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Capabilities of next generation telescopes for cosmic magnetism

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Abstract. The next generation of radio telescopes offer significant improvement in bandwidth and survey speed. We examine the ability to resolve Faraday thick objects in Faraday space as a function of survey parameters. The necessary combination of $\lambda_{\rm max}$ and $\lambda_{\rm min}$ to resolve objects with modest Faraday thick components requires one or two surveys with instantaneous bandwidth 300 MHz to 750 MHz offered by next generation telescopes. For spiral galaxies, bandwidths in excess of 1.5 GHz are required. Correction for Galactic Faraday rotation must account for common gradients of order 10 rad m^{-2} per degree. How effective a new rotation measure grid is in probing the foreground depends on off-axis polarization calibration.

Keywords. magnetic fields, polarization, techniques: polarimeters, techniques: polarimetric

1. Introduction

Research in cosmic magnetism has entered a transformational period with the commissioning of new and upgraded radio telescopes that have much larger fractional bandwidth and larger field of view than the previous generation of telescopes. Among the new facilities are meter wave telescopes Low Frequency Array (LOFAR) and the Murchison Widefield Array (MWA), and centimeter wave telescopes Australian SKA Pathfinder (ASKAP) and MeerKAT, and large filled-aperture FAST. Existing telescopes that have made major upgrades for broad-band, wide-field imaging are the Jansky Very Large Array (JVLA), the Westerbork Synthesis Radio Telescope (WSRT/Apertif), the upgraded GMRT, eMERLIN, and the Arecibo radio telescope. On the horizon are the Square Kilometre Array (SKA) and the next generation Very Large Array (ngVLA).

Most of these facilities have polarization surveys planned or well underway. Naturally, these surveys are optimized for the main science drivers of the survey, given the capabilities of the observatory with which they are made. Factors that impact the effectiveness of an observatory for cosmic magnetism include the instantaneous bandwidth, operating frequency range, and the spatial frequencies probed over the observed frequency range. Important secondary factors are survey speed and available time for PI-driven follow-up observations. After all, one of the main drivers of a survey is discovery, to be followed by more detailed targeted observations.

Most extragalactic radio emission is synchrotron radiation. Its intensity and polarization contain information on magnetic field strength and structure. High angular resolution is a major factor as polarization angle structure within the beam causes depolarization. On the other hand, as we explore more of the low-surface-brightness universe, short spacing information can become a higher priority for extragalactic magnetism than it

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has been in the past. Interpretation of broad-band polarization observations of well-resolved sources requires careful consideration of the spatial frequencies sampled by an interferometer across the observed frequency range.

In this paper, I focus on two aspects of extragalactic cosmic magnetism enabled by the next generation radio telescopes: the ability to resolve a source in Faraday depth, and correction for Galactic Faraday rotation to the extent that it does not dominate the uncertainty in extragalactic Faraday rotation.

2. Resolving structure in Faraday depth

Structure in Faraday depth arises from differential Faraday rotation across the beam and from differential Faraday rotation along the line of sight (see R. Laing, this meeting, for a discussion how higher angular resolution reduces complexity, up to a point). The ability of a survey with continuous data between a minimum wavelength $\lambda_{\rm min}$ and a maximum wavelength $\lambda_{\rm max}$ to resolve an object in Faraday depth depends on Faraday depth resolution (Brentjens & De Bruyn 2005),

$$\Delta\phi = \frac{2\sqrt{3}}{\lambda^2_{\rm max} - \lambda^2_{\rm min}}, \tag{2.1}$$

