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Anisotropy of Ultra High Energy Cosmic Rays from Luminous Infrared Galaxies

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Abstract. Ultra High Energy (UHE) particles coming from discrete extragalactic sources are potential candidates for EAS events above a few tens of EeV. Galaxies with huge infrared luminosity are possible sites of UHECR acceleration (starburst's superwinds, colliding galaxies, AGNs). Using the PSCz catalog of IRAS galaxies we calculate a large scale anisotropy of UHE protons originating in the population of the luminous infrared galaxies (LIRGs). Small angle particle scattering in weak irregular extragalactic magnetic fields as well as deflection by regular Galactic field are taken into account. We give analytical formulae for deflection angles with included energy losses on CMB. The hypotheses of the anisotropic or isotropic distributions of the experimental data above 40 EeV from AGASA are checked, using Smirnov-Cramer-von Mises free of binning test. The famous AGASA UHE triple event is found to be very well correlated on the sky with the brightest extragalactic infrared source within 70 Mpc - merger galaxies Arp 299 (NGC 3690 + IC 694).

1 Introduction

The existence of UHE cosmic rays, after their discovery almost half a century ago, remains still puzzling. In advent of the new giant experiment named in honour of Pierre Auger, there are many proposals to explain their origin. In this work we check the hypothesis that the luminous infrared galaxies (LIRGs) might be the UHECR sources. In such extragalactic objects[1] the huge infrared luminosity is caused by intense starburst activity, which itself is triggered by galaxy collisions and merging. As a result of gravitational compression, strengthened magnetic fields on the scale of tens kpc, as well as high relative galactic velocities and/or superwinds from multiple supernovae explosions may provide favourable circumstances for accelerating particles to UHE regime via first order Fermi process (Cesarsky , 1992; Cesarsky and Ptuskin , 1993). There have been several observational claims that colliding galaxies could be possible sites of the UHECR origin. Al-Dargazelli et al. (1996) have proposed that some clustering of UHECR shower directions above 10 EeV are associated with nearby colliding galaxies. Takeda et al. (1999) have noticed that the interacting galaxy VV 141 at z=0.02 is a possible candidate for triplet of events above 50 EeV from the AGASA experiment. However, as we shall show, there is another favourable candidate for origin of this UHECR cluster - Arp 299 (Mrk171, VV 118a/b), a member of LIRG class of extragalactic objects. This system, consisting of two interacting starburst galaxies, is the closest extragalactic object (distance 42 Mpc for $H_0 = 75$ km/s/Mpc) with IR luminosity greater than $5 \times 10^{11} L\odot$ ($\simeq 2 \times 10^{45}$ ergs/s) and it is the brightest IR source within 70 Mpc. Such high IR luminosity is related to young and violent star forming regions. There is also observational evidence of superwind outflows and the estimated supernova rate is about 0.6 per year.(Alonso-Herrero et al. , 2000; Hibbard and Yun , 1999; Heckman et al., 1999).

Using the PSCz Catalog (Saunders et al., 2000) we calculate a large scale anisotropy of UHE protons originating in LIRGs, taking into account effects of particle propagation through the extragalactic medium and, as an example, possible influence of the regular galactic magnetic field (GMF). We check both hypotheses: origin in LIRGs and, on the other hand, the isotropic distribution of the experimental data above 40 EeV from AGASA (Hayashida et al., 2000), using Smirnov-Cramer-von Mises test.

2 Anisotropy calculations

The PSCz Catalog of IR galaxies is used to select objects with luminosities exceeding $L_{FIR} = 9 \times 10^{10} L_\odot$, (about one order of magnitude greater than FIR luminosity of our Galaxy, (Cox and Mezger , 1989)), and with distances up to 1 Gpc. Protons are injected at sources with a spectrum

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[1]discovered by IRAS satellite in 1983, (Soifer et al., 1984)

