

SIMULATING THE MAGNETIC FIELD IN THE LOCAL SUPERCLUSTER

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Abstract

We construct the first realistic map of deflections of ultra-high energy cosmic rays by extragalactic magnetic fields, using a magneto-hydrodynamical simulation of cosmic structure formation that reproduces the positions of known galaxy clusters in the local universe. Large deflection angles occur in cluster regions, which however cover only an insignificant fraction of the sky. More typical deflections of order $\sim 1^\circ$ are caused by crossings of filaments. For protons with energies $E \geq 4 \times 10^{19}$ eV, deflections do not exceed a few degrees over most of the sky up to a propagation distance of 500 Mpc. Given that the field strength of our simulated intergalactic magnetic field forms a plausible upper limit, we conclude that charged particle astronomy is in principle possible.

1 Introduction

Considerable effort (such as Auger¹ and EUSO²) is presently undertaken around the world to build experiments devoted to determining the composition, the energy spectrum and the arrival directions of Ultra High Energy Cosmic Rays (UHECR). This challenge is in part motivated by the Greisen-Zatsepin-Kuzmin (GZK) puzzle (Greisen et al. 1966) which became particularly acute with Fly-Eye and AGASA data (Bird et al. 1995, Takeda et al. 1998), and by the realization that the UHECR flux at $E > 10^{19}$ eV is probably dominated by the emission of sources which are quite different from conventional galactic sources. The directional information may allow the identification of UHECR

sources, provided primary particles are not deflected too much by galactic and intergalactic magnetic fields (IGMFs). Several arguments suggest that UHECR are electrically charged nuclei; most probably they are protons, a point of view we will adopt in the following. Galactic magnetic fields with $B_{\text{gal}} \sim 1 \mu\text{G}$ are not expected to produce significant deflections at extremely high energies, $E \gtrsim 10^{20}$ eV. Even at lower energies $E \sim 4 \times 10^{19}$ eV, strategies have been proposed which allow source identification without detailed knowledge of the galactic magnetic fields (Tinyakov & Tkachev 2003).

The attractive prospect of doing astronomy with UHECRs might be spoiled by the presence of strong IGMFs. So far, evidences of the presence of IGMFs have been found only within, or very close to, rich clusters of galaxies. The most relevant observations are those based on Faraday rotation measurements (RM) of the polarized radio emission of sources located within or behind clusters, and on the synchrotron emission of relativistic electrons in the intracluster magnetic fields. The results of both methods imply the presence of magnetic fields with strength at the μG level extending up to 1 Mpc from cluster centers. The coherence length of the field is inferred to lie in the range 10–100 kpc (see recent review by Carilli & Taylor 2002 and references therein). Such fields do certainly induce large deflections of UHECR protons that cross clusters of galaxies. However, galaxy clusters fill only a tiny fraction of the volume of the universe, so that we may expect them to produce large deflections only over a small portion of the sky (Berezinsky et al. 2002, Blasi & Marco 2003). Outside clusters, only upper limits on the IGMF strength are avail-

¹<http://www.auger.org>

²<http://www.euso-mission.org>

able. They are at the level of 10^{-9} – 10^{-8} G for fields extending over cosmological distances with coherence lengths in the range 50 to 1 Mpc, respectively (Blasi et al. 1999). These limits do not hold for magnetic fields in clustered regions, like filaments connecting galaxy clusters where the field might be as large as 10^{-7} G. In principle, either a weak all pervading smooth field, or stronger fields localized in a complex web of filaments, may produce sizable deflections of UHECR over a large portion of the sky. It is therefore evident that a better knowledge of the large-scale magnetic field structure of the universe is called for.

2 MHD simulations of the Local Universe.

We use initial conditions that were constructed from the IRAS 1.2-Jy galaxy survey by first smoothing the observed galaxy density field, evolving it linearly back in time, and then using it as a Gaussian constraint for an otherwise random realization of the Λ -cold dark matter (Λ CDM) cosmology. Mathis et al. (2002) showed that these constrained initial conditions, when evolved to the present time, reproduce the observed density and velocity field of the local universe. In addition, they allow a direct identification of prominent clusters (Virgo, Coma, etc.) with counterparts formed in the simulation, which are found at the right places, and with approximately the correct observed masses. We extended the initial conditions of Mathis et al. (2002) by adding gas, together with an initial magnetic field. The volume filled by high resolution particles within our simulation is a sphere of radius ~ 115 Mpc centered on the Milky Way (in this letter we assume the Hubble parameter to be $h = 0.7$). This region comfortably includes the entire Local Supercluster (LSC).

