ICRC'07 Mérida, México

Search for global asymmetry of UHECR arrival directions with the TUS space detector

P. KLIMOV [1],O. KALASHEV [2], B. KHRENOV[1], S. SHARAKIN[1], S. TROITSKY[2]
[1] *D.V. Skobeltsyn Institute for Nuclear Physics, Moscow State University, 119992, Moscow, Russia*
[2] *Institute for Nuclear Research of the Russian Academy of Sciences, 60th October Anniversary Prospect 7a, 117312, Moscow, Russia*
pavel.klimov@gmail.com

Abstract: A space detector has an advantage of observing during a year the arrival directions of ultra-high-energy (UHE) cosmic-ray (CR) particles from all directions in the sky. We study prospects of detecting global asymmetries predicted by two distinct scenarios of the origin of UHECR: the Galactic dipole asymmetry predicted by the superheavy dark-matter scenario and asymmetries expected if sources of UHE protons or nuclei follow the distribution of the visible matter in the Universe. The first space-based detector of UHECR particles, TUS, will be able to test the predicted asymmetries in two years of running.

Introduction

Space-based ultra-high-energy cosmic-ray detectors such as TUS or JEM/EUSO are best suited for searches of the global anisotropies in the distribution of arrival directions of cosmic-ray particles because they provide full-sky coverage with a single experiment. We calculate quantitatively the strength of anisotropies associated with two models of the origin of the highest-energy particles: the superheavy dark-matter model (sources follow the distribution of the dark matter in the Galactic halo) and the extragalactic model (sources follow the distribution of galaxies in the Universe). Based on the expected exposure of the TUS experiment, we estimate the optimal strategy for searches of these effects.

The problem

One of the important signatures of particular models of the ultra-high-energy cosmic rays is the global anisotropy of arrival directions of the highest-energy events. In particular, the "top-down" models [1] (see Refs. [2, 3] for reviews and references) with the distribution of sources in the Galactic halo following that of the dark matter (which is the case for the superheavy dark-matter (SHDM) particles and some of topological defects) predict [4] the Galactic center-anticenter asymmetry due to the non-central position of the Sun in the Galaxy (see Refs. [3, 5, 6, 7] for extensive discussions). This kind of models predict unsuppressed continuation of the cosmic-ray spectrum and gamma-ray dominance beyond 10^{20} eV. On the other hand, the "bottom-up" models where the origin of UHECRs is attributed to the acceleration in astrophysical objects naturally predict that the distribution of arrival directions follows the distribution of these cosmic accelerators. In the most common scenario with extragalactic protons and/or nuclei, the patterns of the distribution of galaxies in the nearby Universe should be seen [8] on the UHECR skymap because of the limited propagation length of these particles due to the GZK effect [9] or nuclear photodisintegration. Strong suppression of the cosmic-ray flux and hadronic dominance are predicted at highest energies in these models.

Currently, neither the spectrum nor anisotropy observations can favour one of the two scenarios (though the gamma-ray limits disfavour [10] the dark-matter one; see Ref. [11] for a review). Indeed, the AGASA experiment claims [12] the super-GZK continuation of the spectrum while the

HiRes collaboration reports [13] the observation of the GZK cutoff (data of other experiments, including preliminary results of the Pierre Auger Observatory [14], are not yet conclusive). Current experiments do not see any deviations from the global anisotropy at the highest energies which is also not conclusive both due to the low statistics and due to a limited field of view of any terrestrial installation.

The steeply falling spectrum of cosmic rays makes it very difficult to obtain a reliable measure of the global anisotropy in *any* combination of terrestrial experiments. Indeed, the relative systematic difference in the energy estimation between two installations located in different parts of the Earth (and thus observing different parts of the sky) can hardly be made smaller than some $\sim 15\%$. Such a relative error would give $\sim 50\%$ higher flux seen by one of the experiments with respect to the other at the same reconstructed energy. Thus, any possible observation of global anisotropy can be attributed both to the physical effect and to the unknown systematics in the energy determination. Moreover, the seemingly isotropic distribution of the arrival directions over the sky might represent a physically anisotropic one masked by the systematic effects.

