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Magnetic Field in the Local Universe and the Propagation of UHECRs

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We construct a model of extragalactic magnetic fields using a magneto-hydrodynamical simulation of cosmic structure formation that realistically reproduces the positions of known galaxy clusters in the Local Universe. We find excellent agreement between RMs of our simulated clusters and observational data. By tracing the propagation of UHE protons in the simulated MF we construct full-sky maps of expected deflection angles of protons with arrival energies $E = 10^{20}$ eV and $E = 4 \cdot 10^{19}$ eV. We argue that over a large fraction of the sky the deflections are likely to remain smaller than the present angular resolution of air shower experiments.

1. Introduction

Although the chemical composition of the UHE primaries flux is still uncertain, several arguments suggest that considerable fraction of this flux reaching the Earth is made by protons. As a consequence, intervening magnetic fields (MFs) should bent their trajectories affecting both the arrival angular distribution and the energy spectrum. While Galactic MFs with $B_{\rm gal} \sim 1\ \mu$G are not expected to produce too large deflections of protons at highest energies, Inter Galactic Magnetic Fields (IGMFs) might give rise to significant effects. Indeed, although it is generally believed that IGMF strength is smaller that Galactic fields, their extension and correlation length can be considerably larger.

Unfortunately, very little is known about IGMF properties. 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 intra-cluster MF (see e.g. [1]). Outside clusters, only loose upper limits on the IGMF strength are available [2] which allow for considerable deflections even of protons with extremely high energies.

Until recently the possible effects of IGMFs on the propagation of UHECR have been modeled by assuming a statistically homogeneous field with a cellular structure, with a Kolmogorov power spectrum at scales smaller than the cell size, and a uniform correlation length and rms field strength. None of these assumptions, however, is well supported by observational or theoretical arguments. For these reason several groups started to develop physically more realistic models based on numerical simulations [3, 4, 5] combining the magneto-hydrodynamics (MHD) of the magnetized IGM with N-body simulations of the driving gravitational dynamics of the dark matter. However, due to the low resolution in the galaxy cluster core and the absence of constrained initial conditions, these simulations did not allow an unambiguous normalization of IGMF absolute strength and the construction of realistic maps of UHECR deflections. In this contribution we present the results of a new type of simulation which has solved these caveats.

2. MHD simulations of the Local Universe

The basic hypothesis in our approach is that the MFs observed in galaxy clusters are the outcome of a Magneto-Hydro-Dynamical (MHD) amplification process which started from a seed field generated at high redshift, before galaxy clusters formed as gravitational bound systems ($z \gtrsim 2-3$). The seed field is expected to be amplified by the compression of the gas, due to flux conservation in the highly ionized IGM, as well as from the induction produced by the shear flows driven by the cluster hierarchical accretion. This process has been previously studied [6] for individual clusters by combining conventional N-body simulations for the dynamically dominant dark matter component with the MHD of the magnetized gas, using the Magnetic Smooth Particle Hydrodynamics (MSPH) technique. Such simulations succeeded to reproduce the basic features of observed RMs. In particular, obtained radial profile of RMs does nicely fit the observed ones. Furthermore, these simulations predicted an almost linear correlation between X-ray determined cluster temperature and RMs which was also confirmed by observations [7].

In order to get a, as much as possible, realistic map of MFs in the local Universe we combined [8, 9] MSPH with an N-body *constrained* simulation of the dark-matter. The initial conditions which we used for density fluctuations in a Λ-CDM Universe are similar to those adopted by Mathis et al. [10] in their study of structure formation in the Local Universe. It was demonstrated that the resulting final state provides a good match to observations, making it possible to identify most of the prominent halos and structures found within the simulation with known galaxy clusters and superclusters of the Local Universe. In particular, this setup removes the arbitrariness in choosing the observer position inherent to unconstrained simulations, which is crucial step towards realistic estimate of expected UHECR deflections by extra-galactic magnetic fields.

The volume that is constrained by the observations covers a sphere of radius ~ 115 Mpc, centered on the Milky Way. This region is sampled with high resolution where needed. We stress that in the adaptive SPH simulation scheme the mass and length resolution get improved in the high density regions. The most massive clusters in our simulations are resolved by nearly one million DM and gas particles. The maximal gravitational force resolution was set to be $10\,\mathrm{kpc}$, which is comparable to the inter-particle separation reached by the SPH particles in the dense centers of our simulated galaxy clusters. The region outside the constrained volume is embedded in a periodic box of ~ 343 Mpc on a side and is described with low resolution; it serves to represent the long range gravitational tidal forces.