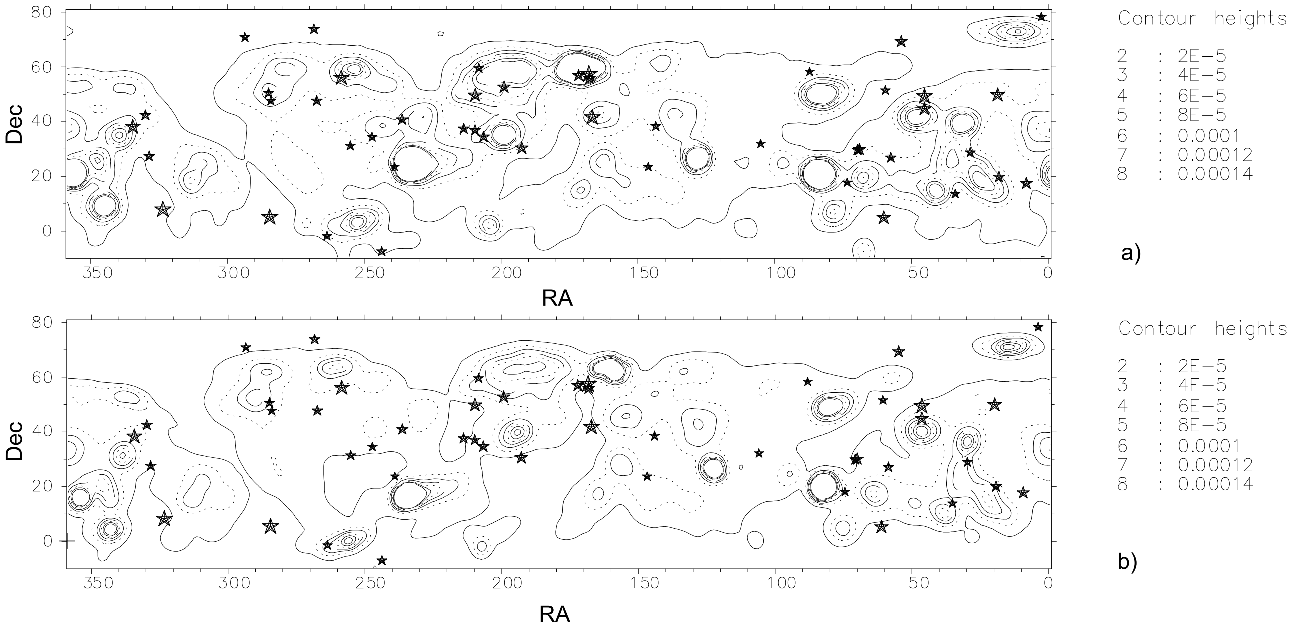

Fig. 1. Expected maps of proton intensities without (top) and with (bottom) influence of the regular galactic magnetic field (BSS-A) for protons of 40-80 EeV originating in LIRGs to be seen by AGASA, with superimposed 47 AGASA shower directions in this energy range (stars scaled with energy). Units arbitrary, proportional to flux per unit solid angle.

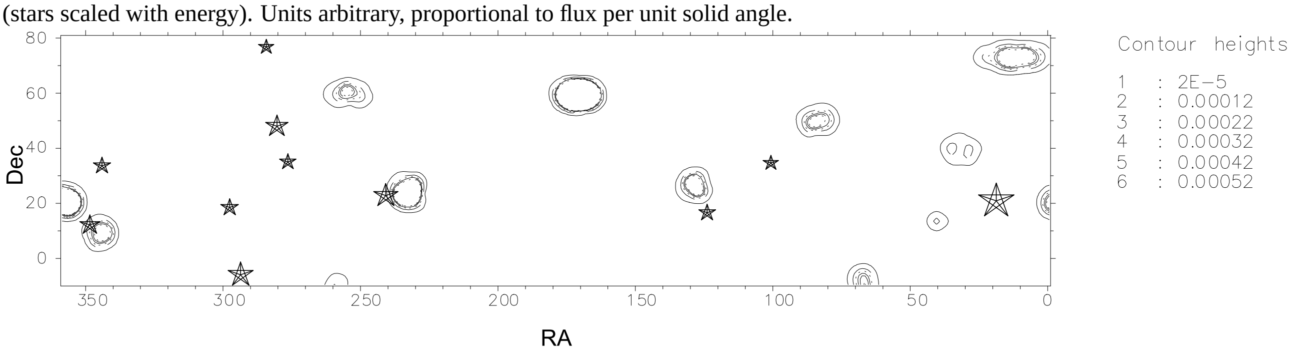

Fig. 2. Expected map of proton intensities (energy above 80 EeV) from LIRGs to be seen by AGASA, with superimposed 11 AGASA showers in this energy range (no GMF).

