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THE OPTICAL DEPTH OF THE UNIVERSE SEEN THROUGH ULTRAHIGH ENERGY COSMIC RAY SPECTACLES

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Abstract. We provide an analytical description of the transport of ultrahigh energy cosmic rays in a universe made up of magnetized scattering centers, with negligible magnetic fields between them. Magnetic deflection is no longer a continuous process: it is rather dominated by scattering events. We calculate the optical depth of the Universe to cosmic ray scattering and discuss its phenomenological consequences for various source scenarios. It is found that part of the correlation reported recently by the Pierre Auger Observatory between active galactic nuclei and the arrival directions of ultrahigh energy cosmic rays may be affected by a scattering delusion. This experiment may be observing in part the last scattering surface of particles, rather than their source population.

1 Introduction

The problem of the origin of ultrahigh energy cosmic rays is higly related to their propagation in the extragalactic medium. Our lack of knowledge on the distribution of the magnetic fields on very large scales hinders significantly our study on that domain. At extremely high energies ($E > 6 \times 10^{19}$) though, one can reasonably assume that the ambient extragalactic magnetic field plays a negligible role in the propagation of particles, the only notable deflecting regions being localized magnetized spots. Radio halos, magnetized galactic winds, clusters of galaxies and filaments of large scale structures are altogether numerous, magnetized and spatially extended enough in order to influence the trajectory of ultrahigh energy cosmic rays.

We study here different modes of propagation of ultrahigh energy particles in such a model of magnetized universe. According to the parameters of scattering centers, the energy of the observed particles, and the direction in the sky, the Universe can appear more or less opaque to cosmic ray scattering.

2 Optical depth and last scattering surface for cosmic ray scattering

Out of simplicity, we will assume here that the scattering centers are distributed homogeneously in the Universe, with a typical mean free path to interaction. It is shown in Kotera & Lemoine (2008) that an inhomogeneous distribution is quite similar to the case where the dominant scattering centers are filaments. The details of the interaction between a particle and each type of magnetized structure is described in this paper.

The optical depth τ characterizes the number of scatterings along a path length l. In order to study the angular spread of the cosmic ray images on the detector, we also define the effective optical depth $\tau_{\rm eff}$, which becomes unity when the path length l is such that the particle has suffered a deflection of order unity. We write: $\tau = l/\overline{d}$ and $\tau_{\rm eff} = l/l_{\rm scatt}$, where $\overline{d}$ is the mean free path to interaction with any scattering center, and $l_{\rm scatt}$ the scattering length of cosmic rays in the medium, corresponding to the distance over which the deflection becomes of order unity. To make concrete estimates, we assume that one type of scattering center dominates, with typical interaction length d_i: $\tau \simeq 3.1\,(l/100\,{\rm Mpc})(d_i/32\,{\rm Mpc})^{-1}$. The fiducial value $d_i = 32\,{\rm Mpc}$ corresponds to spherical scattering centers of density $n_i = 10^{-2}\,{\rm Mpc}^{-3}$ and radius $r_i = 1\,{\rm Mpc}$; it is also a typical value for the interaction distance to filaments of the large scale structure.

A simple calculation shows that the flux received from sources located within a distance l increases as l. Hence most of the flux comes from sources located at distance $l_{\rm max}(E)$, the energy loss distance (by pions and pair production) of a particle of a given energy. Replacing l by $l_{\rm max}$ in the definitions of τ and $\tau_{\rm eff}$, one obtains the dependence in energy of these quantities, as shown in Figure 1 for one particular type of scattering center.

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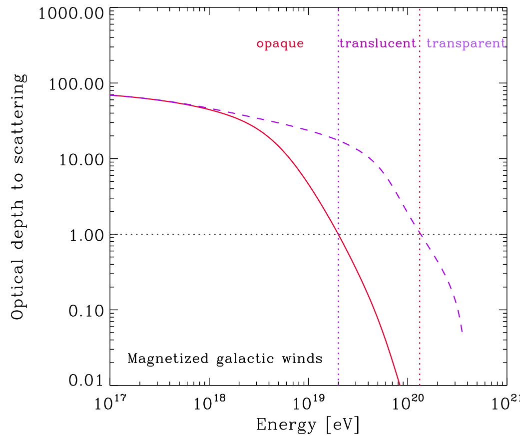

Fig. 1. Optical depth to cosmic ray scattering by magnetized galactic winds, with number density $n_{\rm gw} = 10^{-2}\,{\rm Mpc}^{-3}$, magnetic field intensity $B_{\rm gw} = 3 \cdot 10^{-8}\,$G, coherence length $\lambda_{\rm gw} = 50\,$kpc, and radius $r_{\rm gw} = 0.8\,$Mpc. Solid line: optical depth $\tau_{\rm eff}$ to scattering by an angle of order unity; dashed line: optical depth τ.

