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MAGNETIC FIELD IN THE LOCAL UNIVERSE AND THE PROPAGATION OF UHECRS

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ABSTRACT

We use simulations of large-scale structure formation to study the build-up of magnetic fields (MFs) in the intergalactic medium. Our basic assumption is that cosmological MFs grow in a magnetohydrodynamical (MHD) amplification process driven by structure formation out of a magnetic seed field present at high redshift. This approach is motivated by previous simulations of the MFs in galaxy clusters which, under the same hypothesis that we adopt here, succeeded in reproducing Faraday rotation measurements (RMs) in clusters of galaxies. Our ΛCDM initial conditions for the dark matter density fluctuations have been statistically constrained by the observed large-scale density field within a sphere of 110 Mpc around the Milky Way, based on the IRAS 1.2-Jy all-sky redshift survey. As a result, the positions and masses of prominent galaxy clusters in our simulation coincide closely with their real counterparts in the Local Universe. We find excellent agreement between RMs of our simulated galaxy clusters and observational data. The improved numerical resolution of our simulations compared to previous work also allows us to study the MF in large-scale filaments, sheets and voids. By tracing the propagation of ultra high energy (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 4×10^{19} eV, respectively. Accounting only for the structures within 110 Mpc, we find that strong deflections are only produced if UHE protons cross galaxy clusters. The total area on the sky covered by these structures is however very small. Over still larger distances, multiple crossings of sheets and filaments may give rise to noticeable deflections over a significant fraction of the sky; the exact amount and angular distribution depends on the model adopted for the magnetic seed field. Based on our results we argue that over a large fraction of the sky the deflections are likely to remain smaller than the present experimental angular sensitivity. Therefore, we conclude that forthcoming air shower experiments should be able to locate sources of UHE protons and shed more light on the nature of cosmological MFs.

Key words : cosmology – magnetic fields – numerical simulation – UHECRs

I. INTRODUCTION

Considerable effort is presently undertaken around the world to build experiments (e.g. Auger, EUSO) 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) puzzlewhich became particularly acute with Fly-Eye and AGASA data, 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. For an overview on UHECR see the contribution by Olinto within these proceedings.

The very attractive perspective to do astronomy with UHECR might however 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 MF. Outside clusters, only upper limits on the IGMF strength are available. 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 hence evident that a better knowledge of the large-scale MF structure of the universe is called for.

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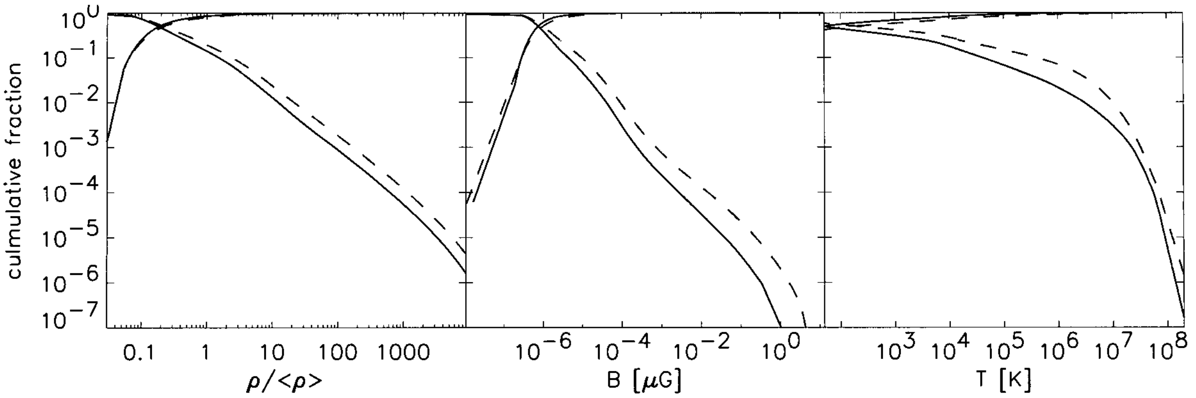

Fig. 1.— Volume-weighted cumulative filling factors of mean baryonic density (left panel), magnetic field strength (middle panel) and gas temperature (right panel). Filling factors are calculated above (decreasing curves) and below (increasing curves) a given threshold, and are shown as a functions of the corresponding thresholds. We present filling factors calculated for two boxes of 70 Mpc on a side, centered on different points in the simulation. The solid lines are for a box centered on the 'Milky Way' (observer position), while the dashed lines are for a box centered on a void within the Centaurus supercluster.