By extracting the most massive clusters, within a temperature range of $\approx 3-8\ \mathrm{keV}$, and examining the properties of the MF evolved in these systems, we confirm findings from earlier work. Radial profiles of the MF strength are similar to that of the gas density in the outer parts, but the central magnetic field value strongly scales with the cluster temperature. During cluster formation, the MF seed is not only amplified by adiabatic compression but also by shear flows that drive magnetic induction, a process that is ultimately powered by anisotropic accretion and merging events. The initial field geometry is wiped out completely by the violent cluster formation history, a result that is almost independent of the exact mechanism for generating the initial magnetic seed field, provided it is generated early enough, say before $z \sim 3$. This makes the strength of the comoving intensity of the seed field, B_0, essentially the only relevant free parameter of our model.

We constructed synthetic Faraday rotation measures from the simulated clusters and compared them to a variety of observational data. We demonstrated that a comoving seed field of $B_0 = 0.2 \times 10^{-11}$ G reproduces the observed amplitude, correlation with other observables, and the radial scaling of rotation measurements found in galaxy clusters very well.

3. Deflections of UHE proton primaries

Having a realistic 3D map of MFs in the Local Universe, we can construct associated maps of deflections of charged particles under the action of the Lorentz force. We considered protons with arrival energy $E = 4 \times 10^{19}$ eV and $E = 1 \times 10^{20}$ eV. Corresponding maps are presented in Fig. 1. Accumulated deflections were computed along rectilinear paths. This is a reasonable simplification since we are not interested in actual

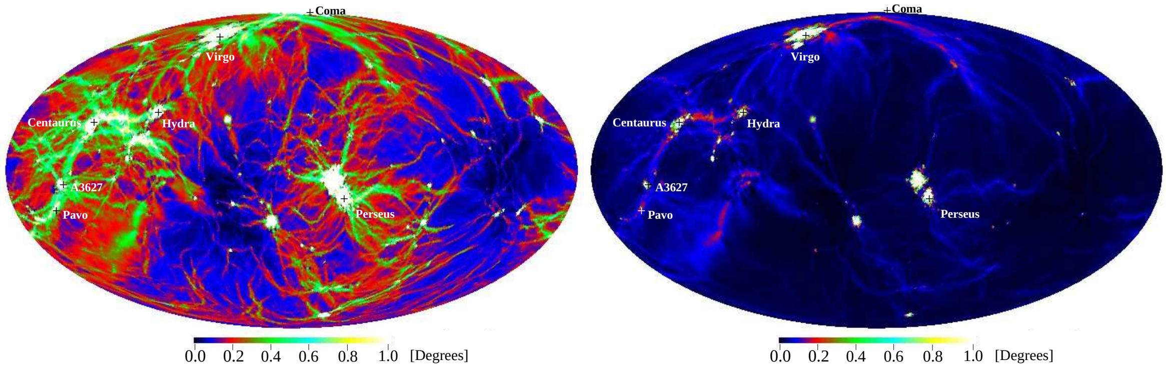

Figure 1. Full sky maps of expected deflection angles for protons with the arrival energy $E = 4 \times 10^{19}$ eV (left panel) and $E = 1 \times 10^{20}$ eV (right panel). The coordinate system is galactic, with the galactic anti-center in the middle of the map.

source positions, but rather in finding directions with small deflections. For the same reason, we distribute sources uniformly over a sphere around ovserver. The radius of a sphere corresponds to the maximal feasible propagation distance. We choose this distance to be 100 Mpc for $E = 1 \times 10^{20}$ eV. This distance corresponds to an energy at the source of $E_{\rm source} = 1 \times 10^{22}$ eV which we think to be a generous upper limit to the maximal acceleration energy of protons (a ten times smaller, and perhaps more reasonable, value of $E_{\rm source}$ would correspond to $d_{\rm max} \sim 80$ Mpc giving rise only to a minor change of the deflection map). Clearly, physical sources can be located at a smaller distances, but in this case deflections can only be smaller than those represented in our map. The deflection map of protons with arrival energy $E = 4 \times 10^{19}$ eV was obtained by putting sources at a distance of 110 Mpc, which is the limit of our simulation volume.