On the other hand, the planned space-based experiments, e.g. TUS [15] or JEM/EUSO [16], will provide a unique opportunity to observe all 4π sr of the sky with a single detector. While not being free from systematic uncertainties in the energy determination, an experiment of this kind would not introduce direction-dependent systematics and thus would be able to perform the studies of the global anisotropy at high confidence.

The "top-down" scenario

In "top-down" models, UHECRs originate from decays of superheavy particles (the latters themselves may be produced in decays or collisions of the topological defects). The distribution of sources thus follows the distribution of the initial particles; for many realistic models it corresponds to the distribution of the dark matter. Decays of particles from the Milky-Way halo dominate the cosmic-ray flux at high energies in this case. At lower energies, this flux should be supplemented by a contribution of astrophysical sources to explain the observed spectrum. Due to a non-central position of the Sun in the Galaxy, the flux should be higher from the direction of the Galactic center than from the opposite one.

For this study, we follow Ref. [3] with considerable refinements and improvements.

- The spectrum of the particles produced in the decays of SHDM is taken from Ref. [7].
- For the distribution of the dark matter, we use two most common profiles: the NFW [17] and Moore [18] ones. The distribution of the sources transforms into the direction-dependent flux $F_{SH}(E, l, b)$ by simple geometry (we corrected the equations of Ref. [3] so they could be used for the full-sky analysis; E is the energy).
- The AGASA spectrum [12] is fit by a sum of the contribution $F_{EG}(E)$ of uniformly distributed astrophysical sources (which follows the GZK cutoff) and $F_{SH}(E, l, b)$. Unlike any of the previous studies (see e.g. Ref. [3]), we take into account the effect of anisotropy (AGASA sees the Northern sky and has higher exposure towards the Galactic anti-center). This correction enhances the full-sky anisotropy by a factor of ~ 1.2.
- The total flux $F(E, l, b)$ is used to simulate the observable distribution of events at different energies.

The "bottom-up" scenario

A number of astrophysical sources were suggested where acceleration of cosmic rays up to the highest energies can take place (see Refs. [19] for reviews and summary). A common assumption is that the distribution of the sources follows that of luminuous matter, that is of galaxies. Interaction of UHE hadrons with cosmic background radiation limits the propagation distance at high energies; hence, a limited part of the Universe may contain the sources of UHECRs detected at the Earth. Non-uniform distribution of matter in this part should reflect itself in the distribution of the arrival directions of cosmic rays [8]. For this study, the following scheme was used.

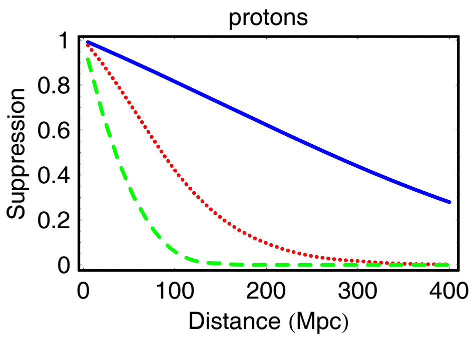

Figure 1: The fraction of survived hadrons with $E > E_0$ as a function of the distance d from the proton-emitting source. with spectral index $\alpha = 2$ and a cutoff at 10^{21} eV. Solid line, $E_0 = 4 \cdot 10^{19}$ eV; dotted line, $E_0 = 7 \cdot 10^{19}$ eV; dashed line, $E_0 = 10^{20}$ eV.