II. SIMULATION

Our simulations use similar initial conditions as Mathis et al. (2002) in their study of structure formation in the Local Universe. Their initial density fluctuations were constructed from the IRAS 1.2-Jy galaxy survey by first smoothing the observed galaxy density field on a scale of 7 Mpc, evolving it linearly back in time, and then using it as a Gaussian constraint for an otherwise random realization of the ΛCDM cosmology. The volume that is constrained by the observations covers a sphere of radius $\sim$ 115 Mpc, centered on the Milky Way. This region is sampled with high resolution dark matter particles and is embedded in a periodic box of $\sim$ 343 Mpc on a side. The region outside the constrained volume is filled with low resolution dark matter particles, allowing a good coverage of long range gravitational tidal forces.

Mathis et al. (2002) demonstrated that the evolved state of these initial conditions provides a good match to the large-scale structure observed in the Local Universe. Using semi-analytic models of galaxy formation crafted on top of dark matter merging history trees measured from the simulation, they showed that density and velocity maps obtained from synthetic mock galaxy catalogues compared well with their observed counterparts. Also, many of the most prominent clusters observed locally can be identified directly with halos in the simulation, and their positions and masses agree well with their simulated counterparts.

For the work presented here, we extended the initial conditions by splitting the original high resolution dark matter particles into gas and dark matter particles with masses of 0.69×10^9 $M_\odot$ and 4.4×10^9 $M_\odot$ respectively. The most massive clusters in our simulations are hence resolved by nearly one million particles. The gravitational force resolution (i.e. the comoving softening length) of the simulations was set to be 10 kpc, which is comparable to the inter-particle separation reached by the SPH particles in the dense centers of our simulated galaxy clusters.

Following Dolag et al. (1999,2002), we assume the existence of a cosmological magnetic seed field generated at high redshift. We take the field to be uniform on the scale of the simulation, noting that this will maximize deflections of electrically charged UHECRs. While ICMFs are independent of the adopted seed field orientation, we note that this will not always be true for low density environments on larger scales where some memory of the initial field geometry may survive. Therefore some attention will be required when discussing the generality of our final results.

III. CONCLUSIONS

As a result, the evolved simulation at $z = 0$ reflects the large-scale structure observed in the real Universe quite well, 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. This setup removes the arbitrariness involved in choosing a suitable observer position in ordinary simulations when trying to estimate how much the observed UHECRs may be deflected by extra-galactic magnetic fields.

We extracted the most massive clusters within the high resolution region of the simulation, leading to a set of 16 clusters (volume limited sample) within a temperature range of $\approx 3-8$ keV. Examining the properties of the magnetic field formed in these systems, we confirm findings from earlier work. Radial profiles of the magnetic field 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 magnetic seed field is not only amplified by adiabatic compression but also by shear

