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Isotropization of ultra-high energy cosmic ray arrival directions by radio ghosts

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Abstract. The isotropy in the ultra high energy cosmic ray (UHECR) flux observed by Yakutsk and AGASA experiments, is a very strong constraint to production and propagation models alike. Most of the scenarios proposed in the literature should produce a sizable anisotropy as either extragalactic luminous or dark matter is normally associated with the invoked particle sources. We explore the possibility that the magnetic fields in fossil cocoons of former radio galaxies – so called *radio ghosts* – are able to scatter UHECR in the intergalactic medium giving rise to the observed isotropy. We show, through numerical simulations, under which conditions this process can be operative and the magnitude of the effect. We further demonstrate, that if radio ghosts mix with the ambient medium, they might be able to produce the observed magnetic fields in clusters of galaxies. In the case of mixing, the UHECR isotropization would be even stronger than in our conservative estimates.

1 Introduction

The upper end of the cosmic ray spectrum, at total energies above $\sim 4 \times 10^{19}$ eV represents a challenge to our understanding of CR physics. The nature of the sources of these ultra-high energy cosmic rays and their distance scale are still unknown. Only our own galactic disk can be ruled out at present as a major source site, as a compatible anisotropy has not been observed by any of the experiments sensitive to the UHECR energy range Takeda (1999); Bird et al. (1999); Medina Tanco and Watson (1999).

Although photons, neutrinos, or some unknown particle cannot be disregarded, the muon to electron ratio measured for extensive air showers points to hadrons as the primaries hitting the upper atmosphere and triggering the cascades. Neutrons with relativistic factor $\gamma \sim 10^{11}$ decay into protons after a path of ~ 1 Mpc. Heavy nuclei, on the other hand, may lose as much as $\sim 2-4$ nucleons per Mpc due to photo-disintegration in interactions with the cosmic microwave and infrared backgrounds. Therefore, UHECR, unless galactic, are very likely light nuclei, probably mainly protons. We will assume the latter in the remaining of this work.

Depending on the large scale configuration of the intergalactic magnetic field (IGMF), field values as low as $B_{IGMF} \sim 10^{-9}$ G Kronberg (1994) may be expected. Consequently, proton gyroradius at $E \sim 10^{20}$ eV can be of the order of 10^2 Mpc. Therefore, UHECR should point to their sources and, in general, an anisotropic flux at Earth should be expected.

If UHECR are charged particles originated inside the large scale structures in the nearby Universe, then the observed isotropization must be due to intervening magnetic fields. This could happen either inside the galactic halo, like in the presence of a magnetized galactic wind Ahn et al. (2000), by the interaction with highly structured IGMF inside walls and filaments Medina-Tanco (1998b) or by the scattering off magnetic irregularities permeating the intergalactic medium.

In the present work we analyze the latter possibility considering radio ghosts Enßlin et al. (1999) as scattering centers of UHECR protons.

2 The nature of Radio Ghosts

Active galaxies eject large amounts of radio emitting plasma – short: *radio plasma* – into their environment. There it forms the typical cocoons of radio galaxies. The radio emission results from synchrotron emission of a population of relativistic electrons in the radio plasma's magnetic fields. It is possible to estimate the minimal energy density of the electron and magnetic components of the radio plasma required in oder to produce the observed emissivity. This minimum is given by rough energy equipartition between electron population and the magnetic fields. The resulting minimal pressure is typically of the order of the environmental thermal pressure, indicating that relatively strong magnetic fields are present.

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After a cosmological short time of $10^7 - 10^8$ years the radio luminosity of the cocoon decays strongly due to radiation and expansion energy losses of the electron population, or since the central engine of the radio galaxy stopped its activity. Although undetectable by our instruments, the radio plasma is still present in the IGM inside a fossil radio cocoon, a so called radio ghost. The subsequent evolution of the radio plasma is unclear, since observationally poorly constrained. It can be expected that the strong magnetic fields of the ghosts allow it to resist erosion by subsonic turbulence. The fossil radio cocoon should be kinematically decoupled from the ballistic motion of the parent galaxy and follow mostly the flow pattern of the embedding material. From this one would expect the ghosts to have a cosmological distribution comparable to that of the galaxies. And one would further expect that the oldest ghosts are swept into clusters of galaxies by the flow of structure formation.

But buoyancy of the probably very light radio plasma can produce some relative motion between ghosts and the IGM gas. This might allow the ghosts in clusters or filaments of galaxies to ascend to larger radii, until they get stopped by freely infalling matter at the accretion shock. It depends crucially on the topology of this accretion shock surface if the ghosts are able to escape from gravitationally bound structures as clusters and filaments of galaxies, or not. It is therefore difficult to predict the spatial distribution of ghosts.

