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# LARGE SCALE STRUCTURE AND COSMIC RAYS REVISITED

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We investigate the possibility that ultra high energy cosmic rays ($E > 10^{19}$ eV) are related to the distribution of matter on large scales. The large scale structure (LSS) data stems from the recent *IRAS PSC*z redshift survey. We present preliminary predictions drawn from an anisotropic distribution of sources which follows the galaxy distribution.

## 1 Introduction

Ultra high energy cosmic rays (UHECR) are particles with kinetic energies above $\sim 10^{18}$ eV.[1] The nature of these energetic particles is presently unknown. The reason is twofold: *i)* These particles interact on the top of the Earth's atmosphere producing extensive air showers (EAS) that can be observed from the ground; in this case, the primary particle can not be observed directly; and *ii)* at these ultra high energies (UHE) the fluxes are extremely low (less than 1 particle per square kilometer per year). This makes it impracticable to observe the UHE particles directly using balloons, satellites or spacecrafts due to their small acceptance.

The observation methods are indirect and rely on the observation of the secondary particles produced in the EAS. The hadronic particles, as well as muons and electrons created by the interactions of the primary particle in the atmosphere, are detected on the ground. The EAS also produces detectable fluorescent light photons due to the excitation of nitrogen molecules in the air by the charged secondary particles. Yet, the secondary charged particles that travel with velocities higher than the velocity of the light in the air generate Cherenkov radiation that can also be detected. Despite the fact that the EAS can be observed by the detection of different kinds of secondaries using various techniques, the determination of the nature of the primary particle is very difficult and model dependent. As the fluxes are low it is necessary to use large ground arrays, and/or many fluorescent light and Cherenkov radiation detectors. Until the present moment, the ground arrays and the fluorescent light detectors have gathered only a handful of events in the UHE range.

The number of events has not been enough to tell us whether the sources are extragalactic or are located in the Galaxy.

If the primary particle is a $\gamma$-ray or a neutrino the arrival direction would point back directly to the source. This would also be the case for charged particles if the Galactic magnetic field is $\lesssim 10^{-6}$ G and the extragalactic magnetic fields are $\lesssim 10^{-9}$ G in the case of extragalactic sources. The distance to the source is also constrained for most kinds of primaries: If the primary particle is a nucleus or a proton (antiproton) the distance to the source is limited to less than $\sim$ 100 Mpc for particles with arrival energies above $\sim 6 \times 10^{19}$ eV (GZK cutoff, see Fig.(1)). Due to interactions with the cosmic microwave background (CMB) photons these particles rapidly lose energy. Sources of $\gamma$-rays must be even closer because of the short mean absorption length for the UHE photons traveling in the CMB.

The mechanism that provides particles with UHE is also not known. The ignorance about the sources makes it harder to determine the mechanism at work. For the UHE events no source candidate in the vicinity of the region to where the arrival direction points back has been found yet. On the other hand, some analysis of the showers profile have been favoring protons as the primary particle.[2] As it was mentioned above, the number of UHE events is still too small to allow us, based on the statistics, to answer questions about their isotropy and composition.

In this work, we assume that the UHECR primary particles above $10^{19}$ eV are predominantly extragalactic protons and that the sources are related to the distribution of matter on large scales. It means that without specifying the sources themselves or the acceleration mechanism, we would expect an excess of events coming from regions with mass overdensities and less events coming from regions with mass underdensities. In the § 2 we briefly describe the formalism used; the propagation code is described in the § 3; and the smoothing procedure of the density field is described in § 4. Our results are presented in the § 5.

## 2 Formalism

In this contribution we apply a generalization of the formalism described in Waxman, Fisher and Piran.[3] We model the population of UHECR sources $S$ within a "box" $\Delta V$ centered at $(z, \hat{\Omega})$ as drawn from a Poisson distribution

$$\mathrm{prob}_S(z, \hat{\Omega}) = \frac{\bar{S}(z, \hat{\Omega})^S}{S!} \exp\left[-\bar{S}(z, \hat{\Omega})\right],$$

whose mean value is $\bar{S}(z,\hat{\Omega}) = \bar{s}(z)\mathfrak{B}\left[\delta\rho(z,\hat{\Omega})\right]\Delta V$. Here $\bar{s}(z)$ denotes the average comoving number of UHECR sources at redshift $z$ and $\mathfrak{B}$ is some bias functional of the local galaxy distribution $\delta\rho(z,\hat{\Omega})$. The generating function (*g.f.*) of such a distribution is

$$f_S(u;z,\hat{\Omega}) = \exp\left[\bar{S}(z,\hat{\Omega})(u-1)\right], \tag{1}$$

where $u$ is a dummy variable.