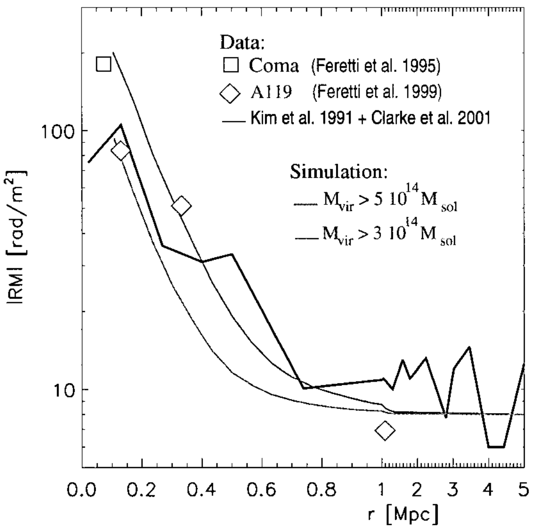

Fig. 2.— Comparison of RMs from the simulation with observations for Abell clusters, as a function of distance to the closest cluster. Smooth lines represent median values of |RM| produced by simulated clusters with masses above 5×10^{14} $M_\odot$ and 3×10^{14} $M_\odot$. The broken line represents the median of combined data taken from the independent samples in Kim et al. (1991) and Clarke et al. (2001). We also include data (diamonds) for the three elongated sources observed in A119 (Feretti et al. 1999a) and for the elongated source observed in the Coma cluster (Feretti et al. 1995)

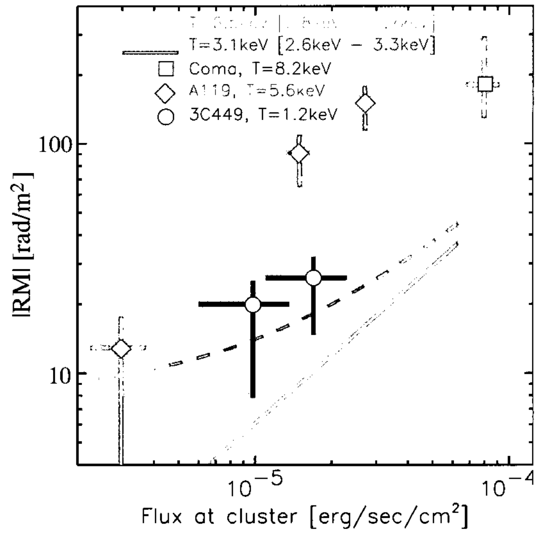

Fig. 3.— Correlation of rotation measurements with X-ray surface brightness for different galaxy clusters. The data points are observations for the two massive clusters A119 (Feretti et al. 1999), Coma (Feretti et al. 1995) and for the very poor ($T \approx 2$ keV) system 3C449, which has a central radio source (Feretti et al. 1999b). The predictions from the simulations are obtained by averaging over the 5 most massive clusters (upper gray region), or all clusters in the range 2.5 – 3.5 keV (lower gray region). The dashed line represents the predictions from the simulations, if we account for errors and noise within the real observations by adding 8 rad/m^2.

flows that drive magnetic induction, a process that is ultimately powered by anisotropic accretion and merging events. The initial field geometry is wiped out complectly 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 and the radial scaling of rotation measurements found in galaxy clusters very well. The strong dependence of the cluster magnetic field on cluster temperature leads to correlations between other measurable physical quantities. The predictions of our simulations for these correlations can also be confronted with observations. We demonstarted a good agreement for the scaling of the X-ray surface brighness with the rotation measure. Using two different models for the relativistic electron population, we also demonstrated that the simulated clusters are able to account for the observed correlation between radio power and temperature.

In low density regions outside of clusters, such as filaments, sheets and voids, no significant non-linear structure formation takes place and the magnetic seed field evolves mainly due to adiabatic compression. While within these regions large scale flows can still reorient the magnetic field, it will remain correlated with the geometry of the initial seed field. The detailed structure of the field in these regions therefore depends stongly on the properties of the seed, and thereby ultimately on the mechanism which creates the seed field in the first place.

We calculated the expected deflections of ultra high energy cosmic rays by the magnetic field in the large-scale structure of the simulated Local Universe. Given that the simulation reproduces in a realistic way positions, masses and sky coverage of the prominant clusters and superclusters of the Local Universe, we have no freedom to choose the observer position. Instead, we expect that placing the observer at the position of the "Milky Way" will provide a good model for what one expects to see in the real Universe.

