

Synchrotron Emission on the Largest Scales: Radio Detection of the Cosmic-Web

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Abstract. Shocks and turbulence generated during large-scale structure formation are predicted to produce large-scale, low surface-brightness synchrotron emission. On the largest scales, this emission is globally correlated with the thermal baryon distribution, and constitutes the ‘synchrotron cosmic-web’. I present the observational prospects and challenges for detecting this faint emission with upcoming SKA pathfinders.

Key words. Relativistic plasmas; cosmology: cosmic-web.

1. Introduction

In the current epoch roughly half of the number of baryons expected from concordance cosmology remain missing. At higher red-shifts ($z > 2$) these baryons are visible through Ly α forest observations of the photoionized intergalactic medium (IGM) and ordinary galaxies (e.g. Rauch *et al.* 1997; Weinberg *et al.* 1997; Schaye 2001). Simulations suggest that the collapsing diffuse IGM was shock heated and now resides in filaments as $T \sim 10^{5-7}$ K WHIM, where it is practically invisible at most wavelengths (Cen & Ostriker 1999, 2006; Davé *et al.* 2001). Absorption detections of the coolest WHIM components in the UV and X-ray have been reported (see Bregman *et al.* 2010, and references therein), but they give no information on the spatial distribution. However, shocks from infall into and along the filamentary structures between clusters are now widely expected to generate relativistic plasmas which track the distribution of the WHIM (Keshet *et al.* 2004; Pfrommer *et al.* 2006; Ryu *et al.* 2008; Skillman *et al.* 2011); Indeed, merger/accretion shocks are seen as polarized radio sources (the peripheral relics) at the edges of the dense X-ray gas in clusters. This radio emission also has the potential for probing into the lower density regions further from cluster cores. When such features are detected, they can be used to set limits on the pressure of the (invisible) thermal gas, delineate shock structures and illuminate large-scale magnetic fields (Rudnick *et al.* 2009).

2. The synchrotron cosmic-web

The presence of faint synchrotron emission permeating large-scale structure (LSS), which we call the ‘synchrotron cosmic-web’ (SCW), is a theoretical prediction that

predictions for the SCW. Pfrommer *et al.* (2008) and Battaglia *et al.* (2009) predict levels reaching at most a few $\mu\text{Jy arcmin}^{-2}$ in the outskirts of massive clusters at 1.4 GHz.

3. Observational obstacles and issues

Sensitivity

The predicted surface-brightnesses mentioned above, while extremely faint, are not out of reach for current radio telescope arrays. The raw thermal noise of a large array like the EVLA¹ can reach these sensitivities in a reasonable amount of time. The real problem is the spatial filtering of large-scale emission that naturally arises with interferometric telescope arrays. The Fourier transform nature of aperture synthesis means that the shortest baselines (correlation of the signal from the closest telescopes) are sensitive to the largest scale emission, but also the most sensitive to external/internal radio frequency interference (RFI). It is thus critical to obtain as many short baselines as possible, while insuring the least amount of corruption from RFI – not an easy task. The nominal largest-scale that the EVLA can detect with a short integration at 1.4 GHz in its most compact configuration (D-array) is roughly 15' (e.g., Rudnick & Brown 2009), which is 1 Mpc at $z \sim 0.06$. Thus, smooth emission associated with large-scale structure closer than $z \sim 0.06$ will be resolved out by the EVLA. This can be improved by going to lower-frequencies and/or longer integration times (more short projected baselines as the source moves away from the zenith).

Confusion

The most significant obstacle for reaching $\mu\text{Jy arcmin}^{-2}$ sensitivities is confusion, both from resolved and un-resolved sources. The RMS confusion, σ_c , from unresolved continuum sources can be estimated by

$$\frac{\sigma_c}{\text{mJy beam}^{-1}} \approx 0.2 \left(\frac{\nu}{\text{GHz}} \right)^{-0.7} \left(\frac{\theta}{\text{arcmin}} \right)^2, \quad (1)$$

where θ is the FWHM of the Gaussian beam. To overcome this limit, one must utilize sensitive observations at higher resolution in order to model and subtract the point-source contamination. Statistical reduction of this confusion is also possible (see below), as long as the sources causing the confusion are uncorrelated to large-scale structure.

