Astronomy in Focus - XXX
Proceedings IAU Symposium No. XXX, 2018
M. T. Lago, ed.

doi:10.1017/S1743921319004514

Techinques and algorithmic advances in the SKA era

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Abstract. The new generation of radio interferometers will deliver an unprecedented amount of deep and high resolution observations. In this proceedings, we present recent algorithmic advances in the context of the study of cosmic magnetism in order to extract all the information contained in these data.

Keywords. magnetic fields, polarization, methods: numerical methods: statistical

1. Introduction

Magnetism in the cosmic web is widely unknown. Magnetic fields have revealed themselves in galaxy clusters in the form of diffuse synchrotron sources and via the Faraday effect on background radio galaxies that indicate strengths of a few μG and fluctuation scales up to a few hundreds of kpc (e.g., Feretti *et al.* 2012). Beyond galaxy clusters, along filaments and in the voids of the cosmic web, some indication of their presence has been found so far but needs to be confirmed. To shed light on cosmological magnetic field origin and evolution, the analysis of magnetic properties in these environments is crucial. Nowadays, magnetic fields are thought to originate from a seed magnetic field whose strength has been amplified and geometry modified during processes of structure formation. The investigation of non-thermal components in galaxy clusters and in the low density environments between them has the potential to shed light on their evolution and formation. In the following, we give an overview of the effort done by the scientific community in the last years in this direction. In §2 and §3, we respectively describe the progress concerning the study via diffuse synchrotron emission and Faraday effect and in §4 we present the conclusions.

2. Diffuse emission

Diffuse synchrotron sources called radio halos have been observed to permeate the central volume of about 60 galaxy clusters where they reveal μG magnetic fields and ultra-relativistic particles ($\gamma \gtrsim 10^4$). Their emission permits to directly probe the intracluster magnetic field. Magnetic fields fluctuating on scales larger than the resolution of the observations are expected to generate radio halos with disturbed morphology and high degrees of polarization. Magnetic fields with fluctuation scales smaller than the beam could be responsible of regular morphology and no polarized signal (e.g., Vacca *et al.* 2010). To date only in three systems a polarized signal likely associated with the diffuse emission of the halo has been detected (Girardi *et al.* 2016). Numerical three-dimensional simulations by Govoni *et al.* (2013) indicate that, at 1.4 GHz, radio halos show intrinsic fractional polarization levels of 15-35% at the cluster center that increase in the cluster outskirts. This level of polarization corresponds to a polarized signal of about 2-0.5 μJy/beam for strong and intermediate luminosity radio halos at $3''$ of resolution but, due to instrumental limitations (resolution and sensitivity), it is hard to detect. The JVLA has the potential to detect already polarized emission in high-luminosity radio halos, while for intermediate-luminosity sources only SKA1 can succeed. The detection of faint-luminosity radio halos instead will be very difficult even with the SKA1.

Properly imaging these sources is very important to investigate the magnetization of the medium. However, standard imaging tools as CLEAN (e.g., Högbom 1974) are unsatisfactory since they rely on the assumption of a completely uncorrelated point source sky, while radio halos are diffuse and extended. In the last years new imaging algorithms have been developed based on either compressed sensing (e.g., MORESANE Dabbech *et al.* 2015) or Bayesian statistics (e.g., RESOLVE, Junklewitz *et al.* 2016), capable of exploiting the capabilities of the new generation of radio telescopes to accurately reproduce the complexity of the radio sky in total intensity as well as in polarization. This progress is particularly important in the context of the investigation of faint diffuse emission beyond galaxy clusters, from the filaments of the cosmic web. Recently, we observed a region of the sky of $8^\circ \times 8^\circ$ containing several galaxy clusters of which about ten at z≈0.1, with the Sardinia Radio Telescope (SRT) at 1.4 GHz (Vacca *et al.* 2018). The data revealed a field very bright in radio especially crowded at the location of galaxy clusters and between them (Fig. 1). To overcome the limited spatial resolution of $\sim 13'$ and separate possible diffuse emission from embedded discrete radio sources, we combined these data with higher resolution data from the NRAO VLA Sky Survey (NVSS, $45''$, Condon *et al.* 1998) and subtracted point-sources. In the resulting image, we identified 28 new diffuse sources with radio emissivity and X-ray emission 10-100 times lower than cluster radio sources. The comparison with magneto-hydro-dynamical simulations suggests that they could represent the tip of the iceberg of the emission associated with the warm-hot intergalactic medium and correspond to magnetic field strengths of ∼20-50 nG.