The detected number $N$ of UHECR produced by a source within $\Delta V$ with observed energy larger than $E$ is also modeled by a Poisson distribution

$$\mathrm{prob}_N(\geq E) = \frac{\bar{N}(E,z)^N}{N!}\exp\left\{-\bar{N}(E,z)\right\},$$

with mean value

$$\bar{N}(E,z) = \mathcal{A}\mathcal{T}\frac{\dot{n}_0\left[E_{inj}(E,z)\right]}{\bar{s}_0}\frac{(1+z)}{4\pi d_L(z)^2},$$

where $\bar{s}_0 = \bar{s}(z=0)$, $d_L^2(z) = 4c^2H_0^{-2}(2+z-2\sqrt{1+z})$ for an $\Omega = 1$ Universe; $\mathcal{A}$ and $\mathcal{T}$ denote the detector area and observation time, respectively; $E_{inj}$ is the energy with which a UHECR observed with energy $E$ was produced at redshift $z$; and $\dot{n}_0$ is the number of UHE protons emitted by a source per unit time and is assumed to be proportional to $dN/dE_{inj}$. We have assumed that the source differential spectrum is a power law in energy $dN/dE_{inj} \propto E_{inj}^{-(\gamma+1)}$. The *g.f.* of the last probability distribution is given by

$$g_N(u;z,E) = \exp\left[\bar{N}(E,z)(u-1)\right]. \tag{2}$$

Hence, it is straightforward to show from equations (1) and (2) that the *g.f.* for the probability of observing a total of $N$ events from $\Delta V$, with an energy larger than $E$, is expressed by

$$F(u;z,\hat{\Omega},E) = \exp\left\{\bar{S}(z,\hat{\Omega})\left[\exp\left(\bar{N}(E,z)(u-1)\right)-1\right]\right\}.$$

The overall UHECR distribution coming from a collection of independent volume elements $\Delta V_i$ has the following *g.f.*:

$$F(u;\bigcup_i \Delta V_i, E) = \prod_i F\left(u;z_i,\hat{\Omega}_i,E\right),$$

which for a given line of sight (*l.o.s.*) can be expressed as an integral over $z$

$$F(u;\hat{\Omega},E) = \exp\left\{\int_0^{z_{max}} \bar{S}(z,\hat{\Omega})\left[\exp\left(\bar{N}(E,z)(u-1)\right)-1\right]dV\right\}, \tag{3}$$

where $dV = c\ |dt/dz|\, d_L^2(z)(1+z)^{-1}\, dz$.

In defining $\lambda(\hat{\Omega})$ as

$$\lambda(\hat{\Omega}) \equiv \int_0^{z_{max}} \bar{S}(z, \hat{\Omega}) dV,$$

one can characterize the distribution of UHECR produced by sources along the *l.o.s.* with energy larger than $E$ by the *g.f.*.

$$G(u; \hat{\Omega}, E) \equiv \frac{1}{\lambda(\hat{\Omega})} \int_0^{z_{max}} \bar{S}(z, \hat{\Omega}) \exp\left(\bar{N}(E, z)(u-1)\right) dV.$$

From equation (3) is then straightforward to show that

$$F(u; \hat{\Omega}, E) = \exp\left\{\lambda(\hat{\Omega}) \left[G(u; \hat{\Omega}, E) - 1\right]\right\},$$

which still is a compound Poisson distribution, although $G$ is not Poissonian.

## 3 Propagation code

The propagation equation takes into account energy losses of the UHE protons due to: *i)* Adiabatic expansion of the Universe; *ii)* $e^+e^-$ pair production; and *iii)* pion production due to interactions with CMB photons. A proton observed at present ($z = 0$) with energy $E$ must have been produced at an epoch $z$ with energy $E_{inj} = E_{inj}(E, z)$. We assume that the influence of the magnetic fields on particles with energies $E > 10^{19}$ eV is negligible. Figure 1 shows the decrease of energy as a function of the distance from the source for UHE protons. We note that for a proton to be observed with energies above $\sim 6 \times 10^{19}$ eV the source must be within $\sim 100$ Mpc from the observer irrespective to $E_{inj}$.