Ordinary galaxies, which produce synchrotron and free-free emission of their own, can also introduce significant confusion. More importantly, this confusion is perfectly correlated with LSS. Ponente *et al.* (2011) recently calculated the integrated surface-brightness of ordinary star-forming galaxies out to $z = 10$ in an attempt to estimate their contribution to the cosmic radio background (CRB; Fixsen *et al.*

¹<https://science.nrao.edu/facilities/evla/>

2011; Seiffert *et al.* 2011; Singal *et al.* 2010). The brightness temperature due to synchrotron radiation is

$$T_{\text{syn}} = 0.1402 \text{ K} \left(\frac{\nu}{\text{GHz}} \right)^{-2.7} = \frac{c^2 I_\nu}{2k\nu^2}. \quad (2)$$

This translates into $I_\nu \sim 0.4 \text{ mJy arcmin}^{-2}$ at 1 GHz, which is well above the expected surface-brightness of filament fields. However, this includes the combined contribution from all normal galaxies out to $z = 10$, and the integrated brightness for $z < 0.3$ is an order of magnitude less. The brightness is less still when considering the emission due to a single red-shift slice. In order to deal with this confusion, one needs to either work at a resolution that resolves the galaxy emission, or estimate and subtract the contamination through other means (e.g., the radio/IR correlation). In any case, this correlated emission sets the current fundamental limit for correlation studies (see below).

Diffuse emission from the Milky Way presents yet another obstacle for the detection of the synchrotron cosmic-web. Synchrotron emission from the Milky Way dominates the SCW at all frequencies and scales, though surface-brightness fluctuations decrease at smaller angular scales (La Porta *et al.* 2008). Figure 2 compares a map of large-scale structure ($0.06 < z < 0.07$) and the corresponding galactic synchrotron emission from the Stockert 1.4 GHz survey (Reich & Reich 1986). Most of the power from the Galaxy is on angular scales $\theta > 10 \text{ Mpc}$ at these red-shifts. Interferometric observations will filter most of this emission, though small-scale galactic fluctuations are still an order of magnitude greater than the SCW. Unlike in CMB analysis, this foreground has a similar frequency behaviour to the SCW, and thus cannot be removed with template matching at other wavelengths (e.g., Gold *et al.*

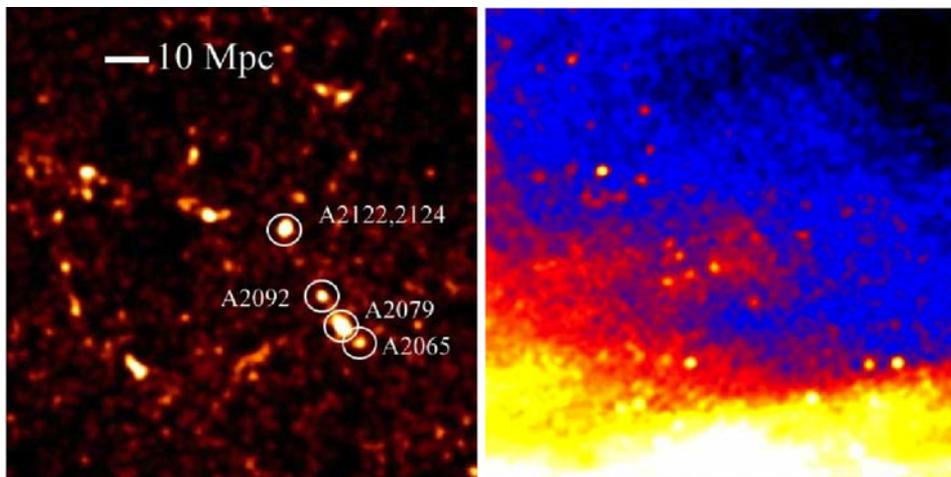


Figure 2. Center co-ordinates for each image are $16^{\text{h}}00^{\text{m}}00^{\text{s}} + 35^{\text{d}}00^{\text{m}}00^{\text{s}}$ (Brown *et al.* 2010). *Left:* The surface-density of galaxies from 2MASS with $0.06 < z < 0.07$, convolved to $36'$. *Right:* Radio continuum image of the same field at 1.4 GHz from the Stockert 25-m telescope ($36'$ resolution; Reich & Reich 1986).