We have computed full sky maps of expected deflections for particles with an energy at the detector of 4×10^{19}eV and 1×10^{20}eV. These maps show that strong deflections occur only at crossing galaxy clusters. Filaments, or sheets seen in projection, can lead to some

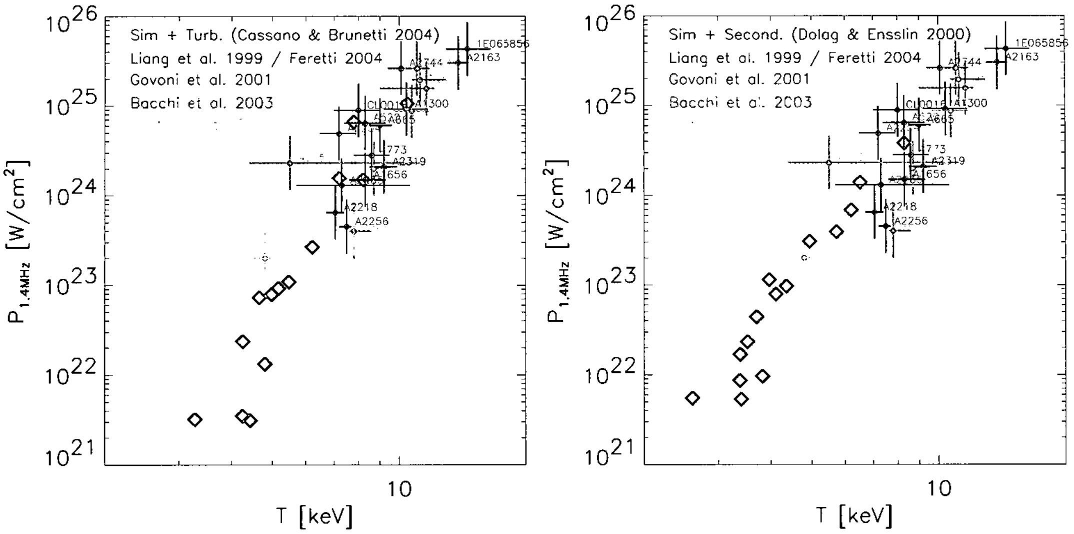

Fig. 4.— Total power of radio haloes observed at 1.4 MHz vs. cluster temperature. We plot data from Liang et al (2000), which were partially re-observed by Feretti (2004, in preperation) together with data from Govoni et al. (2001), Bacchi et al. (2003) and Venturi et al. (2003). To compare with our simulations, we applied two different models for the relativistic electron component in galaxy clusters. In the panel on the left, we show the result obtained from a primary model based on acceleration by turbulence (Cassano & Brunetti 2004, in prep.), while for the panel on the right, we used a secondary hadronic model as described in Dolag & Enßlin (2000). Both models where normalized so that our simulated Coma cluster has the same radio luminosity as observed for the real Coma cluster. The slope of the observational data is reproduced well by our simulated clusters in both cases.

noticeable deflections, but UHECRs approaching from most areas of the sky will not suffer significant deflections by the extragalactic magnetic field. For UHECRs with arrival energies of 1×10^{20}eV, we also demonstrated that, if energy losses are included, the deflection will be reduced, as the travelled distance will decrease (for UHECRs with the same injection energy) and parts of the distance will be travelled at higher energies. UHECRs with energies of 4×10^{19}eV could in principal originate from sources up to a distance of 500 Mpc, which cannot be directly probed by our simulation. We therefore extrapolated the distribution of deflection angles for these distances, still finding that most of the sky should be covered by areas with small deflections.

Using another earlier simulation, where we chose a five times larger initial seed field that pushes the magnetic field within galaxy clusters towards (or even slightly above) the upper limit of observationally allowed magnetic field strength, we verified that even in such a more extreme model a significant fraction of the sky is covered by deflections below or comparable to the resolution of current experiments (Dolag et. al 2004). In this second simulation we also used a different initial direction of the magnetic seed field, allowing us to explicitly verify that the statistical distribution of deflection angles is insensitive to the direction of the initial seed field.

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. This is because an initially homogeneous magnetic seed field is expected to lead to the maximum deflection for a given field strength. Any tangled component in the seed field will reduce the deflection and therefore strengthen our final conclusion. Note also that our modelling 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 an additional contribution will increase the cluster magnetic field. 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 final conclusion.

