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Magnetic fields in galaxy clusters in the SKA era

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Abstract. The study of the polarization of faint diffuse synchrotron sources, named radio halos, found in some galaxy clusters, is of paramount importance to characterize large scale magnetic fields. This is an hard task with the current radio telescopes but a next generation radio interferometer, the Square Kilometre Array (SKA), could help to shed light on the origin of cosmic magnetism. Thanks to its sensitivity, its broader bandwidth and its resolution, the SKA will allow us to perform complete and accurate studies of magnetic fields in clusters. In order to explore the potentiality of the SKA, we used state-of-art magneto-hydro-dynamical numerical simulations to produce synthetic maps of radio halos, taking into account the expected performances of the SKA1-MID in the radio band from 350 to 1050 MHz. Starting from the resulting maps, we were able to verify that radio halos could be intrinsically polarized and that SKA1-MID could detect their polarization, crucial to constraining the properties of large scale magnetic fields.

1. Introduction

Galaxy clusters are the largest gravitationally bound systems in the Universe, with typical masses of $10^{15} M_{sun}$ and volumes of about 100 Mpc^3. Their major component is Dark Matter (~80%), but they contain also an X-ray emitting thermic plasma (~15-17%), called intracluster medium (ICM), and a small percentage of luminous matter (~3-5%), due to the presence of optical and/or radio emitting galaxies.

Massive galaxy clusters form and grow through merging event, like the collision of sub-clusters. Some of the known clusters undergoing merger events show a diffuse central emission in the radio band, called radio halo. This is a faint ($\simeq 1\mu$Jy/arcsec^2 at 1.4 GHz)[1] steep-spectrum (the flux density is $S_\nu \propto \nu^{-\alpha}$, where ν is the frequency and the spectral index $\alpha > 1$) synchrotron source, with typical dimension of 1 Mpc, not associated with discrete radio sources and that does not show any optical counterpart (see [13] for a review). For this reason, radio halos are the direct proof of the existence of a non thermal component in the ICM, made by relativistic electrons, with density of the order of 10^{-10} particles per cm^{-3}, Lorentz factors $\gamma \gg 10^3$, and magnetic fields spread all over the cluster volume. Magnetic fields in merging clusters are turbulent

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[1] 1 Jy = 10^{-26} W Hz^{-1} m^{-2}

and they have a typical strength of few μG. Our knowledge of these fields is still incomplete, but it is of paramount importance to study them in order to understand the origin and the evolution of cosmological magnetic fields. Constraining their properties is possible by analyzing the Faraday rotation effect of the polarized signal of background and cluster-embedded radio galaxies. Each time that a linearly-polarized signal pass through a foreground magnetized plasma its polarization plane rotates from its intrinsic angle Ψ_0 to the observed angle Ψ, depending on the wavelength λ squared and on the rotation measure RM:

$$\Psi = \Psi_0 + RM \times \lambda^2 \tag{1}$$

This relation holds when the radio emitting plasma is not mixed with the rotating thermal plasma. The RM is proportional to the integral of the line of sight (LOS) component of the intracluster magnetic field $B_{||}$ times the thermic plasma density n_e, performed along the distance covered by the signal across the galaxy cluster:

$$RM \propto \int_0^L B_{||} \cdot n_{\mathrm{e}} \; dl \tag{2}$$

Even if this method can give good results in constraining the properties of intracluster magnetic fields, it is limited to the small areas covered by the background and cluster-embedded radio galaxies. Therefore, we can think to estimate the Faraday rotation effect of the polarized emission of radio halos, typically diffuse over the Mpc scale. Unfortunately, these objects are polarized up to a few percent and it has been possible to detect filaments of polarized emission associated with a radio halo just in three cases: in A2255 ([15], but see also [19]), in MACS J0717.5+3745 [1] and in A523 [14]. This technique is limited by the sensitivity of the current radio telescopes and to the external (beam and bandwidth) and internal depolarization. More specifically, the last case refers to the fact that the radio emitting plasma and the Faraday rotating plasma are mixed. The resulting rotation depends on the ICM depth that the linearly polarized signal crosses to reach the radio telescope: polarized signals coming from a given LOS experience a different rotation of the polarization plane and sum up incoherently, reducing the observed polarization degree.