2011). At the present time, statistical detection of the SCW may be the only option to get around the problem of confusion.

Statistical Methods

As is evident in Fig. 1, the SCW is spatially correlated with large-scale structure. Statistical methods can be used to infer the presence and average surface-brightness of this large-scale emission (e.g., Brown *et al.* 2010). Both stacking and cross-correlation have been used extensively in other areas of astrophysics and cosmology to detect faint, spatially correlated, emission below the noise limit of a given survey. These methods can be directly applied to the problem of detecting the SCW, though care must be taken into account for the sources of confusion mentioned above.

The method of ‘stacking’ refers to the process of averaging together independent images of some class of objects, e.g. galaxies or clusters of galaxies, whose positions have been identified at other wavelengths. Even though the images are non-detections, by averaging N images together, the signal-to-noise increases by \sqrt{N} , assuming that the source emission is spatially correlated and the image noise is truly independent. When searching for the SCW, it is not obvious what images to stack. The optical/IR distribution of galaxies can be used to trace large-scale structure, but the fact that these galaxies do not perfectly trace the diffuse thermal baryon distribution, and that the SCW is in turn not perfectly correlated with the diffuse thermal baryon distribution, means that the signal will not add perfectly coherently. This in turn means that the signal-to-noise will not increase as \sqrt{N} . The presence of radio emission from the galaxies making up the LSS (see above) means that some of the confusion noise will add coherently as well, further reducing the effectiveness of stacking. The most effective method of stacking LSS in order to detect the SCW remains to be determined, though the next generation of all-sky radio surveys (see below) may provide sufficient sky coverage and sensitivity to make stacking a promising technique.

Cross-correlation is another technique to statistically detect emission below the noise level of a map. The widest use of this technique has been in the CMB community, where it has been used to detect the late Integrated Sachs-Wolfe (ISW) effect (e.g., Crittenden & Turok 1996; Boughn & Crittenden 2004; Nolta *et al.* 2004; McEwen *et al.* 2007; Liu *et al.* 2011). The task of cross-correlation is to assess the extent to which image \mathcal{R} (e.g., an all-sky radio map of synchrotron emission; Fig. 3 (left)) is correlated with image \mathcal{G} (e.g., a map of the distribution of galaxies at some red-shift; Fig. 3(right)). However, what one wants to do is assess the probability that a signal m , represented by a model that is some function of image \mathcal{G} , is present in image \mathcal{R} . Cross-correlation can be performed in many ways, and has been attempted successfully in real (e.g., Nolta *et al.* 2004), harmonic (Afshordi *et al.* 2004), and wavelet (McEwen *et al.* 2007) space. The benefit of cross-correlation, relative to stacking, is that it makes use of all the data available to assess the probability. However, interpreting the results of a cross-correlation experiment is more difficult, as one must account for all possible sources of correlation. For example, Fig. 3 shows that, on large scales, the surface-density of galaxies (right) is anti-correlated with the synchrotron brightness (left), because the latter also traces areas of high optical depth through the Milky Way. It is this effect that gives rise to the need to mask low

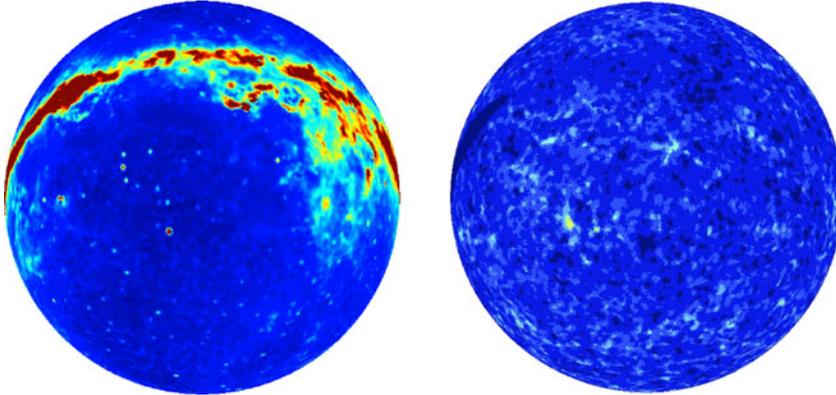


Figure 3. *Left:* WMAP 7-yr K -band synchrotron map (image \mathcal{R} , see text); *Right:* 2MASS surface density of galaxies ($13 < K < 13.5$; image \mathcal{G}). The goal of cross-correlation is to detect evidence of our model for the SCW, which is a function of \mathcal{G} , in map \mathcal{R} .