3. Radio galaxies

A complementary and alternative approach to investigate magnetic fields in the cosmic web is given by the analysis of polarimetric properties of background radio galaxies. While crossing the magneto-ionic media in between the source and the observer, their signal suffers a rotation $\Delta\Psi$ of the polarization angle

$$\Delta\Psi = \Psi_{\rm obs} - \Psi_{\rm int} = \phi\lambda^2 \tag{3.1}$$

where $\Psi_{\rm int}$ and $\Psi_{\rm obs}$ are respectively the intrinsic and observed polarization angle, λ the wavelength of observation, and ϕ the Faraday depth, related to the magnetic field along the line of sight $B_{||}$ and to the thermal gas density $n_{\rm e}$ of the magneto-ionic medium

$$\phi = 812 \int_0^{l[\rm kpc]} n_{\rm e}[\rm cm^{-3}] B_{||}[\mu G] dl \qquad \rm rad/m^2. \tag{3.2}$$

In the case of a screen external to the radio source, the Faraday depth does not change as a function of λ^2 and is defined as Rotation Measure (RM, Burn 1966). If the radio and X-ray plasma are mixed, the Faraday depth is no more constant and the observed

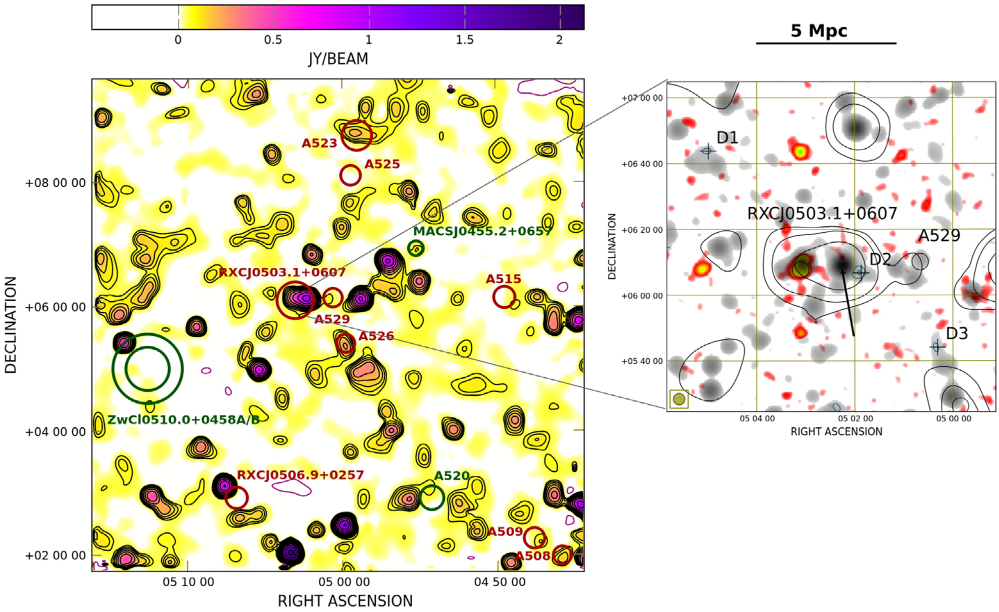

Figure 1. Left: SRT image (angular resolution $13.9' \times 12.4'$) in colors and contours at 1.4 GHz. The circles and labels identify the position of the galaxy clusters in the field of view with known redshift: in red clusters with $0.08 < z < 0.15$, in green clusters with redshift outside this range. Right: Zoom of the central region of the full field of view. SRT contours (negative in magenta and positive in black) and SRT+NVSS after compact-source subtraction contours (in blue, resolution $3.5' \times 3.5'$) overlaid on X-ray emission from the RASS in red colors and radio emission from the SRT+NVSS in grey colors. Images from Vacca *et al.* (2018).

polarized intensity may be associated with a range of Faraday depths. In this case more advanced approaches are necessary to properly recover polarimetric properties of the radio sources as QU-fitting, RM Synthesis, and Faraday Synthesis (e.g., O'Sullivan *et al.* 2012; Brentjens & de Bruyn 2005; Bell & Enßlin 2012).