These limits are going to be overcome with the Square Kilometre Array (SKA): the higher sensitivity and resolution, the broader bandwidth will permit to observe the polarized emission of radio halos [16, 17] and to apply sophisticated techniques to finally perform systematic and complete studies of the intracluster magnetic field. The RM Synthesis [4,6], applied to the broad bandwidth of the SKA, is a really promising technique to recover the missed polarized signal.

Making prediction on the results that the SKA will achieve is possible through numerical simulations. From cosmological magneto-hydro-dynamical simulations (MHD) one can study the evolution of magnetic fields in clusters [2,5,7,8,11,12,9,20,21,22,23], interpret observed radio and X-ray characteristics of particular systems [10,3] and produce simulated maps of radio halos [16,17].

In this work, starting from cosmological MHD simulations and numerical simulations we produced full-resolution (simulated) radio halos, in the frequency band from 350 to 1050 MHz, and their emission as it will be observed with the resolution and sensitivity of the SKA1-MID (synthetic) in the same frequency band. Starting from these simulated and synthetic radio halos, we explored the possibility that radio halos could be intrinsically polarized and we checked if their polarization could be detected with the SKA1-MID.

2. Numerical Simulations

The cosmological MHD numerical simulations studied in this work, refer to a collision between two galaxy clusters that lasts 2 Gyrs approximately. This event has been obtained as part of

