Constrained Simulations of the Magnetic Field in the Local Supercluster and the Propagation of UHECR

Klaus Dolag[1], Dario Grasso[2], Volker Springel[3] and Igor Tkachev[4]
(1) Dipartimento di Astronomia, Università di Padova, Padua, Italy
(2) Scuola Normale Superiore, Pisa - Italy
(3) Max-Planck-Institut für Astrophysik, Garching, Germany
(4) CERN - Theory Division, Geneve, Switzerland

Abstract

Magnetic fields (MF) in the Local Supercluster (LSC) of galaxies may have profound consequences for the propagation of Ultra High Energy Cosmic Rays (UHECR). Faraday rotations measurements provide some informations about MF in compact clusters. However, very few is known about less dense regions and about the global structure of MF in the LSC. In order to get a better knowledge of these fields we are performing constrained magnetohydrodynamical simulations of the LSC magnetic field. We will present the results of our simulation and discuss their implications for the angular distribution of expected UHECR deflections.

1. Introduction

Several arguments suggest that Ultra High Energy Cosmic Rays (UHECR) are extragalactic in origin (see e.g.[1]). Propagation of electrically charged CR primaries is affected by intergalactic MF. Resulting picture crucially depends on magnetic field mean intensity and power spectrum. MF have been observed in several clusters of galaxies [7]. An indisputable evidence of these fields is provided by diffuse cluster-wide synchrotron emission from several clusters compatible with a field strength larger than 0.1 μG. In addition, indirect observational evidence of the magnetization of the Inter Cluster Medium (ICM) comes from Faraday Rotation Measurements (RM) of the polarized radio sources located within or behind the clusters. Analyzing these observations several authors (see e.g. [3]) found that the ICM in clusters are permeated with a high filling factor by magnetic fields at a level of $1-10$ μG with a correlation length of $10 \div 100$ kpc extending up to 1 Mpc from the cluster center. Beyond this distance the IGM density becomes too low to allow an observable Faraday rotation since the effect is proportional to the free electron density. In this case only upper bounds are available which are $B < 10^{-9} \div 10^{-8}$ G in unclustered regions and a significantly weaker upper limit $B \lesssim 10^{-6}$ in the sheets or the filaments of galaxy clusters [2]. What is most crucial for UHECR reaching the Earth is the MF in the Local Supercluster (LSC)

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since it comprise most of the GZK volume. The MF structure of the LSC is very poorly known. RM allowed to determine its intensity only in some overdense regions like the Virgo cluster where it was found to be about 10^{-6} G. A method to determine the power spectrum of IGMF from a systematic analysis of RM of a large number of distance sources may allow a better knowledge of the LSCMF in a not too distant future [5]. Meanwhile, however, the only way to improve our understanding of UHECR observational data is to estimate the LSCMF large scale structure by numerical simulations.

2. MHD simulations in clusters

Magneto Hydrodynamical (MHD) simulations of MF evolution in galaxy clusters have been already performed by one of us (KD) and collaborators [4]. This kind of codes combines the merely gravitational interaction of a dominant dark-matter (DM) component with the hydrodynamics of a magnetized gas to simulate the formation of magnetized galaxy clusters. Initial conditions are specified at redshift $z_{in} \sim 20$ by a random choice of density perturbations compatible with standard ΛCDM cosmology and an initial seed field to be tuned to reproduce RM of clusters at redshift close to zero. The MF is amplified by adiabatic compression during cluster collapse and, more efficiently, by the Kelvin-Helmholtz instability where merger events give rise to strong shear flows. It was found that the simulation reproduce quite well the general features of the observed RM with an initial field strength of $\sim 5 \times 10^{-9}$ G. In the outer regions of the clusters, the average field strength follows the gas density profile quite well though with a steeper slope compared to estimates based on flux conservation and adiabatic compression ($B \propto \rho_{\rm gas}^{2/3}$), showing that shear flow have to play an important role there. As a consequence the required initial intensity of the MF is smaller than expectation based on a mere adiabatic amplification. The MHD simulations are designed to study individual clusters within a cosmological environment, and therefore can not describe voids or filaments. Nevertheless an order of magnitude estimate can be obtained on the basis of the following simple argument. In the voids, as well as in low density regions around the LG, we do expect the adiabatic compression to give a rather good description of the MF evolution. Using flux conservation, which implies $B(z = 0) = B(z_{\rm in})(1+z_{\rm in})^{-2}$, we see that a field strength of 5×10^{-9} G at $z_{\rm in} = 20$, as required for the MHD simulations to reproduce RM of clusters, corresponds to the present time intensity of $B(z = 0) \sim 10^{-11}$ G in the unclusterized IGM. The rms deflection angle of a particle of charge Ze traveling over the distance d through an irregular MF with a coherence length $l_c \ll d$ and local intensity B is given by the expression

$$\theta(E, d) \simeq 1^o \; Z \left(\frac{10^{20}\ \mathrm{eV}}{E}\right) \left(\frac{d}{10\ \mathrm{Mpc}}\right)^{1/2} \left(\frac{l_c}{1\ \mathrm{Mpc}}\right)^{1/2} \left(\frac{B}{10^{-9}\ \mathrm{G}}\right) \ . \qquad (1)$$