- We calculated the number density of galaxies $n(l, b, d)$ for given direction (l, b are Galactic coordinates) and distance d. Due to deflection of charged hadrons in the Galactic magnetic field (and to poor angular resolution of the detector), the function was smoothed at the scale of $\sim 5°$ on the celestial sphere. Because the actual density of the sources is much less than that of the galaxies, the function was also smoothed at the scale of ~ 10 Mpc in d.

- By making use of a numerical propagation code [6, 20], we estimated the fraction of survived hadrons with $E > E_0$ at the distance d from the source, assuming either proton or iron injected primaries. Some of the fractions are plotted in Fig. 1 for different E_0.

- The density of the sources $n(l, b, d)$ was convolved with the survival function $f(d)$ to obtain the expected distribution of the UHECR arrival directions.

Considerable improvements with respect to previous studies [8] are related to the construction of both $n(l, b, d)$ and $f(d)$. We use a detailed propagation code which is based on kinematic equations written in the expanding Universe and accounts for numerous interaction processes, tracing the propagation of nuclei (iron and lighter), nucleons, gamma-rays, electrons and neutrinos. For the construction of the density function, most of the previous studies used the PSCz catalog [21]; due to the limited angular resolution of IRAS it may not resolve all galaxies in the regions of high density (clusters) [22] and thus may systematically diminish the expected anisotropy due to underestimation of high number densities of galaxies. For this study, we combine the volume-limited ($d <$ 50 Mpc) complete subsample [23] of the LEDA database [24] and the 2MASS XSC [25] with photometric redshifts calculated following Ref. [26] for $d > 30$ Mpc. Our sample is complete up to the distances of order 270 Mpc (we assume $H_0 = 72$ km/s/Mpc) and hence (see Fig. 1) the study makes sence for $E_0 \gtrsim 7 \cdot 10^{19}$ eV (see Ref. [27] for a related study).

Predictions for TUS

The space detector TUS [15] is under construction and is planned to be launched in 2010. The TUS energy threshold is estimated as $7 \cdot 10^{19}$ eV and its exposure factor per one year of operation is of about 3000 km^{2}sr. The UHECR arrival direction accuracy is different for different zenith angle θ: for $\theta < 30°$, the direction is estimated only roughly as being vertical in the error cone of 30°; for $30° \lesssim \theta \lesssim 60°$ the error is coming down to 10° and for $60° \lesssim \theta \leq 90°$ the error is less than 10°. This latter region was used for our estimates; the arrival-direction distribution was recalculated for the real detector operated in one year. The TUS direction-dependent exposure is determined by the satellite orbit parameters and by the zenith angle cut. It can be conveniently parametrized by a sum of a monopole and quadrupole over the celestial sphere. We determine the strategy to search for the global anisotropies: the balance between the strength of the effect (which increases with energy) and the number of observed events determines the optimal energy. Observation/exclusion of the anisotropy at the 99% confidence level would require ~ 1 year for the top-down scenario with the Moore distribution of dark matter, and ~ 2 year for the NFW distribution. The proper observable is the ratio of the number of events with $E \geq 8 \cdot 10^{19}$ eV observed within 70° from the Galactic Center to the number of events in the same cone from the opposite direction. The bottom-up scenario can be tested on a similar timescale; precise numbers will be reported at the Conference and in the forthcoming publication [28].

Conclusions

In this work, we made quantitative predictions for the global anisotropy of the UHECR arrival directions expected in two distinct scenarios ("top-down" and "bottom-up") of the origin of the highest-energy cosmic rays. Several refinements and improvements resulted in considerable changes in the predictions as compared to previous studies. We developed optimal observables for distinction (exclusion) of these two scenarios with the limited statistics of the first space-based UHECR detector, TUS, before the planned launch of JEM/EUSO.

We are indebted to D. Gorbunov, M. Kachelrieß and D. Semikoz for discussions. We acknowledge the use of online catalogs [24, 25]. This work was supported in part by the grants INTAS 03-51-5112 (ST), RFBR 07-02-00820 and NS-7293.2006.2 (OK and ST) and by the Russian Science Support Foundation fellowship (ST).