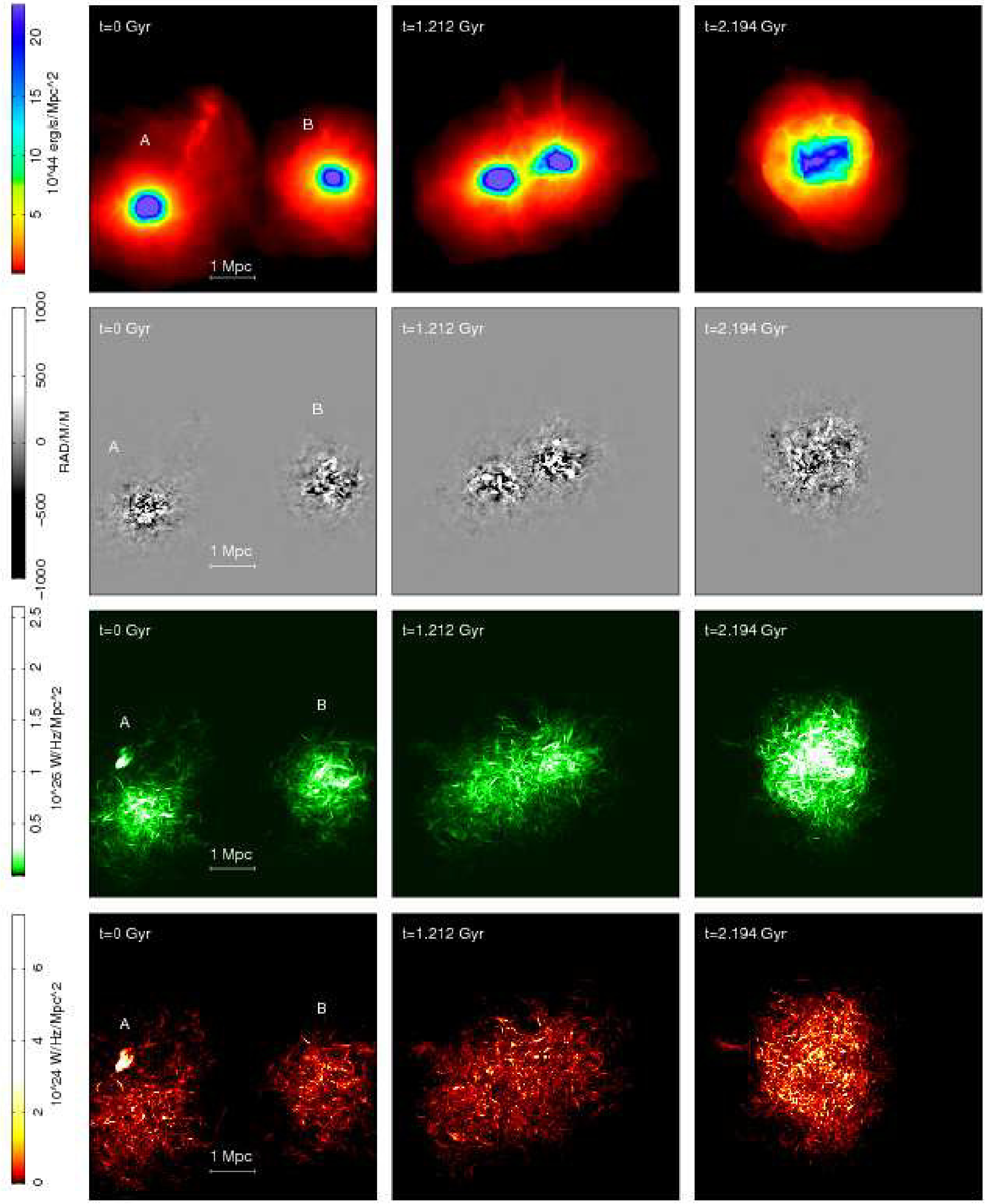

Figure 1. Simulated maps of the event: from left to right maps refer to three different stages of the collision. The first row represents the X-ray emission in the band 0.1÷2.4 keV, the spatial resolution is equal to 10.7 kpc, the field of view of the maps is equal to $(6.6\ \mathrm{Mpc})^2$. Second row shows the RM maps. Third and fourth row refer respectively to the total and linearly-polarized intensity of the radio halos in the frequency band 350÷1050 MHz.

a larger project, aimed at describing the formation of a galaxy cluster and the evolution of the intracluster magnetic field [20,21,22,23]. In this simulation the magnetic field is injected at low redshift (z$\simeq$2) from an active galactic nucleus, placed in the center of a proto-cluster of galaxies. Through the merger event the magnetic field will diffuse in the ICM and it will change its morphology and intensity, up to the μG-level. For further details on the cosmological simulation refer to [21]. Starting from the produced physical cubes of temperature, magnetic field and thermic plasma density, we simulated, thanks to the FARADAY software package [18], X-ray and radio properties of the ICM. Figure 1 showS the results obtained in three different stages of the collision (from left to right) for the emission in the X-ray between 0.1$\div$2.4 keV (first row), the RM image (second row) and the total (third row) and polarized intensity (fourth row) in the radio band from 350 to 1050 MHz, with a channel resolution of 0.5 MHz. From the last row we can infer one of the most important results of this work: radio halos could be intrinsically polarized.

In order to reproduce the images of the polarization of our radio halos as they will be observed with the SKA1-MID, we convolved the simulated maps with a Gaussian with a Full-Width-Half-Maximum of 10 arcsec and we added a noise of 1 μJy/beam [17]. In Figure 2 we report the results obtained for the radio halos in the same evolutionary stages shown in the previous figure.

