations \[25\] imply. Then the flux of UHE photons in the direction \((\zeta, \phi)\) per unit solid angle can be written as

\[
I(\zeta) = K \int_0^{r_{\text{max}}(\zeta)} \text{d}r \rho_X(R),
\]

where \(r\) and \(R\) are the distances to a decaying X-particle from the Sun and the Galactic Center, respectively, \(\zeta\) is the angle between the line of observation and the direction to the Galactic Center, \(\phi\) is the azimuthal angle in respect to Galactic plane (the flux depends only on \(\zeta\)), \(\rho_X(R)\) is the mass density of superheavy particles \((X)\) at a distance \(R\) from the Galactic Center, \(K\) is an overall constant, \(r_{\text{max}}(\zeta) = \sqrt{R_h^2 - r_\odot^2 \sin^2 \zeta + r_\odot \cos \zeta}\), \(r_\odot = 2.8\)...
8.5 $kpc$ is a distance between the Sun and Galactic Center, $R_h$ is the size of the halo, in our calculations we shall use $R_h = 50$ $kpc$ (the values of 100 and even 500 $kpc$ result in similar anisotropy); the distance $R$ from the Galactic Center to the decaying particle is given by

$$R^2(\zeta) = r^2 + r_\odot^2 - 2rr_\odot \cos \zeta.$$ 

We shall use two distributions of DM in the halo: one given by the Isothermal Model (ISO) \cite{26},

$$\rho(R) = \frac{\rho_0}{1 + (R/R_c)^2}, \quad (2)$$

and the other – following the NFW numerical simulation \cite{27}

$$\rho(R) = \frac{\rho_0}{R/R_s(1 + R/R_s)^2}. \quad (3)$$

In the ISO model we shall use for $R_c$ the values $5$ $kpc$, $10$ $kpc$ and $50$ $kpc$. For the NFW model the calculations are performed for $R_s$ equal to $30$ $kpc$, $45$ $kpc$ and $100$ $kpc$. The NFW distribution \cite{27} is given in terms of the virial radius $r_{200}$, the rotational velocity at the virial distance $v_{200}$, the constant $\delta_c$ and the dimensionless Hubble constant $h$. We applied this distribution to our Galaxy using the following parameters: the local density of DM $\rho_{DM}(r_\odot) = 0.3$ GeV/cm$^3$, $v_{200} = 200$ km/s and $h = 0.6$. As a result we obtain $R_s \approx 45$ $kpc$.

The flux \cite{1} was expressed first in terms of galactic coordinates, longitude $l = \phi$ and latitude $b$, which is given by $\cos b = \cos \zeta / \cos \phi$, and then transferred into equatorial coordinates, declination $\delta$ and right ascension $\alpha$. We calculated the amplitudes of the first and the second harmonics ($A_1$ and $A_2$, respectively) and the phase $\alpha$ of the first harmonic for the geographical position of the Yakutsk and AGASA arrays. These quantities are the standard ones used for measured anisotropy. The results are given in Table 1 (predictions for the AGASA array are shown in brackets). Depending on the parameters of the DM distribution, the anisotropy varies from 10% to 45%. The phase of the first harmonic $\alpha \approx 250^\circ$ is close to the RA of Galactic Center, $\alpha \approx 265^\circ$.

After this paper was submitted for publication we receved the preprint by Medina-Tanco and Watson \cite{28}, where similar calculations were performed. The results of both calculations
are displayed in Fig. 1 for $E > 4 \cdot 10^{19} \text{eV}$ together with the data of AGASA (AG) and Yakutsk (YK) arrays. The AGASA anisotropy is taken from analysis of Ref. [28]. Our calculations (BM) agree well with that of Ref. [28]. Both agree with the data of AGASA array and do not contradict to the Yakutsk data.

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TABLES

TABLE I. Anisotropy

| $R_c$ (kpc) | $A_1$ | $A_2$ | $\alpha$ (°) | $R_s$ (kpc) | $A_1$ | $A_2$ | $\alpha$ (°) |
|-------------|-------|-------|--------------|-------------|-------|-------|--------------|
| 5           | 0.43(0.46) | 0.11(0.13) | 250          | 30          | 0.41(0.45) | 0.10(0.13) | 250          |
| 10          | 0.32(0.35) | 0.06(0.07) | 250          | 45          | 0.37(0.41) | 0.09(0.11) | 250          |
| 50          | 0.15(0.15) | 0.01(0.01) | 250          | 100         | 0.33(0.36) | 0.07(0.08) | 250          |

FIGURE CAPTIONS

**Figure 1**: Amplitude and phase of the first harmonic of anisotropy for the AGASA and Yakutsk arrays. Solid lines are for the ISO distribution of DM and dots (NFW) – for the NFW numerical simulation. BM and TW show the results of this paper and Ref. [28], respectively. The three dots of BM (from left to right) are given for $R_s = 30$, $45$ and $100$ kpc, respectively; five dots of TW – for $R_s = 10$, $20$, $30$, $50$ and $100$ kpc. The AGASA data are taken from Ref. [28].