We evolved the initial conditions with the newest version of the GADGET-code (Springel et al. 2001), adding the Magnetic Smoothed Particle Hydrodynamics (MSPH) technique (Dolag et al. 2002) to follow magnetic field evolution. Previous work (Dolag et al. 2002) showed that magnetic seed fields in the range of $(1\text{--}5)\times 10^{-9}$ G at redshift $z_* \simeq 20$ will be amplified due to the structure formation process and reproduce the RM in clusters of galaxies. This corresponds to $B(z_*) (1 + z_*)^{-2} \simeq 0.2\text{--}1 \times 10^{-11}$ G at the present time in the unclustered intergalactic medium (IGM). It was also demonstrated that the magnetic field's amplification process completely erases any memory of the initial field configuration in high density regions like

galaxy clusters. Therefore, we can safely set the coherence length $l_c(z_{\text{in}})$ of the initial seed field to be infinite in our simulation. Although this assumption is probably unrealistic, it does not lead to underestimation of the UHECR deflections. Concerning the initial strength of the magnetic fields, we used the highest value which still allowed previous MSPH simulations to successfully reproduce RM in clusters, i.e., the results presented here give safe upper bounds on UHECR deflections.

Clusters are generally connected by magnetized filamentary structures of gas and dark matter, where high-density filaments often harbor small clusters or groups. We find that shock fronts and shear flows are ubiquitous in these filaments, giving rise to substantial MHD amplification in these structures, boosting the magnetic field's intensity far above the expectation of adiabatic compression alone, as pointed out in previous work (Dolag et al. 2002). We find no significant magnetic fields in the neighborhood of the Milky Way. Within a sphere of 7 Mpc there is a group of four halos aligned within the super galactic plane. As they are close, they cover a large fraction of the sky, but the magnetic fields associated with them are weak. Therefore, we do not expect important local effects at the observer position.

3 Deflections of charged UHECR.

Having a realistic three-dimensional map of magnetic fields in the local universe, we can construct an associated map of deflections of charged particles under the action of the Lorentz force. We here consider only protons with energy $E = 4 \times 10^{19}$ eV. This is the threshold value for the process of photo-pion production in collisions with Cosmic Microwave Background (CMB) photons ($p + \gamma_{\text{CMB}} \rightarrow p(n) + \pi^{0(+)}$). The energy loss length is large, $l_E \sim 1000$ Mpc (for a recent review see, e.g., Ancho et al. 2003), and initially higher proton energies quickly degrade into this range. Neglecting energy losses and taking $E = 4 \times 10^{19}$ eV to be the energy at detection, we obtain upper bounds for the deflections of protons with higher energy since the deflection angle decreases linearly increasing the energy. Furthermore, since l_E becomes drastically smaller at higher energies ($l_E \sim 20\text{--}50$ Mpc for $E > 10^{20}$ eV), the UHECR flux is expected to be dominated by close sources at these extreme energies so that the probability for a proton to cross a magnetized region and to be deflected becomes smaller.