and the largest observable continuous Faraday depth range in the source,

$$\delta\phi = \frac{\pi}{\lambda^2_{\rm min}}. \tag{2.2}$$

Figure 1 shows a diagram of Faraday depth resolution and largest observable Faraday depth scale. A survey occupies a particular locus in this diagram through Equations 2.1 and 2.2. We can now choose a bandwidth, and vary the lowest frequency $\nu_{\rm min}$ (or $\lambda_{\rm max}$), to define a curve that represents all surveys with a set bandwidth. Figure 1 shows four curves representing surveys with bandwidths of 50 MHz (red), 100 MHz (blue), 750 MHz (green), and 1.5 GHz (magenta). Dots on the curves mark $\nu_{\rm min} = 100$, 600, 1000, and 2000 MHz (from left to right). The black diagonal marks the locations where Faraday depth resolution is equal to the largest detectable Faraday depth scale. We can only resolve objects in a survey with a particular bandwidth if their internal Faraday depth range is between the curve and the black diagonal. Deconvolution of Faraday depth structure below the resolution limit is difficult because both the phase and the amplitude of blended Faraday depth components matter (Kumazaki *et al.* 2014, Sun *et al.* 2015).

Different classes of objects can now be painted into the diagram, with the horizontal range limited by depolarization on the low-frequency side and the black diagonal on the high frequency side. Disks of spiral galaxies for example depolarize strongly below 1 GHz, but polarization has been detected as low as 350 MHz (Giessübel *et al.* 2013). The green and yellow regions in the left panel of Figure 1 mark approximate loci for diffuse polarized emission from spiral galaxy disks. Lobes of radio galaxies may have little internal Faraday rotation, but a range of Faraday depth may arise from structure in the surrounding medium. Steep spectrum sources such as relics in clusters may be better detectable at lower frequencies, as indicated by the purple region in Figure 1.

Figure 1 shows that in practice, it is easier to resolve objects with a modest Faraday depth range than objects with a larger intrinsic Faraday depth range. The latter require multiple surveys with telescopes with instantaneous bandwidth in the range 300 MHz to 750 MHz. Transformation of wavelength from the observer's frame to the source frame at redshift z amounts to translation along the black diagonal line in the sense that the same source at high z would be less resolved in Faraday depth.

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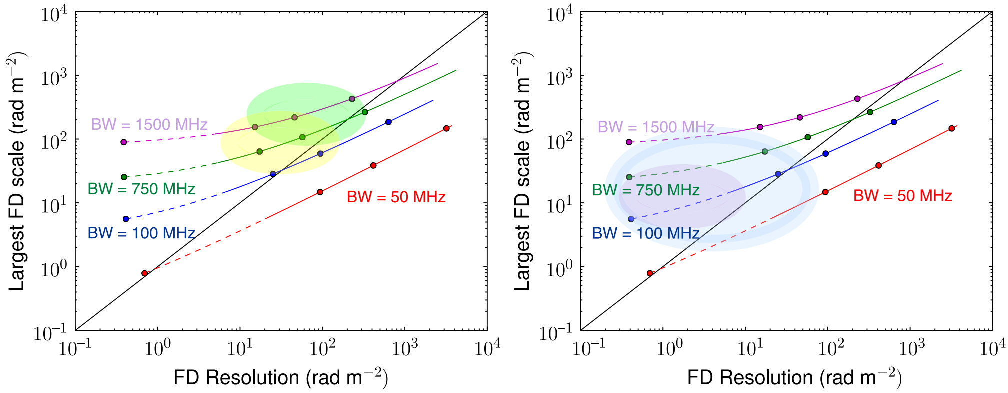

Figure 1. Diagram of Faraday depth resolution and largest observable Faraday depth scale for surveys with total bandwidth 50 (red), 100 (blue), 750 (green), and 1500 MHz (magenta). Dots mark surveys with $\nu_{\min} = 100$ MHz, 600 MHz, 1 GHz and 2 GHz (left to right). Dashed curves (frequency less than 350 MHz) are within the realm of aperture plane arrays, while the continuous curves have frequencies accessible with traditional arrays. The black diagonal line indicates where resolution is equal to the largest detectable Faraday depth scale. In order to resolve an object in Faraday depth, the Faraday depth range of the object must be between the curve and the black diagonal line. In the left panel, the green region marks the approximate parameter space for edge-on galaxies, and the yellow region the same for face-on galaxies. In the right panel, the blue region marks the approximate parameter space for lobes of radio galaxies, and the purple region a fiducial range for relics in galaxy clusters.