It is clear that a MF with strength $\sim 10^{-11}$ G have a negligible influence on UHECR propagation. Therefore we expect significant deflections only when UHECR trajectory crosses cluster or a strongly magnetized filament. In that case deflection of few degrees can be produced (see Fig.1). A different situation was examined recently by Sigl at al. [9]. The authors of [9] performed an Eulerian hydro+N-body simulation of the entire LSC and added to it a MF which follows passively the gas. Such simulation, however, is not a constrained simulation (see below) which implies that it is not suited to reproduce the real spatial distribution of matter and of magnetic fields. In [9] the authors chosen the observer position to lie in a region with a rather strong magnetization $B \sim 0.1\mu$G. This was required in order to reproduce the observed isotropy in the arrival directions of UHECR under the hypothesis that the source distribution trace that of the matter in the LSC. Such an hypothesis, however, has not been proved so far and other reasonable possibilities have been discussed in the literature. In our opinion the assumption of a widely extended MF with intensity around 10^{-7} G in the surrounding of the LG is unrealistic. Indeed the LG lie in a quite peripherical region of the LSC and it is neither within a rich cluster nor within a strongly radio emitting region. So far these are the only extended systems where observational evidence of MF with strength comparable or larger than 0.1 μG have been found.

3. Constrained simulation in the LSC

Realistic maps of expected UHECR deflections by EGMF as a function of distance to plasuable sources are highly desirable. Ideally, such maps should reflect obsreved distribution of galaxies and clusters and therefore different kind of simulations is needed. A promising approach is that of *constrained simulations*, i.e. simulations with initial conditions constrained to reproduce the observed large-scale structures in the nearby universe. Simulations of this kind have been already performed for the collisionless DM and the gaseous components of the LSC (see e.g.[6,8]) which succeed to recover the main observed structures starting from initial conditions at high redshift compatible with standard cosmology.

We are now working to produce a fully MHD constrained simulation of the LSC. Our code incorporates the MSPH technique [4], which was developed to follow MF evolution in simulated galaxy clusters, into a constrained N-body simulation of the DM and the gas in the LSC. Hopefully, at the end we will have simulated 3D maps resembling real local structure of MF fields. Once we will be in possession of such maps we will trace UHECR trajectories through the magnetic web. We will not limit ourselves by UHECRs sources located inside the LSC. In particular, we are interested to find out if and when correlations of charged UHECR with BL Lacs, found in Ref. [10], are compartible with expected EGMF structure. In other words, one of our main goals is to produce maps of expected UHECR deflections for a wide range of source distances.

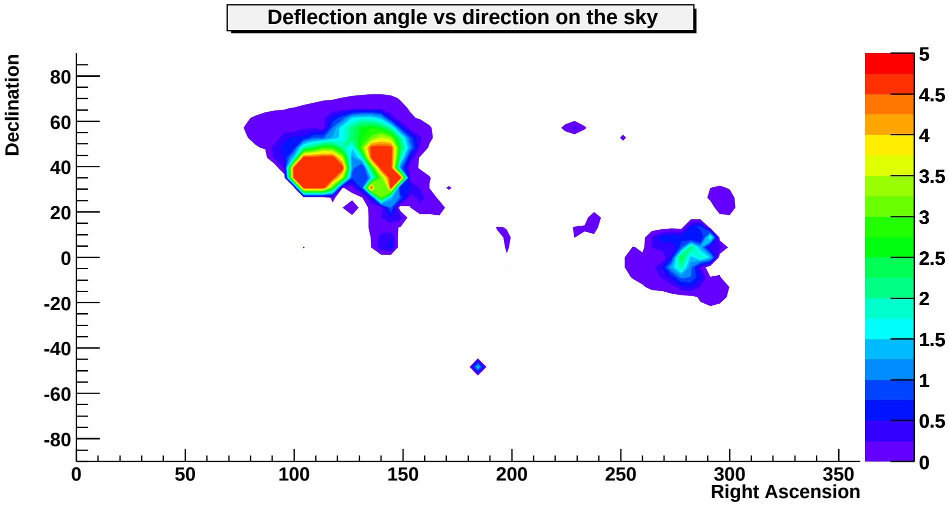

Fig. 1. Deflection angle as a function of the direction.

We will present detailed results of our simulation in the course of ICRC2003. We provide here a sample of our simulation. Fig. 1 represents a map of deflections of protons with energy $E = 4 \times 10^{19}$ eV derived from a Virgo like cluster, seen from 5 Mpc. The MF intensity at the cluster center corresponds to $\sim 1\ \mu$G which is representative of a clusterized region. Rays have been propagated about 10-15 Mpc in each direction. Deflections larger than 5 degrees are cut at this value to increase dynamical range of the plot for small deflections.

Bibliography

1. Berezinsky V., Gazizov A. Z. and Grigorieva S. I., arXiv:astro-ph/0210095
2. Blasi P., S. Burles S. and A. V. Olinto A.V. 1999, Astrophys. J. **514**, L79
3. Clarke T.E., Kronberg P.P. and Boehringer H. 2001, Astrop. J. **547**, L111
4. Dolag K., Bartelmann M. and Lesch H., 2002, A&A **387**, 383
5. Kolatt T., 1998, Astrophys. J. **495**, 564
6. Kravtsov A.V., Klypin A.A. and Hoffman Y., 2002, Astrop.J., **571**, 563
7. Kronberg P.P., 1994, Rep. Prog. Phys. **57**, 325
8. Mathis H. et al., 2002, MNRAS, **333**, 739
9. Sigl G., Miniati F. and Ensslin T., arXiv:astro-ph/0302388
10. Tinyakov P.G. and Tkachev I.I. 2002, Astropart. Phys. **18**, 165