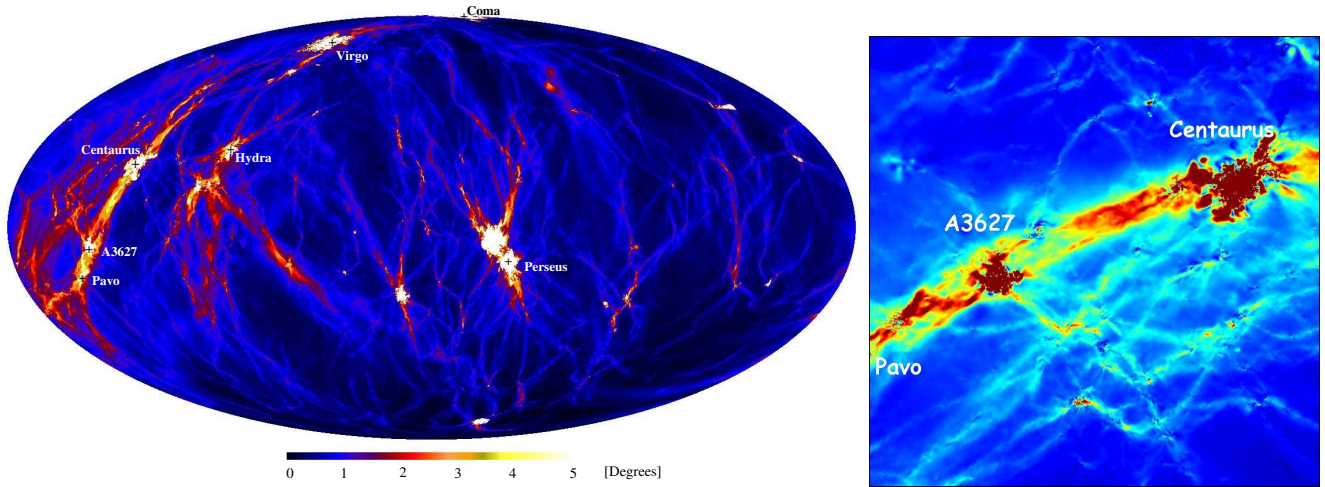


Figure 1: Full sky map (area preserving projection) of deflection angles for UHECRs with energy 4×10^{19} eV using a linear color scale. All structure within a radius of 107 Mpc around the position of the Galaxy was used. The coordinate system is galactic, with the galactic anti-center in the middle of the map. Positions of identified clusters are marked using the locations of the corresponding halos in the simulation. Right panel shows a zoom in of the deflection map focused on a large filament connecting A3627 with Centaurus.

We do not follow particle trajectories directly; instead we compute accumulated deflections along rectilinear paths. This is a reasonable simplification since we are not interested in actual source positions, but rather in finding directions with small deflections. In Fig. 1, we show a deflections map obtained by tracing an isotropic distribution of protons from a maximal distance of $d_{\text{max}} = 107$ Mpc to the observer. Recall that Fig. 1 represents a map of deflections, not a distribution of arrival directions. The former is independent of the assumed distribution of UHECR sources.

The pattern of clusters and filaments is clearly visible in Fig. 1. Large deflections are produced only when protons cross the central regions of galaxy clusters, and most of these strongest deflections are found along a strip which can be approximately identified with the Great Attractor. The observed positions of Virgo, Coma, Hydra and Centaurus lie in this region. Their locations quite precisely coincide with regions where the deflections exceed 4° . Perseus and other minor clusters produce large deflections in other well delineated regions of the sky. Outside clusters, which occupy only a small fraction of the sky, deflections of 1° – 2° occur along an intricate network of filaments, covering a larger area. The regions with $\delta \ll 1^\circ$ correspond to voids where the magnetic fields strength is even smaller than 10^{-11} G.

In order to investigate the relative importance of deflec-

tors at different distance, we also produced deflection maps that only included deflectors up to some maximum distance. We observe no significant deflections produced at distances smaller than 7 Mpc. Massive clusters at large distances (~ 100 Mpc) produce large deflections but cover only a negligible fraction of the sky, so that the bulk of the deflections is produced by passages through filaments.

In Fig. 2, we plot the fraction of the sky, $A(\delta_{\text{th}})$, over which deflections larger than δ_{th} are found, for different propagation distances. We see that deflections larger than 1° are to be expected over less than 20% of the sky up to the distance $d = 107$ Mpc. For large distances d , we find that $A(\delta_{\text{th}}, d)$ approaches a self-similar behavior, viz. $A(\delta_{\text{th}}, d) = A_0(\delta_{\text{th}} \times (d_0/d)^\alpha)$. Numerically, we observe $\alpha = 0.8$ for $70 < d/\text{Mpc} < 110$. Self-similarity is consistent with the assumption that the density of deflectors (filaments) reaches a constant value at large distances. Since magnetic fields are uncorrelated in different filaments, multiple filament crossings should produce a “random walk” in the deflection angle, resulting in $\alpha = 0.5$. The value of $\alpha = 0.8$ we observe may hence indicate that the regime of multiple filament crossings is not yet reached over the distances probed by our simulation. We include an extrapolation of $A(\delta_{\text{th}}, d)$ up to a distance of 500 Mpc in Fig. 2, shown for two values of α , the observed one of $\alpha = 0.8$, and the expected one for large propagation distances, $\alpha = 0.5$. We expect that these two curves