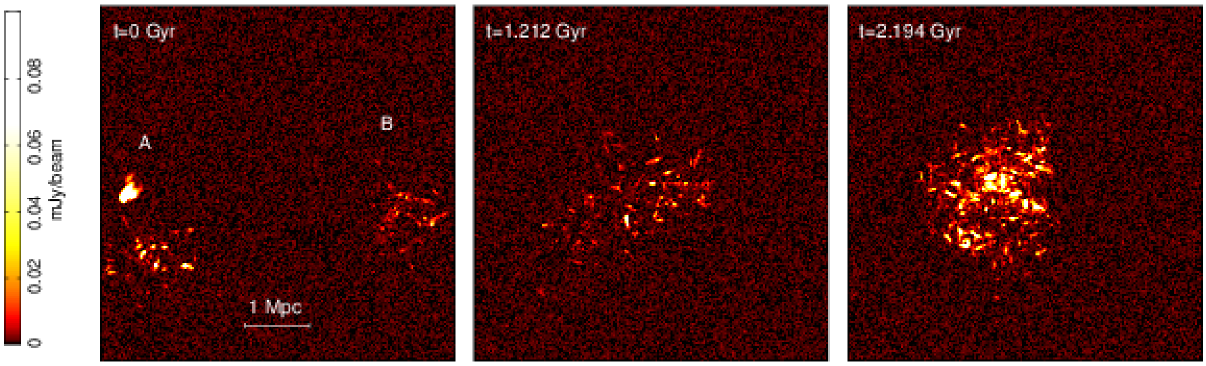

Figure 2. Polarized emission of synthetic radio halos in the frequency band 350$\div$1050 MHz, with a resolution of 10 arcsec and a noise of 1μJy/beam. The maps have been obtained after the application of the RM Synthesis technique.

From these maps, we can state that the polarization of the simulated radio halos could be detected with the SKA1-MID.

3. RM Synthesis

As already mentioned, the RM Synthesis technique has been proposed to recover the missed polarized signal of radio halos, more specifically, the one associated to the internal depolarization due to the Faraday effect. When we consider radio halos, we have to understand that the emitting and the rotating plasma are mixed, so that Eq. 1 does not hold anymore. The polarized signals emitted at different positions l along the LOS, through the cluster, experience a different rotation, called Faraday depth. It is impossible to identify the contribution of each polarized structure from the observed polarization without the application of specific techniques. The idea of the RM Synthesis is to apply different values of the Faraday depth to the polarization, in order to identify each filament and its own Faraday depth. This is done by convolving the polarization with the RM Synthesis transfer function, that represents the response that a unitary polarized signal gives, for each frequency channel of the bandwidth, assuming different values of Faraday depth. We chose an interval of Faraday depth from -1000 rad/m^2 to 1000 rad/m^2 with a resolution of 1 rad/m^2, enough to properly cover the resolution of the RM Synthesis transfer function (6.3 rad/m^2) in the radio band from 350 to 1050 MHz. Fig. 3 shows the results for the LOS indicated in the image on the left. In the last panel on the right, we report the recovered filaments of polarized signals (red) associated to different values of Faraday depth.

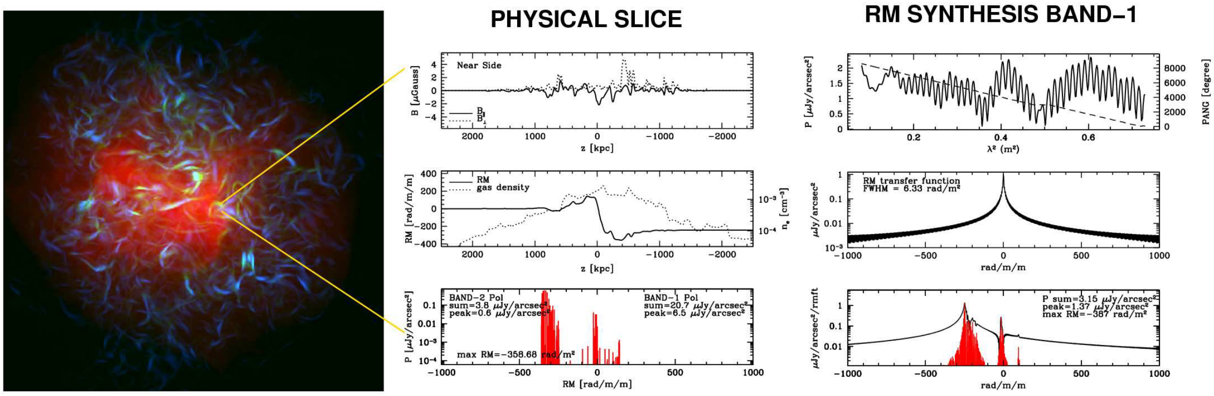

Figure 3. The image (left) shows the X-ray (red), the total (green) and polarized (blue) intensity of the cluster. The central block shows the selected LOS values of the parallel and perpendicular components of the magnetic field along the cluster length (top), the thermic plasma density and the RM values (central), for each value of polarized signal encountered along the LOS, the corresponding RM value (bottom). The right block shows the results of the RM Synthesis technique: the variation of the polarized intensity (solid line) and the polarization angle (dashed) with respect to λ^2 (top), the transfer function (central) and the recovered polarized signals along the LOS (bottom).