Since protons with $E \approx 4 \times 10^{19}$ eV can travel over hundreds of Mpc with small energy losses, the UHECR flux at this energy is expected to be dominated by sources at distances well beyond 110 Mpc. In order to estimate to which extent the angular correlations of the arrival directions of primaries with the source positions is expected to be preserved beyond this distance, we extrapolated the distribution of deflection angles to larger distances. The relevant quantity is the fraction of the sky area $A(\delta_{\rm th}, d)$ over which deflections larger than $\delta_{\rm th}$ are found in our deflection maps. The extrapolation was possible thanks to the self-similar behavior of A as a function of the distance d, observed in our simulations for $35 < d/{\rm Mpc} < 110$, namely $A(\delta_{\rm th}, d) = x^{-\beta} A(\delta_{\rm th} \times x^{\alpha}, d_0)$,, where $x \equiv d_0/d$. Self-similarity is consistent with the assumption that spatial distribution of deflectors becomes uniform at large scales. This allows to extrapolate $A(\delta_{\rm th}, d)$ up to a distance of 500 Mpc. We found that even with such large distances to the sources, the expected sky coverage by deflections larger than 1° does not exceed 30%, see Fig. 2, left panel.

4. Conclusions

We presented the results of MHD simulations of the magnetic field structure in the nearby universe. These simulations are based on the assumption that the MF observed in galaxy clusters is outcome of various processes which amplified a magnetic seed generated at high redshift, see Fig 2, right panel. We showed that our simulations reproduce a number of observations, the most relevant being the RMs in galaxy clusters.

A major systematic uncertainty of our model is the structure of the initial magnetic seed field. However, we argue that our estimates for the typical deflection angles provide a robust upper limit. Indeed, homogeneous magnetic seed field is expected to lead to the maximum deflections for a given field strength. Any tangled

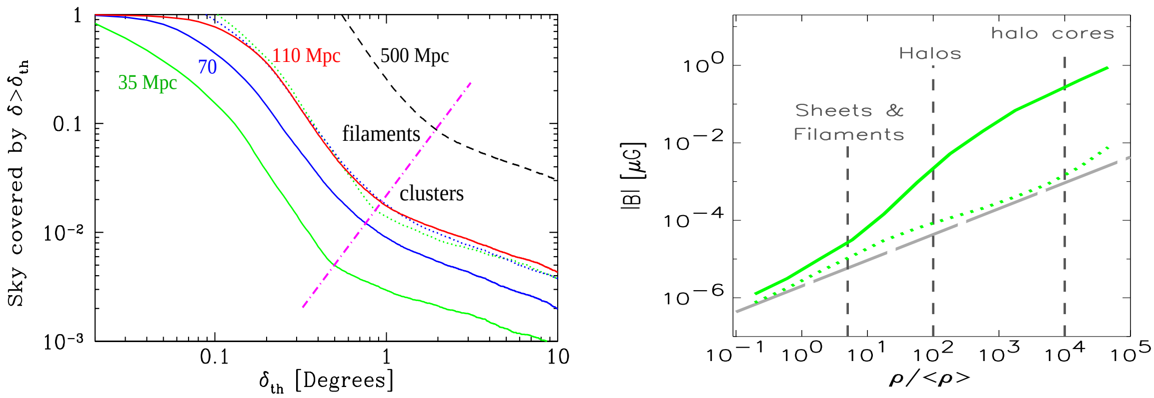

Figure 2. Left panel: cumulative fraction of the sky with deflection angles larger than $\delta_{\rm th}$, for several values of propagation distance. Right panel: the magnetic field strength as a function of baryonic overdensity. The long dashed line shows the expectation for a purely adiabatic evolution, the solid line gives the mean field strength at a given overdensity in our simulation, which includes the magnetic induction.

component in the seed field will reduce deflections and therefore strengthen our conclusions. Note also that our modeling neglects contributions to the intra-cluster magnetic field from local injection processes, related for example to galactic winds or AGNs, which probably occur also in the late phases of cluster formation. Such additional contributions will increase the cluster MF. If important and accounted for, this would then force us to lower the cosmological seed field in order to avoid exceeding the observational limits for the field in clusters. A side effect would then be a reduction of the field and of the deflection angles in low density regions, again strengthening our conclusions.

We expect therefore that our model provides an upper limit for typical deflections of UHE protons by the magnetic field embedded in the large-scale structure of the Local Universe. Resulting deflections of UHE protons with energies larger than 4×10^{19} eV are not big enough to prevent the pointing of UHECR sources in a significant fraction of the sky. Charged particle astronomy should be possible.

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