$dN/dE \sim E^{-2}$ truncated at 10^{21} eV and they propagate through the intergalactic medium, where they suffer energy losses on cosmic microwave background (Berezinsky and Gigor'eva, 1988). We have derived an analytical formula for the distribution of the deflection angles, for the multiple small angle scattering in weak irregular intergalactic magnetic fields including particle energy losses (see Appendix). We have also derived formulae for moments of the time delay distribution with the energy losses included. Our calculations show, however, that the effect of time delay on the energy losses is, for most of the considered here CR sources, small and can be neglected. The conservative upper limit for IGMF magnitude and scale of coherency is assumed: $B \times \sqrt{l_c} \leq 1nG \times \sqrt{1Mpc}$, (Kronberg , 1994).

Maps of expected intensity of UHE protons originating in LIRGs for two energy regions, 40-80 EeV and above 80 EeV, with sky coverage and declination dependent exposure for the AGASA experiment (Takeda et al., 1999), are presented in Figures 1a and 2 with superimposed AGASA events. In Figure 1a, we can see that expected proton intensities in the energy region 40-80 EeV show good correlation with the distribution of the experimental events from AGASA. Especially, clearly visible is the region of the sky where high proton intensities from Arp 299 correlate with the AGASA triplet of events (RA=170°, Dec=60°). Moreover, samples of the 47 events simulated from this intensity map, show good resemblance to the experimental data distribution . In Figure 3 are presented distributions of 47 events from AGASA and equivalent samples of events simulated from the map in Figure 1a. From those simulations, we have estimated that the probability of getting a dublet or a triplet in the vicinity of Arp 299 is $\sim$30%. In Figure 2 no correlation of the data events above 80 EeV with the expected CR intensities can be seen. There is an apparent group of UHE showers in the region with RA=300°, where no possible sources exist.

To examine the influence of the regular GMF on the extragalactic UHE fluxes we have chosen the bisymmetric spiral model with field reversals and odd parity (BSS-A) adopted