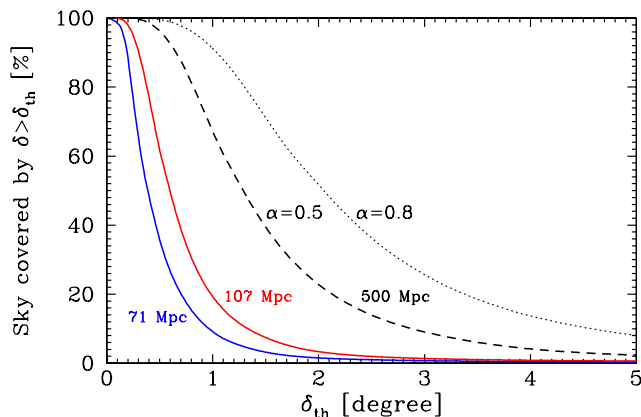


Figure 2: Cumulative fraction of the sky with deflection angle larger than δ_{th} , for several values of propagation distance (solid lines) is shown in the left panel. We also include an extrapolation to 500 Mpc, assuming self similarity with $\alpha = 0.5$ (dashed line) or $\alpha = 0.8$ (dotted line). The assumed UHECR energy for all lines is 4.0×10^{19} eV.

bracket the range of true deflections at $E \sim 4 \times 10^{19}$ eV.

It is also interesting to consider the potential effect of the unclustered component of the IGMF, i.e., the field in voids and low density regions outside of clusters and filaments. In principle, the coherent component may produce significant deflections of proton trajectories over cosmological distances. Note however that we have no reason to assume that the coherence length is so large in reality. We only adopted a large coherence length in our simulation because it is the simplest option, without having any bearing on the field structure in the clustered regions. If $l_c \ll d$ the proton trajectory makes a random walk through the magnetic domains, and the overall deflection is given by $\delta \simeq 0.8^\circ (B_0/10^{-11} \text{ G}) (E/10^{19} \text{ eV}) (d/\text{Gpc})^{0.5} (l_c/\text{Mpc})^{0.5}$. Hence, observable deflections are not produced by the unclustered component of the IGM if l_c is smaller than a few tens of Mpc. Note that such small coherence lengths are expected from most of the proposed generation mechanisms of seed IGMFs (Grasso & Rubenstein 2001). The few mechanisms predicting larger l_c generally give rise to magnetic fields which are too weak to produce observable deflections of UHECR. Furthermore, an unclustered IGMF does not exist at all if the seed field is generated by a battery powered by structure formation (Kulsrud et al. 1997).

4 The magnetic field in filaments

Previous work (Dolag et al. 2002) focused on the magnetic field structure within individual galaxy clusters. In this work - for the a first time - it is possible to predict the properties of magnetic fields in filaments. Therefore we focus on a filament within the Centaurus super cluster, clearly visible as the most prominent feature - beside the individual clusters - within the full sky deflection map (Fig. 1). A closer inspection of the three-dimensional structure (left panel of Fig. 3) showed, that these feature in fact is due to a superposition of many filaments within a ring like structure, containing A3627, Centaurus and Pavo, seen in projection. To avoid projection effects, in Fig. 3 the gas properties along a straight line connecting A3627 with Centaurus are shown. This path coincides with one of the filaments within the super cluster structure. This filament spans roughly $27 \text{ Mpc}/h$, and the centers of the two clusters are located at the left and right side of the plots respectively. As once can see, due to the adaptive nature of SPH the resolution (h) within the filament is low, but the value around $\approx 300 \text{ kpc}/h$ is still good enough to draw some conclusions. The gas density found in this filament is four orders of magnitudes smaller than within the galaxy clusters. Note also that there are three small structures along the filament, visible as small, local density maxima. Figure 3 also shows the three spatial magnetic fields components. Whereas the magnetic field in the clusters is of order μG it drops to $\sim 10^{-4} \mu\text{G}$ within the filament, which is consistent with the adiabatic prediction for this density. Within the galaxy clusters, the magnetic field is very much disordered, but note that within the filament the magnetic field is ordered over very long distances and only get disordered at the three locations, where objects are forming. To demonstrate this in more detail, the cosine of the angle α between the filament and the magnetic field is shown as well. Note that where as the huge coherence length of the magnetic field reflects the coherence within the initial conditions, the magnetic field got rotated by the formation of the filament and is now orientated along the filament, which is not aligned with the initial magnetic field direction.