In this figure, the horizontal dotted line indicates an optical depth of order unity, while the vertical dotted lines indicate at which energy $\tau_{\rm eff} = 1$ and $\tau = 1$ respectively, from left to right. As indicated on the figure, these lines delimit the energy ranges in which the Universe appears opaque ($\tau > \tau_{\rm eff} > 1$), translucent ($\tau > 1 > \tau_{\rm eff}$) or transparent ($1 > \tau > \tau_{\rm eff}$) to cosmic ray scattering. Interestingly, for this example, the Universe is translucent at energies close to the threshold for pion production $E_{\rm GZK} \simeq 6 \cdot 10^{19}\,$eV.

Since the sources of protons with energies beyond the pion production threshold are bound to reside within $100 - 200\,$Mpc, one may expect the optical depth of scattering centers to vary with the direction of observation, just as the matter density. In order to discuss the influence of such variations on existing and upcoming data, we have constructed sky maps of the matter concentration using the PSCz catalog of galaxies (Saunders et al., 2000).

The integrated column density of baryonic matter $N_{\rm g}/\langle N_{\rm g}\rangle$ up to a distance l is shown in Fig. 2 for maximal distances: $l = 80,\,160\,$Mpc (we adopt $H_0 = 70\,$km/s/Mpc). In order to correct for the incompleteness of the catalog, we have followed the prescriptions of Saunders et al. (2000) and smoothed the galaxy distribution with a variable gaussian filter, making use of the `HEALPix` library (Górski et al., 2005). The overall resolution of the maps is of order 7°.

These maps provide an estimate of the optical depth to cosmic ray scattering in the case where the scattering centers are distributed as the galaxies, with a possible bias. A relation of proportionality between the quantity $N_{\rm g}/\langle N_{\rm g}\rangle$ shown in Figure 2 and the optical depth τ, that enables a more precise reading of those skymaps can be found in Kotera & Lemoine (2008).

3 Consequences for cosmic ray transport

In this section, we discuss the phenomenological consequences of the above model of cosmic ray transport with respect to the signatures of different source models, discussing in particular the absence or existence of counterparts.

The optically thin regime, in which $l_{\rm max} < \overline{d} < l_{\rm scatt}$, is trivial in terms of particle propagation: most particles travel in straight line, without interacting in the intergalactic medium, hence one should expect to see the source directly in the arrival direction of the highest energy events. However, in the case of gamma-ray burst sources, the spreading of arrival times through the interaction with cosmic magnetic fields is essential to reconcile the gamma-ray burst rate with the rate of ultrahigh energy cosmic ray detection (Waxman, 1995). In the absence of scattering (hence time delay), such a bursting source would be essentially unobservable as the occurrence rate is much too low when compared to the lifetime of the experiment.

In the intermediate 'translucent' regime ($\overline{d} < l_{\rm max} < l_{\rm scatt}$), the total deflection remains smaller than unity.

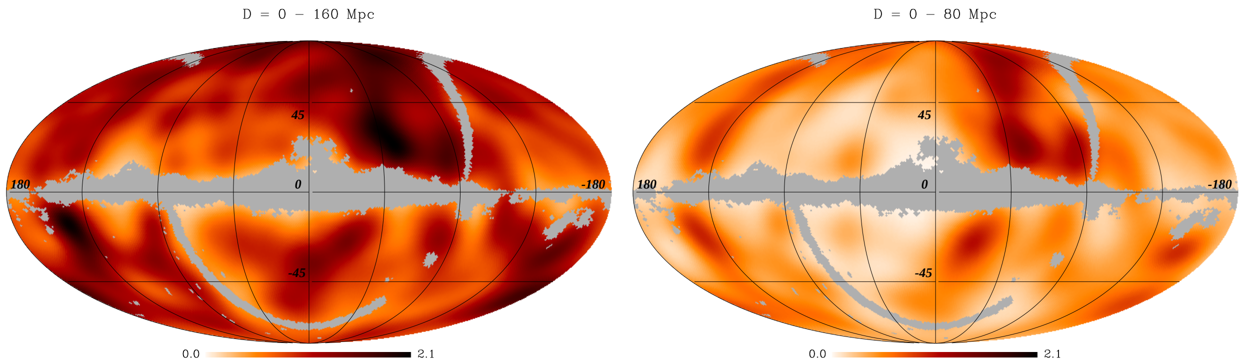

Fig. 2. Integrated galaxy column density as derived from the PSCz catalog of galaxies up to the maximal distances $l = 80\,$Mpc and $l = 160\,$Mpc (Mollweide projection). The contours give the column density $N_{\rm g}$ in units of the mean column density $\langle N_{\rm g}\rangle = \langle n_{\rm g}\rangle \times 160$ Mpc, with $\langle n_{\rm g}\rangle$ the mean galaxy density. The grey mask indicates the regions of the sky that are not covered by the PSCz catalog (Saunders et al., 2000).