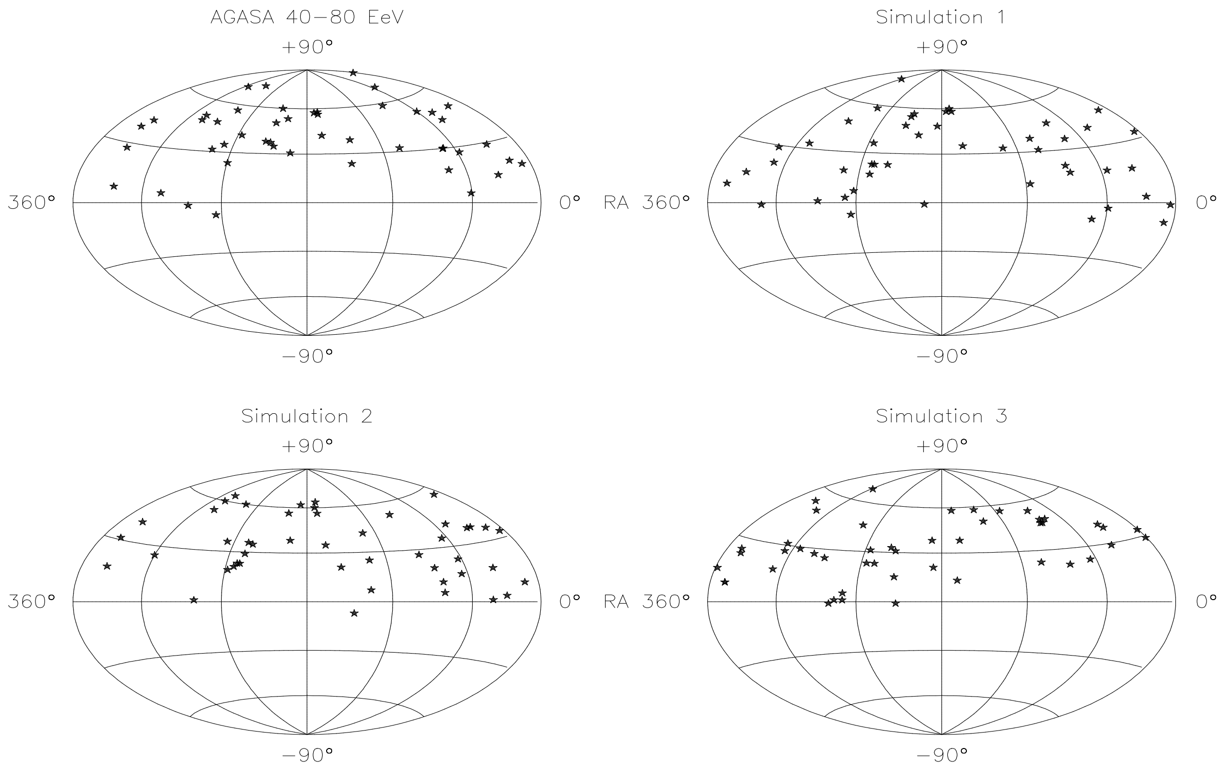

Fig. 3. Sky distribution comparison of the 47 AGASA showers with energy 40-80 EeV (top left) and examples of three simulations from LIRG anisotropy map. Equatorial coordinates.

from Stanev (1997). Simulations of a large number of monoenergetic antiprotons ejected from the Earth and followed to the halo border through GMF allowed to find flux modification factors specific to every region of the 'extragalactic' sky. Distortion effects (dilution or magnification and shifting) of the particle fluxes are visible in Figure 1b. The modification of the extragalactic UHECR intensities due to the influence of the GMF BSS-A model seems to worsen the correlation with the experimental data seen in Fig 1a.

3 Statistical test and results

To check the hypotheses of isotropic and anisotropic distribution of the experimental data above 40 EeV from AGASA, we have used Smirnov-Cramer-von Mises (SCvM) free of binning test (Eade et al., 1971), modified to the 2-dimensional distribution analysis. SCvM test is based on comparing the cumulative distribution function $F(X)$ under hypothesis H_0 with equivalent distribution of the data. The considered statistics W^2 is defined as follows

$$W^2 = \int_{-\infty}^{\infty} \Big(S_N(X) - F(X)\Big)^2 f(X)dX \qquad (1)$$

where $f(X)$ is the probability density function corresponding to the hypothesis H_0, $F(X)$ is its cumulative distribution and $S_N(X)$ is the cumulative distribution based on experimental data (equatorial coordinates of UHECR events) and always increases in steps of equal height, N^{-1}, where N is the total number of data. It is worth to note that this test is reliable even for small statistics ($N \geq 3$). Critical NW^2 values for test size α =0.1 and 0.05 are 0.347 and 0.461 respectively.

E	Tested hypotheses	NW^2 values
40-	Isotropy	0.135; 0.037; 0.304; 0.115
80	LIRGs anisotropy	0.138; 0.050; 0.172; 0.108
EeV	LIRGs anisotropy + GMF	0.249; 0.083; 0.285; 0.127
>80	Isotropy	0.058; 0.484; 0.581; 0.070
EeV	LIRGs anisotropy	0.482; 0.223; 1.251; 0.329

Table 1.

From the 2-dimensional maps we have constructed a 1-dimensional $F(X)$, for four cases depending on the chosen coordinate system (Śmiałkowski et al. , 2001). Although the four obtained NW^2 values are not completely independent, they provide a valuable insight into the analysis. Results of tested hypotheses: isotropy and LIRGs anisotropy (with and without GMF), energies 40-80 EeV and above 80 EeV are shown in Table 1. All the hypotheses in the energy range 40-80 EeV pass, assuming test size α =0.1. However, with the presence of the GMF the agreement is worse. The hypotheses for energies above 80 EeV fail, especially in LIRG anisotropy scenario.

4 Conclusions

Our main goal was to answer the question: are the luminous IR galaxies possible candidates for UHECR origin and do they describe their both isotropic and clustering behaviour ? We have shown that the available data from AGASA in the energy range 40 to 80 EeV are not in contradiction with the expected anisotropy of protons produced in LIRGs. Simulated samples of events from such assumed scenario show good similarity with the experimental distribution. We have obtained, via simulations, a high probability of dublets and triplets of events from Arp 299, estimated to be about 30 percent. At energies above 80 EeV both isotropic and LIRGs anisotropic distribution hypotheses are rejected. However, a rather small number of measured events makes the testing conclusions uncertain. It seems that the test used here is not very sensitive for distinguishing between isotropy and LIRG distributions and a better test should be found, perhaps more sensitive to clustering than to a large scale anisotropy. Nevertheless, with the prospect of new data coming from the Auger experiment in a few years, the arrival direction distribution of UHECR should provide a firmer clue to their origin.