5 Conclusions

We presented the first realistic map of UHECR deflections in the local universe, based on a self-consistent simulation of magnetic field amplification during cos-

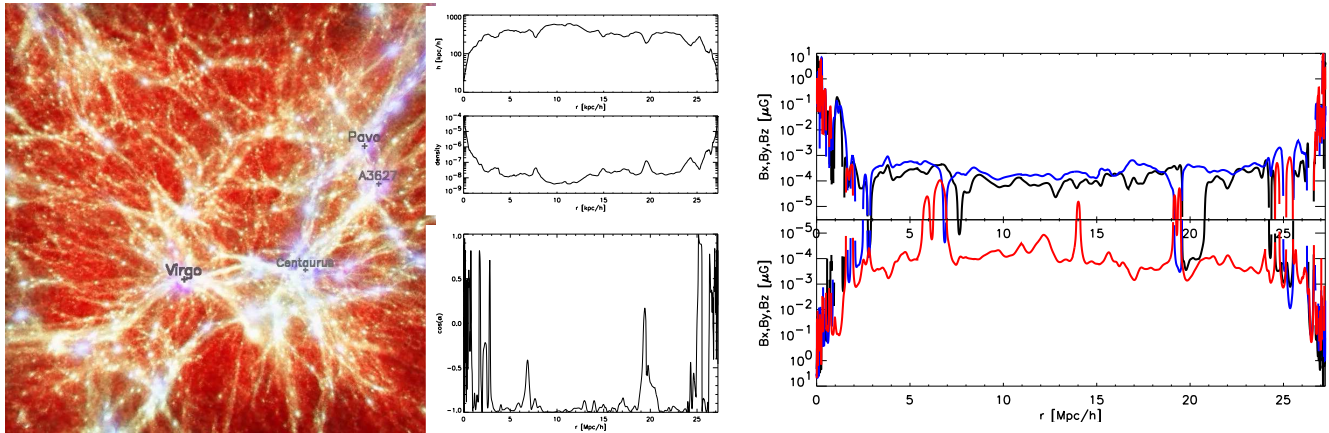


Figure 3: three-dimensional representation of the Centaurus super cluster on the left side and various predicted gas properties from the simulation (as labeled) within the filament connecting the cluster A3627 and Centaurus on the right side are shown.

mic structure formation. The positions and masses of the most prominent clusters are reproduced well in our simulation. This is an important advantage of our technique. Since local structures subtend large angles on the sky, it is important to be able to reliably identify “bad” regions of expected large deflections, a task that can be accomplished using our map, thereby providing important guidance for UHECR source identification. Note that our results should be understood as upper bounds for the expected deflection angles, because we have used the largest seed field still compatible with the RM in clusters, and secondly, we neglected UHECR energy losses on the path to the detector.

We have also extrapolated the distribution of deflection angles to very large source distances in a statistical manner. Out to 500 Mpc and at $E \geq 4 \times 10^{19}$ eV, typical deflections are smaller than the angular resolution of current UHECR detectors over more than half of the sky. This result is consistent with an observed small-scale clustering of UHECR arrival directions (Hayashida et al. 1996, Takeda et al. 1999, Tinyakov & Tkachev 2001) and with evidence for a BLLacs - UHECR correlation (Tinyakov & Tkachev 2001) in the energy range $E \sim 4 \times 10^{19}$ eV being due to protons (Tinyakov & Tkachev 2002). On the other hand, our results do not support models which invoke strong magnetic fields in the local universe to solve the GZK anomaly as well as models which explain small-scale clustering by magnetic lensing.

We conclude that charged particle astronomy should be possible regardless of the way the GZK problem will be resolved.

We also identified low density filaments where the magnetic field is roughly aligned along their axis, with a strength of $\sim 10^{-4}$ μG . This is consistent with a purely adiabatic amplification of the seed magnetic field due to the compression of field lines.

Acknowledgments

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