For this work, to estimate the deflection of UHECR by ghosts. Therefore, only their magnetic fields are required, and their existence is nearly guaranteed by the existence of radio galaxies, and the extremely low magnetic diffusivity in extragalactic plasmas.

3 UHECR flux at Earth

The inclusion of efficient scattering centers in the intergalactic medium (IGM) in the form of radio ghosts, should be able to to produce a diffuse, isotropic, component of UHECR superimposed on the expected direct, anisotropic, component.

The scattering capability of ghosts is shown in figure 1, which show the results of numerical simulations using spherical radio ghosts. Different power spectral indexes ξ and radius were considered. Ghosts were illuminated with a beam protons with a energy spectrum, $dN/dE \propto E^{-3}$, and energy $E > 4 \times 10^{19}$ eV. The angular distribution of the scattered particles is shown in Fig. 1 for ghosts of different sizes and $\xi = 5/3$, 3 and 4. The radii of the ghosts are given in terms of the average gyroradius of the injected UHECR spectrum. As a comparison, an isotropic scattering particle distribution is also shown in the same figure. It can be seen that ghosts are very efficient at scattering UHECR regardless of power spectral index. Forward scattering becomes dominant only at the low end of the ghost size distribution, when the ghost's radius becomes comparable to the average gyroradius of the particles.

Therefore, given the current uncertainties, isotropic scattering is, very likely, an acceptable assumption and it will be used in what follows.

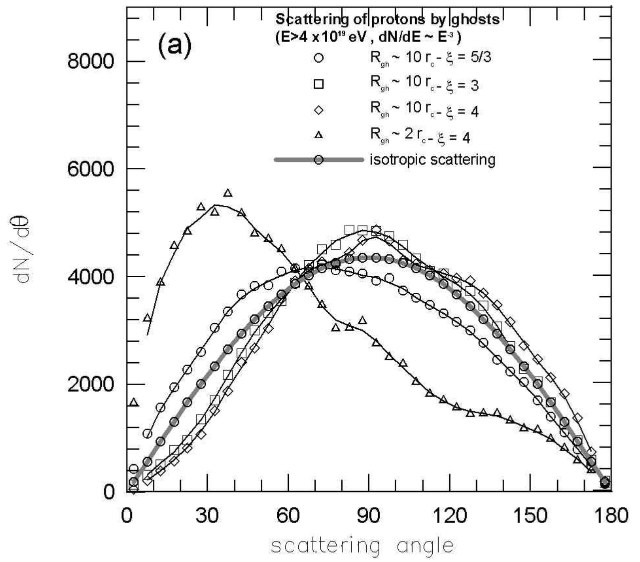

Fig. 1. Angular distribution of scattered UHECR for ghosts of different sizes and turbulent spectral index $\xi = 5/3$, 3 and 4. See text for details.

4 Numerical Model

We use Monte Carlo numerical simulations to track UHECR propagation through the intergalactic medium and to evaluate their arrival distribution at Earth.

We start from the basic assumption that most UHECR are protons of extragalactic origin whose sources aggregate spatially as either luminous or cold DM.

Charged particles, even at the extreme energies considered, are coupled to the intervening magnetic fields.

We restrict the present analysis to a cellular IGMF and neglect the galactic halo. The same procedure as in Medina-Tanco (1998a) is used in the description of the cell-like spatial structure of the IGMF. The cell size is given by the correlation length, $L_c \propto B_{IGMF}^{-2}(r)$. The intensity of the IGMF, in turn, scales with gas density as $B_{IGMF} \propto n_{gas}^{\eta}(r)$ and the proposed IGMF value at the Virgo cluster ($\sim 10^{-7}$ G, Arp (1988)) is used as the normalization condition. We use $\eta = 0.5$, as a compromise between a frozen-in field ($\eta = 2/3$) and Valleé's (1997) estimate ($\eta \sim 0.35$), which may be too flat due to the assumed values for the magnetic field in superclusters and larger scales. Nevertheless, tests have been conducted for different values of η covering the previous interval, and the scaling is not critical to our conclusions.

The formulation given in Medina Tanco and Ensslin (2001) is used to define the size and spatial distribution of radio ghosts. This requires the knowledge of the gas density distribution inside the simulation volume. Actually, as galaxies are easier to survey over large volumes, they are used to transform between galaxy and gas density distributions.