By using the polarization component with the maximum absolute value of the Faraday depth, we were able to estimate the RM of the cluster. In this way, we obtained a RM map (see Fig. 4) of the cluster from the polarized signal of the radio halo. The plot in Fig. 4, shows the profile of RM traced from the obtained map (full points) and the theoretical one (solid line). Assuming a simple single-scale model for the magnetic field, that consider a uniform and constant magnetic field in cells of dimension Λ_C, and a profile that scales with respect to the plasma density following a power-law trend with index η, we plotted, for comparison, the corresponding profiles (dashed lines) for three different values of the central magnetic field.

4. Conclusions

Starting from cosmological MHD simulations, by using the software package FARADAY, we reproduced the polarization properties of radio halos, during a merger event between two galaxy clusters. These radio halos show degrees of polarization as high as 10% at distances larger that 1 Mpc from the cluster center, while, toward the center, the degree is progressively lower because of the higher amount of magneto-ionic plasma. Thus, radio halos could be intrinsically polarized. From the synthetic maps of radio halos, realized by taking into account the performances of the SKA1-MID, we established that this new generation radio interferometer will have the capabilities to detect the polarization of radio halos, by applying the RM Synthesis technique to data.

The SKA will revolutionize cosmic magnetism studies. With its high resolution, sensitivity and a broader bandwidth, it will be the ideal instrument for the observation of radio halos and for the application of techniques, such as the RM Synthesis, capable to recover the polarization, fundamental to constrain intracluster magnetic fields.

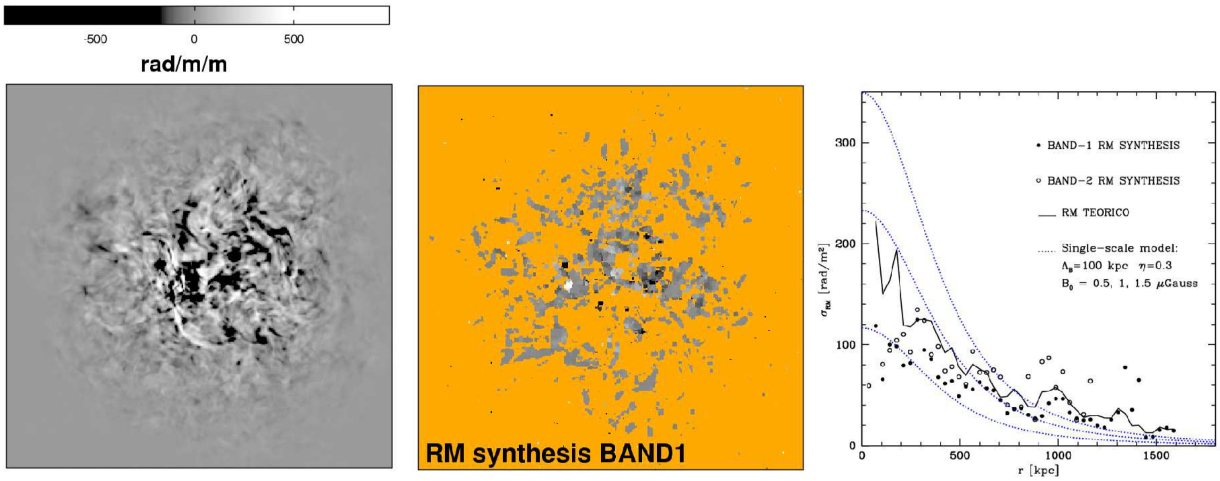

Figure 4. Theoretical RM map (left), recovered RM map from the application of the RM Synthesis (central). On the right, we plot the profile of the σ_{RM}, with respect to the cluster center, of the theoretical map (solid line), of the recovered RM map (full points) and the single-scale models with different values of the central magnetic field (dashed lines).

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