## 4 Smoothed density field

The galaxy distribution is estimated from the *IRAS PSCz* redshift survey.[4] We have computed the smoothed density field on a spherical grid up to $200\, h^{-1}$ Mpc. The Gaussian-smoothed density field at a grid point $n$ is given by

$$1 + \delta_g(c\vec{z}_n) = \frac{1}{(2\pi)^{3/2}\sigma_{sm,n}^3} \sum_i \frac{1}{\phi(c\vec{z}_i)} \exp\left[-\frac{(c\vec{z}_n - c\vec{z}_i)^2}{2\sigma_{sm,n}^2}\right]. \qquad (4)$$

We have divided the sphere in 72 bins of approximately equal area. Radially, the bin size increases in proportion to the *IRAS PSCz* inter-particle spacing $[\bar{n}\phi(cz)]^{-1/3}$. This smoothing scheme is tailored to keep the shot-noise

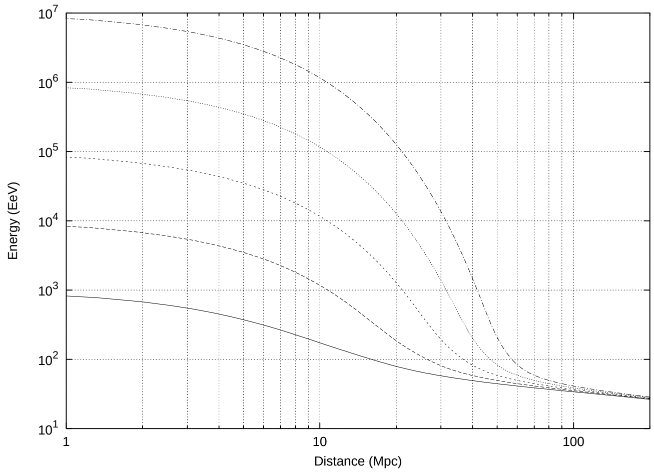


Figure 1. Propagation of UHE protons in the CMB. The lines represent various proton injection energies, $E_{inj} = 10^7, 10^6, 10^5, 10^4, 10^3$ EeV (from top to bottom respectively).

uncertainties in the density field roughly constant through out the sampled volume. A more detailed analysis of the *IRAS PSCz* density field can be found in Branchini *et al.*[5]

## 5 Results

We have found that the final results are independent of the cosmological parameters $(\Omega, \Lambda)$. Thus, we have used $\Omega = 1$ throughout our calculations for the sake of simplicity. For the bias functional $\mathfrak{B}[\delta(\vec{x})]$ we have considered $\mathfrak{B}[\delta(\vec{x})] = 1 + \delta(\vec{x})$. Figure 2 presents maps of fluctuations in the mean Cosmic Ray intensity,

$$\delta_{CR}(E, \hat{\Omega}) = \frac{4\pi \bar{N}(E, \hat{\Omega})}{\int d\hat{\Omega} \bar{N}(E, \hat{\Omega})} - 1, \tag{5}$$

for $E = (6, 10) \times 10^{19}$ eV. In the maps we clearly see the regions from where an excess and a deficit of UHECR events is expected following the LSS. The specific predictions for future experiments as the Auger project and HiRes will be presented elsewhere.[6]

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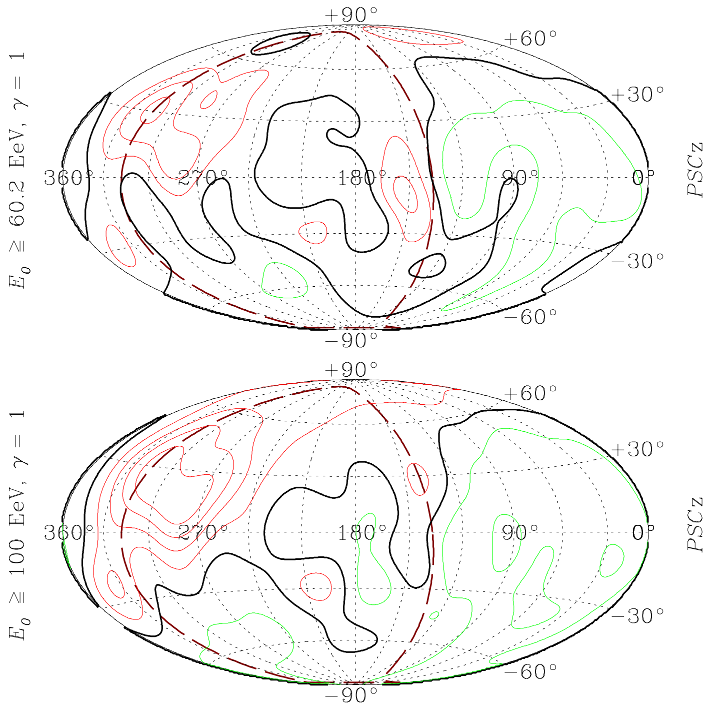


Figure 2. Aitoff projection of $\delta_{CR}$, for $E_{inj} \approx 60$ and 100 EeV ($\gamma = 1.0$). The heavy contour denotes the zero contour. Dark (light) grey contours denote positive (negative) fluctuations equally-spaced at 0.20. The long-dashed line represents the Super-Galactic plane.

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