One may thus describe the transport as nearly ballistic with a non-zero time delay as measured relatively to straight line propagation. The total time delay aquired over a path length δt and the typical deflection angle $\delta\alpha$ between the source direction and the particle arrival direction can be calculated as a function of τ, using random walk arguments.

As $\delta\alpha$ depends on τ, which is itself direction dependent (as shown in Fig. 2), the angular deflection will depend on the observed region of the sky. This property is also valid for the time delay, as $\delta t \propto \tau$. This is particularly interesting if the sources of cosmic rays were bursting sources (like gamma-ray bursts): the time delay and its dispersion induced by the interactions with scattering centers can artificially enhance the flux of particles. Hence the probability of observing particles produced by bursting sources will be lower by a factor τ in regions where $\tau < 1$, as compared to regions where the optical depth is greater than unity. Conversely, if the source is not of the bursting type, one might see it directly in the arrival direction if the source lies in a hole of the foreground scattering center distribution.

The opaque regime corresponds to $\tau > \tau_{\rm eff} > 1$. In this case, cosmic rays diffuse from the source to the detector as in a random billiard. The arrival direction of high energy events will point back to the source (either of bursting or continously emitting) only if this latter is located at a distance closer than $l_{\rm scatt}$. Note that the same delusive effect of finding a scattering center in the arrival direction of cosmic rays occurs in this regime just as in the translucent regime.

4 Discussion on the recent data from the Pierre Auger Observatory

The Pierre Auger Observatory (PAO) has recently released the largest catalog of events above $5.7 \times 10^{19}\,$eV (Abraham et al., 2008), in which 20 out of 27 events originate from within 3 degrees of an active galactic nucleus located within 75 Mpc.

This correlation is puzzling for two reasons: the AGN used in this analysis are mainly Seyfert galaxies that are not favoured candidates for particle acceleration to ultrahigh energy. Second, the distance at which the maximum correlation is observed seems to be much lower than $l_{\rm max}$, the source distance scale from which the maximum flux should be observed. Two main possibilities are advocated in the community to solve this latter incoherence: the energy scale measured by PAO may be underestimated by 30%, or it might be due to a selection bias of the observed particles. In light of the analysis developed above, we suggest that this correlation may actually pinpoint scattering centers correlating with AGN, rather than the sources of ultrahigh energy cosmic rays.

We estimate the fraction of events that are likely to be contaminated by such pollution by calculating the fraction of galaxies in the PSCz catalogue that lie within 3° of an AGN which is itself located closer than 75 Mpc. We obtain that 31% of events above $6 \times 10^{19}\,$eV could correlate with the AGN, assuming that the PSCz galaxies provide an unbiased tracer of the cosmic ray source population and that the magnetic deflection is much smaller than the search radius of 3°. Now, if we repeat the same procedure, taking into account magnetic deflections, the fraction of contaminated events increases as the assumed magnetic deflection angle $\delta\alpha$ becomes of order of a few degrees: it equals 39% for $\delta\alpha = 1°$, 48% for $\delta\alpha = 3°$, then decreases, being 45% for $\delta\alpha = 5°$ and 43% for $\delta\alpha = 7°$.

The above estimates indicate that, within the assumptions of the above discussion, the delusion should not affect all events of PAO, but a significant fraction nonetheless, possibly as high as $\simeq 50\,\%$. Moreover, they also indicate that intergalactic magnetic deflection could be larger than 3° and yet produce a relatively significant false correlation with AGN. This fraction of contaminated events is likely to be enhanced if ultrahigh energy cosmic rays originate from gamma-ray bursts. Indeed, as discussed in Section 3, one expects in this case the number of events in regions of low foreground density to be smaller by a factor of order τ (τ being the optical depth measured in such directions) when compared to that coming from regions of optical depth greater than unity.

In conclusion, it appears that the counterparts seen by PAO seem unlikely to be the sources of ultrahigh energy cosmic rays. One possible interpretation of the observed correlation is that PAO is mistaking the last scattering centers with the sources, which can be either continuously emitting or bursting sources. If the energy scale of PAO was underestimated by 30%, it may have detected the invisible sources within a few megaparsecs, in which case, no other counterpart (gamma rays, neutrinos...) will ever be seen in their direction, as they will have passed through Argentina more than 10^3 years ago. It appears that the most efficient way find the sources of ultrahigh energy cosmic rays will be to look for a signature of one type of sources at the highest energies ($> 10^{20}$ eV).

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