In case of radio galaxies in the background of galaxy clusters, deep and high resolution polarimetric data at multiple frequencies permit to obtain detailed rotation measure images. When the Galactic contribution is negligible, these images represent a two-dimensional picture of the intracluster magnetic field and can be used to derive its power spectrum via the comparison with simulations (e.g., Vacca *et al.* 2012). Unfortunately, to date detailed Faraday depth images are available typically for one source per clusters, apart from a few exceptions (e.g., Govoni *et al.* 2006). With the SKA1, we expect a number of several tens of sources for nearby galaxy clusters ($z < 0.1$) allowing us to study the magnetic field over the complete cluster volume (Bonafede *et al.* 2015).

Thanks to the high sensitivity and resolution of the polarization surveys planned with the SKA precursors and path-finders, the upcoming Faraday depth catalogs will contain several thousands of sources and up to 7-14 million with the SKA1 (Johnston-Hollitt *et al.* 2015). These data will simultaneously carry out the information of all the structures between the source and the observer (our Galaxy, intervening sources, galaxy clusters, filaments, voids, etc). To isolate the Faraday effect due to the cosmic web different strategies have been developed as, e.g., filtering out unwanted contributions by Akahori *et al.* (2014). In this context, we recently developed statistical Bayesian approaches to disentangle the Galactic and extragalactic Faraday rotation while properly taking into account the noise (Oppermann *et al.* 2015) and to further decompose the extragalactic Faraday

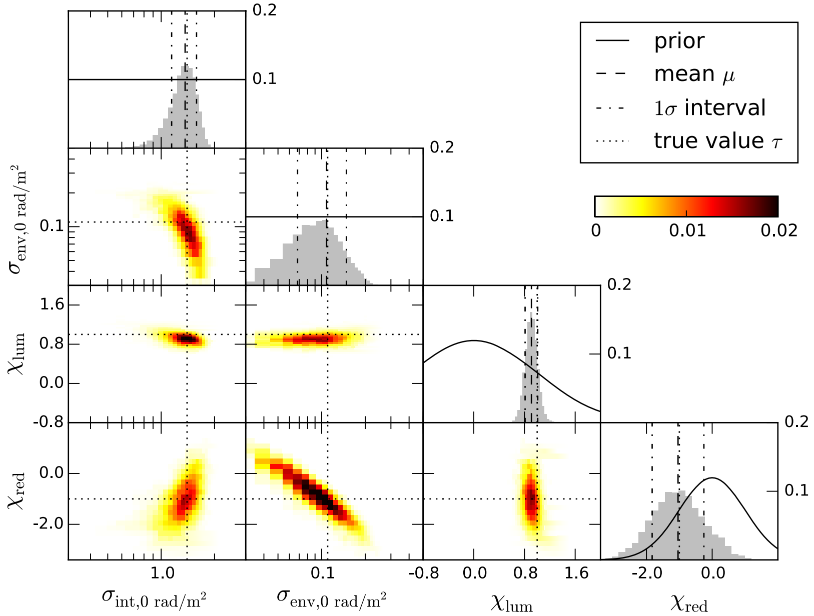

Figure 2. Example of the posterior from the algorithm presented in Vacca *et al.* (2016) for a mock catalog of Faraday depth values for 3500 sources in the frequency range covered by SKA1-LOW and an overall extragalactic contribution of 0.7 rad/m^2.

rotation in the contributions intrinsic to the emitting source, due to any intervening galaxy and associated with different regions of the large scale structure (Vacca *et al.* 2016). We showed that high-quality low-frequency data for a few thousand of sources have the potential to investigate magnetic fields with strengths of ≈0.2-2 nG associated with the large scale structure (Fig. 2).

4. Conclusions

The SKA, its path-finders and precursors are expected to permit a breakthrough in the study of cosmic magnetism, thanks to new data of unprecedented high-quality. To exploit these data and finally uncover the signature of the faint magnetic fields of the cosmic web, advanced and sophisticated techniques of analysis as those developed in the last decades are essential.

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