References

[1] V. Berezinsky, M. Kachelrieß and A. Vilenkin, Phys. Rev. Lett. **79** (1997) 4302; V. A. Kuzmin and V. A. Rubakov, Phys. Atom. Nucl. **61** (1998) 1028.

[2] P. Bhattacharjee and G. Sigl, Phys. Rept. **327**, 109 (2000); M. Kachelrieß, Comptes Rendus Physique **5**, 441 (2004).

[3] R. Aloisio, V. Berezinsky and M. Kachelrieß, Phys. Rev. D **74** (2006) 023516.

[4] S. L. Dubovsky and P. G. Tinyakov, JETP Lett. **68** (1998) 107.

[5] V. Berezinsky and A. Mikhailov, Phys. Lett. B **449**, 237 (1999); G. A. Medina-Tanco and A. A. Watson, Astropart. Phys. **12**, 25 (1999).

[6] O. E. Kalashev, V. A. Kuzmin and D. V. Semikoz, Mod. Phys. Lett. A **16** (2001) 2505.

[7] R. Aloisio, V. Berezinsky and M. Kachelrieß, Nucl. Phys. Proc. Suppl. **136** (2004) 319.

[8] E. Waxman, K. B. Fisher and T. Piran, Astrophys. J. **483** (1997) 1; N. W. Evans, F. Ferrer and S. Sarkar, Astropart. Phys. **17** (2002) 319; A. Smialkowski, M. Giller and W. Michalak, J. Phys. G **28** (2002) 1359; G. Sigl, F. Miniati and T. A. Ensslin, Phys. Rev. D **70** (2004) 043007; A. Cuoco *et al.*, JCAP **0601** (2006) 009.

[9] K. Greisen, Phys. Rev. Lett. **16**, 748 (1966); G. T. Zatsepin and V. A. Kuzmin, JETP Lett. **4**, 78 (1966).

[10] G. I. Rubtsov *et al.*, Phys. Rev. D **73** (2006) 063009; A. V. Glushkov *et al.*, JETP Lett. **85** (2007) 131;

[11] M. Risse and P. Homola, Mod. Phys. Lett. A **22** (2007) 749.

[12] M. Takeda *et al.*, Astropart. Phys. **19**, 447 (2003).

[13] R. Abbasi *et al.*, arXiv:astro-ph/0703099.

[14] P. Sommers *et al.*, arXiv:astro-ph/0507150.

[15] V. I. Abrashkin *et al.*, Adv. Space Research **37**, 1876 (2006); V. Abrashkin *et al.*, this conference (2007).

[16] T. Ebisuzaki *et al.*, this conference (2007).

[17] J. F. Navarro, C. S. Frenk and S. D. M. White, Astrophys. J. **462**, 563 (1996).

[18] B. Moore *et al.*, Astrophys. J. **524**, L19 (1999).

[19] D. F. Torres and L. A. Anchordoqui, Rept. Prog. Phys. **67** (2004) 1663; D. Gorbunov and S. Troitsky, Astrop. Phys. **23**, 175 (2005).

[20] O. E. Kalashev, V. A. Kuzmin and D. V. Semikoz, arXiv:astro-ph/9911035.

[21] W. Saunders *et al.*, MNRAS **317** (2000) 55.

[22] J. Huchra *et al.*, The 2MASS redshift survey, http://cfa-www.harvard.edu/˜huchra/2mass/

[23] H. Courtois *et al.*, Astron. Astrophys. **423** (2004) 27.

[24] http://leda.univ-lyon1.fr

[25] T. H. Jarrett *et al.*, Astron. J. **119** (2000) 2498.

[26] T. Jarrett, arXiv:astro-ph/0405069.

[27] D. Harari, S. Mollerach and E. Roulet, JCAP **0611** (2006) 012.

[28] O. Kalashev *et al.*, to appear.