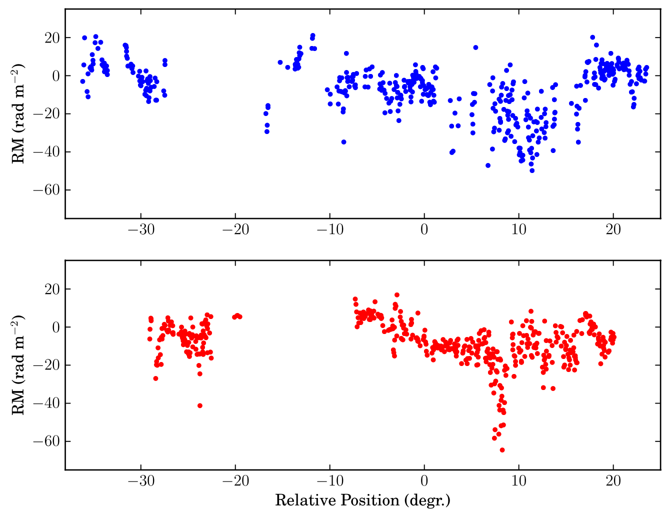

Figure 2. Variation of RM with position from high-latitude diffuse emission in the GALFACTS survey. The panels show two 0.3 degree wide strips, separated by 3 degrees in Galactic latitude in the range 65° to 70°. The horizontal axis is relative separation in the direction of Galactic longitude, corrected for latitude. Only data with strong polarized signal and RM error less than 5 rad m^{-2} are shown. Gaps in the data arise from regions with weaker signal.

3. Importance of off-axis polarization calibration

Arguably the foremost data set that next generation surveys will produce is a dense grid of rotation measures of polarized extragalactic sources across the sky (Beck & Gaensler 2004, Johnston-Hollitt *et al.* 2015). Correcting for Faraday rotation by the Galactic

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interstellar medium will be the most common application of the RM grid for extragalactic cosmic magnetism. The density of the grid and the quality of the RM data will determine the accuracy of this correction. Far from the Galactic plane, the errors in Oppermann *et al.* (2012, 2015) are of the order of 10 rad m^{-2}, which constitutes 22° rotation at 20 cm. An error in the Galactic Faraday rotation is magnified by a factor $(1+z)^2$ for the Faraday depth of a screen at redshift z, introducing significant uncertainty in the redshift dependence of Faraday depth (Hammond *et al.* 2012).

Figure 2 shows variation of RM of diffuse Galactic emission at high Galactic latitude from the GALFACTS survey (Taylor & Salter 2010). Although Faraday rotation of diffuse emission does not measure the same Faraday depth as extragalactic sources, we get an impression of the foreground RM structure on angular scales that are not yet accessible otherwise. Gradients of the order of 10 rad m^{-2} per degree and changes in the variance of RM are common on small scales. These small-scale structures cannot be recognized with the current sampling density of ∼1 polarized source per square degree. The average density of RMs in Figure 2 is ∼30 per square degree, comparable to the RM grid expected from the POSSUM survey (Gaensler *et al.* 2010, Rudnick & Owen 2014).

Constructing an RM grid that allows for consistent subtraction of Galactic Faraday rotation to the level of 1 rad m^{-2} is within reach of next generation sky surveys. The RM grid relies on sources measured across the field of view, far from the field centre where traditional polarization calibration solutions apply. In the absence of direction-dependent polarization calibration, we can expect residual leakage at the level of a few percent of total intensity at Faraday depth zero that blends with the astrophysical signal, unless the Faraday depth resolution of the survey is much better than 10 rad m^{-2} (Figure 2). This requires frequencies below 600 MHz (see Figure 1). The significance of blending of instrumental polarization with astrophysical Faraday rotation was discussed at this meeting by Y. K. Ma *et al.* Off-axis polarization calibration requires an investment by the observatory in terms of commissioning observations and software (e.g. Jagannathan *et al.* 2017). The performance of next generation telescopes for extragalactic magnetism depends in no small way on their ability to calibrate instrumental polarization across the field of view.

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