galactic latitude regions of both images before cross-correlation, as is typically done in CMB analysis. The presence of correlated confusion mentioned above means that high resolution radio images are needed in order to make cross-correlation a feasible technique for detecting the SCW.

4. The future

A number of pathfinders for the Square Kilometre Array (SKA) are being built and tested around the world: ASKAP², EVLA³, LOFAR⁴, LWA⁵, Meerkat⁶, MWA⁷, and more. These telescopes will push the parameter-space of radio observations in the areas of sensitivity, sky coverage, and frequency. Below, I will briefly address how each of these frontiers can be used to probe the SCW, and which telescopes are relevant for these advances.

Deeper

Deeper observations with higher resolution of individual cluster outskirts and filaments are needed for direct detection of the synchrotron cosmic-web. Targeted observations of the peripheries of massive clusters and super-clusters is the most

²<http://www.atnf.csiro.au/SKA/>

³<https://science.nrao.edu/facilities/evla>

⁴<http://www.lofar.org/>

⁵<http://www.phys.unm.edu/lwa/index.html>

⁶<http://www.ska.ac.za/meerkat/>

⁷<http://www.mwatelescope.org/>

promising method for direct detection of the SCW, as these are the locations of the most powerful shocks and turbulence during LSS formation. The EVLA, LOFAR with its international baselines (eLOFAR), and eventually Meerkat, will be ideal for these observations. The removal of confusion using the long baselines, as mentioned above, will still be a big obstacle, and it has not been demonstrated that this can be done to reach $\mu\text{Jy arcmin}^{-2}$ surface-brightness sensitivity yet.

Wider

Planned all-sky surveys with upcoming SKA pathfinders will be commencing in the coming years. These surveys will allow statistical detection through cross-correlation and stacking, subject to the constraints outlined above. The deepest of these surveys may also be able to directly detect the top end of the ‘cosmic-shock’ luminosity function (Battaglia *et al.* 2009; Skillman *et al.* 2011), which may provide candidate sites for deeper follow-up observations. The Evolutionary Map of the Universe (EMU)⁸ survey with ASKAP (Norris *et al.* 2011), as well as the Surveys Key Science Project with LOFAR (Heald *et al.* 2011) are two such surveys.

Lower Frequency

The steep spectral indices of expected in the SCW ($I_\nu \sim \nu^{-\alpha}$, where $\alpha > 1$) relative to both point and diffuse sources of confusion means that, if resolution is not sacrificed too much, going to lower frequencies is ideal for detecting synchrotron emission in LSS. Telescopes such as eLOFAR, the LWA, a possible low-frequency upgrade to the EVLA (Kassim 2010), and the combination of MWA data with high resolution Giant Metrewave Radio Telescope (GMRT) observations, will operate in this regime. Working at the lowest frequencies, however, will likely result in the sacrifice of polarization information (e.g., Farnsworth *et al.* 2011).

Higher Frequency

At frequencies greater than 1 GHz, radio observations will benefit from higher resolution, but suffer from lower intrinsic source surface-brightness. Polarization observations will provide the biggest gains, especially when searching for the shock-structures themselves. Structure formation shocks onto and along filaments are predicted to be narrow, flat spectrum ($\alpha < 1$), and highly polarized (e.g., Ryu *et al.* 2003; Skillman *et al.* 2011). Therefore, both direct and statistical detection of these shocks can ideally be performed at $\nu > 1$ GHz. The Polarization Sky Survey of the Universe’s Magnetism (POSSUM; Gaensler *et al.* 2010) with ASKAP, which will produce polarized maps of the southern sky from 1130–1430 MHz, is one such survey that has the potential to detect these polarized cosmic-shocks.

⁸<http://www.atnf.csiro.au/people/rnorris/emu/>

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