There are, however, serious an unavoidable bias and sampling problems inherent to galaxy surveys. Therefore, we relay on both galaxy surveys and cold DM large scale structure simulations to perform independent evaluations.

The sources of UHECR are distributed according to either the galaxy or cold DM distributions respectively.

The 1999 version of the CfA catalog Huchra et al. (1992) is used to characterize the galaxy distribution.

Cold DM simulation data are from Springel et al. (in preparation). They carried out simulations that mimic the Local Universe. The initial conditions of these simulations have been constrained by the redshift survey of IRAS galaxies. As a result, the simulations develop the same local large-scale structure (e.g., the Great Attractor and Cetus Wall; clusters like Virgo and Coma are also found at the right place).

UHECR protons are injected at the sources with a spectrum $dN/dE \propto E^{-2}$ and propagated through the intergalactic magnetic field up to the detector on Earth. Adiabatic energy losses due to redshift, pair production and photo-pion production due to interactions with the cosmic microwave background radiation (CMBR) are also included.

The flux at Earth can be divided into two components: (a) a *direct* radiation field, constituted by particles that fly from source to detector without encountering ghosts and (b) a *diffuse* radiation field, comprising particles which underwent at least one encounter with a radio ghost.

5 Different Scenarios

Fig. 2 shows the Aitoff projection of the two-dimensional arrival probability density (galactic coordinates with the anti-galactic center at the center of the figure), for sources distributed according to nearby luminous matter (CfA catalog) inside 100 Mpc and no radio ghosts. The same procedure as in Medina-Tanco (1998a) is used in the description of the intergalactic magnetic field (IGMF): a cell-like spatial structure, with cell size given by the correlation length, $L_c \propto B_{IGMF}^{-2}(r)$. The intensity of the IGMF, in turn, scales with luminous matter density, ρ_{gal} as $B_{IGMF} \propto \rho_{gal}^{0.3}(r)$ Vallee (1997) and the observed IGMF value at the Virgo cluster ($\sim 10^{-7}$ G) is used as the normalization condition. The mask covers the plane of the galaxy, where the actual distribution of galaxies is not well known due to obscuration by dust. The curved, thick line is the celestial equator. Northern hemisphere is the sky patch to the right, enclosed by that line.

Superimposed on the figure are the available events with $E > 4 \times 10^{19}$ eV observed by AGASA (47 events Takeda (1999)), Haverah Park (27 Reid and Watson (1980)), Yakutsk (24 Afanasiev (1995)) and Volcano Ranch(6 Linsley (1980)).

The arrival probability contours trace roughly the local large scale structure. Distinguishable observational signatures should be expected towards the region of the Southern branch of the supergalactic plane (to be observed in the near future by the Auger experiment) at $l \sim 45^o$, the lines of sight to the more distant Pisces-Perseus wall and Perseus cluster and, very prominently, towards a large area surrounding the

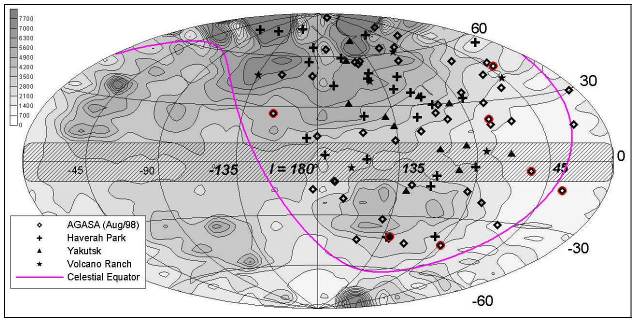

Fig. 2. UHECR propagation without radio ghosts. Aitoff projection of the arrival probability density. Galactic coordinates are used with the antigalactic center at the center of the figure. UHECR sources are distributed according to nearby luminous matter (CfA catalog). Data points correspond to cosmic rays observed by AGASA, Haverah Park, Yakutsk and Volcano Ranch with $E > 4 \times 10^{19}$ eV. Clearly, the observations are more isotropic than what should be expected from the model.

Virgo and Ursa Major clusters.

The actually observed distribution of UHECR is clearly much more isotropic than what one would expect under the implicit assumptions in Fig. 2.

Our study shows that clustered distributions of ghosts produce no noticeable effects in the observed UHECR flux at Earth.