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Appendix A

Let us consider the statistical process of the small angle scattering of a charged particle on N randomly oriented magnetic cells. Here we derive formulae for deviation angles and time delays on simple assumptions that statistical variables $\delta \boldsymbol{n}_k$ (denoting change of unit vector along direction of flight occurring in the k-th cell) are: 1) independent and small, 2) cumulative change of direction is also small, 3) the number of cells N is large. If particle energy changes along its trajectory, we have the relation

$$\langle \boldsymbol{\vartheta}_k^2 \rangle = \langle \boldsymbol{\vartheta}_N^2 \rangle \times \left(\frac{E_N}{E_k} \right)^2 \equiv \langle \boldsymbol{\vartheta}_N^2 \rangle \times \left(\frac{E_{u=1}}{E_u} \right)^2 \quad \text{(A1)}$$

Here E_N and E_k denote particle energies in N^{th} and k^{th} cells and $\langle \boldsymbol{\vartheta}_N^2 \rangle$ is mean square scattering angle in the last N_{th} cell, which is close to the detector. We also denote cells by continuous variable $u = \frac{k}{N}$ instead of k (i.e. $u = 1$ indicates the detector). In this model the particle's trajectory consists of N pieces of lines of equal length $L = 1/N$. If the source of particles is placed in the centre of a sphere of radius $R = 1$, then particle trajectories will end inside the sphere and the time delay is just the additional time the particle needs to reach the sphere. Looking back from the detector we miss the source by the deviation angle η. The formulae for the coordinates of the trajectory end: x,y, z (z-axis is the particle initial direction), time delay T and angle η are shown below. The cumulative change of direction is described by the angle Θ_k as: $\boldsymbol{n_k} - \boldsymbol{n_0} = \sum_{i=1}^{k} \boldsymbol{\delta n_i} = \sum_{i=1}^{k} \boldsymbol{\vartheta_i} = \boldsymbol{\Theta_k}$.

$$x = \frac{1}{N} \cdot \sum_{k=1}^{N} \Theta_{xk}; \quad y = \frac{1}{N} \cdot \sum_{k=1}^{N} \Theta_{yk}; \quad z = \frac{1}{N} \cdot \sum_{k=1}^{N} (1 - \frac{1}{2}\Theta_{xk}^2 - \frac{1}{2}\Theta_{yk}^2); \quad \boldsymbol{\eta_k} = \sum_{k=1} N \frac{k}{N} \cdot \boldsymbol{\vartheta_k} \quad \text{(A2)}$$

$$T \approx \Delta z - \frac{1}{2} \cdot (x^2 + y^2) \quad with$$
$$\Delta z = \frac{1}{N} \cdot \sum_{k=1}^{N} (\frac{1}{2}\Theta_{xk}^2 + \frac{1}{2}\Theta_{yk}^2) \quad \text{(A3)}$$

We are able to calculate statistical moments for the above random variables. Here are some of them:

$$\langle \boldsymbol{\eta^2} \rangle = N \cdot \langle \boldsymbol{\vartheta_N^2} \rangle \cdot f_{12}; \quad \langle \boldsymbol{\eta^4} \rangle - \langle \boldsymbol{\eta^2} \rangle^2 = \langle \boldsymbol{\eta^2} \rangle^2$$
$$\langle T \rangle = \frac{N}{2} \cdot \langle \boldsymbol{\vartheta}_N^2 \rangle \cdot (f_2 - f_{11}) \quad \text{(A4)}$$

The constants f_{11}, f_{12} and f_2 are defined by the following integrals:

$$f_{11} = \int_0^1 (1-u)^2 \cdot A(u) du; \quad f_{12} = \int_0^1 u^2 \cdot A(u) du;$$
$$f_2 = \int_0^1 (1-u) \cdot A(u) du \quad \text{(A5)}$$

where

$$A(u) = \left(\frac{E_{u=1}}{E_u} \right)^2 \quad \text{(A6)}$$

The values of the derived moments have been checked in simulations with various functions $A(u)$ and gave the same results.

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