In summary, we hence conclude that our model provides an upper limit for the expected deflections of UHE protons by the magnetic field embedded in the large-scale structure of the Local Universe. Therefore our main conclusion is that the 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. Note that for this purpose any deflection of the UHECRs within the primary sources or within the direct embedding environment – like for sources embedded in galaxy clusters – is irrelevant, as long as these structures are smaller than the angular resolution of the experiments, which is true even for galaxy clusters, barring the exception of a very small number of nearby clusters.

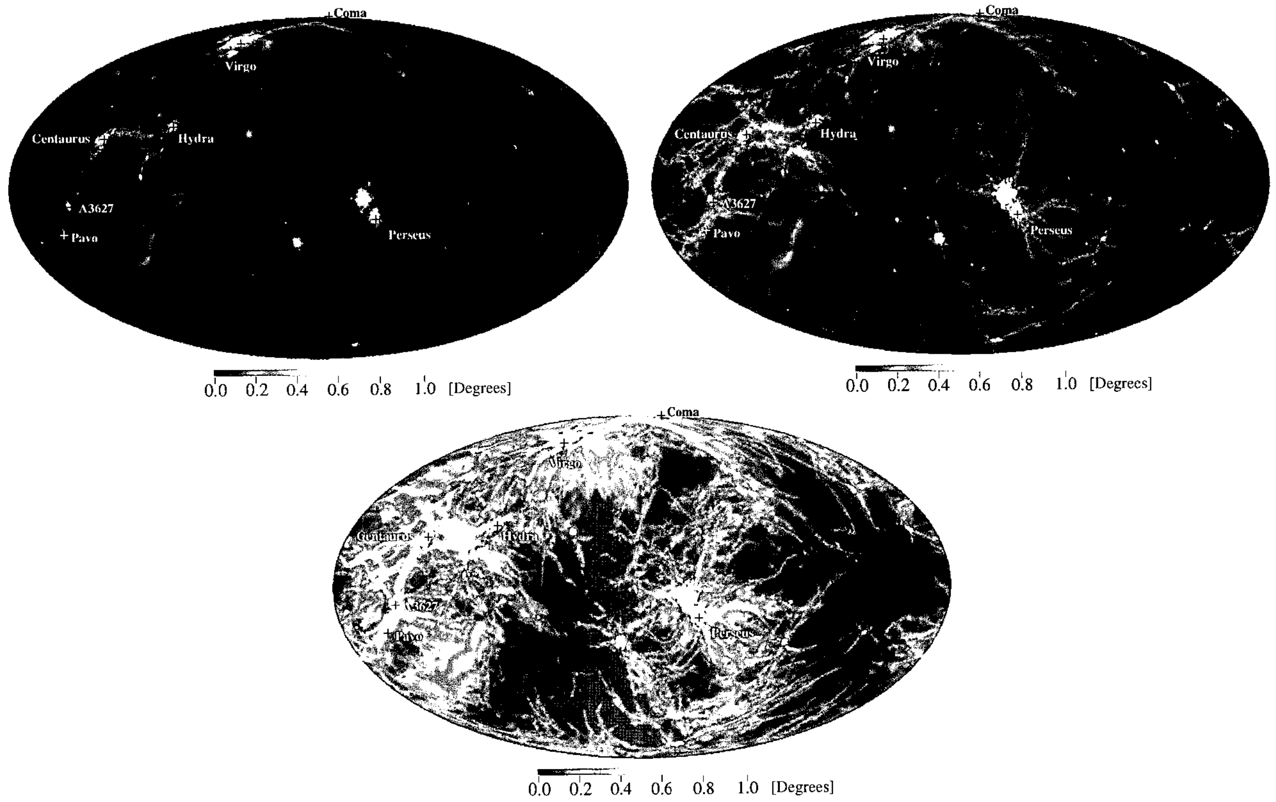

Fig. 5.— Full sky maps of expected deflection angles for protons with the arrival energy $E = 1 \times 10^{20}$ eV (upper panels). For the left panel, energy losses have been taken into account. The lower panel shown the expected deflection angles for protons with the arrival energy $E = 4 \times 10^{19}$ eV, where no energy losses have been taken into account. The coordinate system is galactic, with the galactic anti-center in the middle of the map.

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