The result is different when the scatterers are distributed in a larger volume than the sources. This is the case in figure 3, where $n_{gh} \propto n_{gal}^{b_{gh}}$ and $b_{gh} = 0.5$. In this scenario it is assumed that e.g. radio ghosts buoy out of cosmological structures, creating thick halos around walls and filaments, permeating voids to some extent. This diminishes considerably the direct component (Fig. 3a) and accounts for a considerable increase in the diffuse component (Fig. 3b) which becomes, by far, dominant. The composite flux (Fig. 3c) still shows a smooth, large scale gradient towards the region of the Virgo cluster but is much more isotropic than the previous scenario.

As was mentioned previously, there are uncertainties associated with unavoidable biases and sampling incompleteness associated with galaxy surveys, as is the case with the CfA catalog used up to here. This problem can be specially critical in this analysis, since the results depend on an absolute normalization of the density as a function of depth into the local universe. To check the extension of the distortions occurring in our previous analysis, we repeated our calculations using the distribution of cold DM, calculated by large scale structure hydrodynamic simulations (Springel, in preparation). They carried out simulations that mimic the Local Universe, developing the observed local large-scale structure.

Our simulations show that, regarding isotropization of the UHECR flux, the same kind of effect is present in these new scenarioas long as $b_{gh} \leq 0.5$.

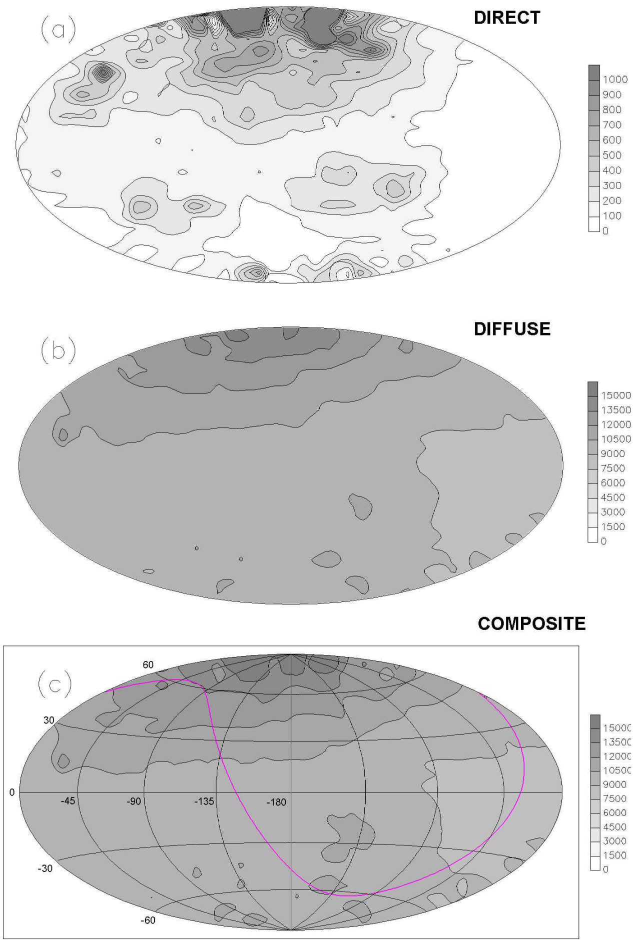

Fig. 3. Composite flux for ghost with a wider distribution than galaxies $n_{gh} \propto n_{gal}^{0.5}$.

6 Discussion

The isotropy in the UHECR flux observed particularly by Yakutsk and AGASA, is a very strong constraint to production and propagation models alike. Most of the scenarios proposed in the literature should produce a sizable anisotropy as either extragalactic luminous or dark matter is normally associated with the invoqued particle sources. If that is really the case, then it is our understanding of the topology and intensities of the intervening magnetic fields that is critically incomplete. The problem could reside inside the network of walls and filaments, in the interior of the large surrounding voids, or even in our **nearby** environment, namely the Galaxy halo.

In the present work we explore the possibility that radio ghosts, blobs of magnetized radio plasma remnant from past periods of activity in radio galaxies, being able to scatter UHECR in the intergalactic medium. Such a process could, in principle, degrade the direct incoming flux from the sources and build up a diffuse UHECR component large enough to be responsible for the observed degree of isotropy.

Our results show that, over the most conservative region of the radio ghost parameter space, such isotropization is not possible. This stands not from an inability of ghosts to scatter UHECR, but mainly from the fact that, under general conditions, ghosts should tend to cluster more strongly than the sources of the particles.

If, however, radio ghosts are able to buoy out into the surroundings of the dense large scale structures and into voids, while surviving the process, UHECR isotropy could be obtained in those cases in which the mean free path for interactions with ghosts is reduced below some few Mpc all over the propagation region ($\sim b_{gh} < 0.5$).

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