Unraveling the Synchrotron Cosmic Web puzzle with LOFAR Low Band Antenna array

Mohan Agrawal

Abstract

What led to the creation of large scale (extragalactic) magnetic fields in the universe is not yet understood, and represents a critical gap in our understanding of early universe physics, and physical structure formation theory. Observations of synchrotron radiation from filaments connecting galaxy clusters could provide information to discriminate amongst magnetogenesis models. However, due to faint and diffuse nature of these filaments, their observation has proven challenging. We propose our observation as a follow-up to a surprising result in 2021 that claimed simultaneous $\approx 5\sigma$ detection of synchrotron cosmic web in data from 3 instruments, 2 in radio and 1 in x-ray (MWA phase 1, OVRO-LWA, ROSAT). More surprisingly, this detection could not be independently reproduced using data from MWA phase 2, which is a more sensitive radio telescope than MWA-I and OVRO-LWA. We request co-observing[1] a patch of sky between $120 \leq RA \leq 240$ and $0 \leq \delta \leq 30$ in LOFAR Low Band Antenna Sky Survey (LoLSS), which will image in 42-66 MHz band, reaching a depth of 1 mJy beam^{-1}. LoLSS will be more sensitive than all previous experiments in this band, making its data perfect for establishing an independent constraint on synchrotron cosmic web surface brightness.

1 Scientific Justification

In the last 3 decades, observations of Cosmic Microwave Background, and galaxy surveys have collected substantial evidence to support the hypothesis that matter at the largest scales in the universe likes to cluster together. Galaxies reside in clusters and groups, and these clusters are connected by long, diffuse, galactic filaments, interspersed with large voids. Leading N-body magnetohydrodynamics simulations of structure formation also predict that nearly 40% of universe's mass at low redshifts ($z < 0.1$) resides in these filaments, which are located at the outskirts of clusters and made up mostly of highly ionized plasma. These diffuse structures are collectively referred to as the Warm Hot Intergalactic Medium (WHIM). Since the temperature of WHIM ($10^5 - 10^7$ K) is lower than that of intracluster plasma, a direct detection of WHIM in x-ray or optical studies has proven to be difficult. However, WHIM is predicted to have an observable radio signature.

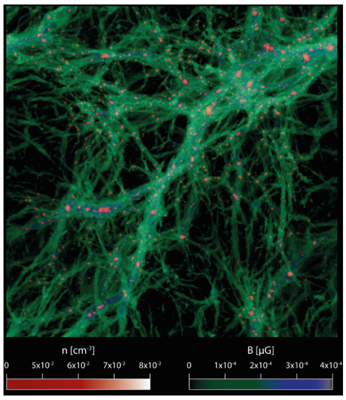

Figure 1: 3-D rendering of gas and magnetic field in 100Mpc^3 from MAGCOW simulation. From Vazza et al. (2021)

Cosmological structure formation simulations predict the existence of strong accretion shocks in these filaments. These shocks accelerate the plasma electrons to relativistic energies, causing them to emit synchrotron radiation as they interact with weak intercluster magnetic fields. **Detection of this so-called "Synchrotron Cosmic Web" (SCW) is a high priority research area because it will take us one step closer to answering one of the biggest open questions in modern astrophysics: how did large scale magnetic fields that pervade the universe emerge?** An SCW detection will directly constrain the poorly understood dynamics intercluster magnetic fields, which in turn are hypothesized to have emerged from a primordial seed magnetic field. Therefore, allowing us to constrain various models of magnetogenesis. SCW is a rich observational probe that will also let us study properties of diffusive shocks in galaxy filaments, cluster mergers, cosmic ray population, and models of magnetic fields at various (galactic to intercluster) scales.

[1]https://science.astron.nl/telescopes/lofar/observing-with-lofar/regular-proposals/upcoming-cycle/#LBACoobservingstrategy

Currently, there are claims of direct detection of intercluster structures like "radio bridges and ridges" Govoni et al. (2019); Botteon et al. (2020), but there's no reported direct detection of SCW. Vernstrom et al. (2017) cross-correlated 180-MHz radio images from Murchinson Widefield Array (MWA) Phase I with galaxy number density maps from 2MASS and WISE surveys, and put an upper limit on SCW surface brightness of 0.01-0.3 mJy arcmin^{-2}. A realistic 5 sigma detection would require sensitivity of the order 10 μJy arcmin^{-2}, which is out of reach of currently operational experiments. However, there are several indirect detection techniques that have made progress towards constraining SCW emission and intercluster magnetic field strength. Vazza et al. (2021)

We propose our observation as a follow-up to a surprising result obtained by Vernstrom et al. (2021) (V2021 hereafter) using one such indirect technique known as image stacking. V2021 reported simultaneous $4-5\sigma$ detection of SCW in 5 maps: MWA phase 1 (in MHz: 154, 118, 88), OVRO-LWA phase 1 (73 MHz), and ROSAT (x-ray: 0.1-2.4 keV). E.g., for OVRO-LWA, they reported excess radio emission that cannot be attributed to clusters as 1.1 ± 0.2K or 4.0 ± 0.9 mJy beam^{-1}. Furthermore, they obtained a spectral index of the excess emission as $\alpha = -1 \pm 0.1$, which, they note, matches well with what's expected for diffuse filamentary emission driven by accretion shocks. After performing several null tests, and excluding various systematic biases, they attributed the radio excess to SCW. (We note that 4.0 mJy beam^{-1} value obtained by V2021 is consistent with the upper-limit put by Vernstrom et al. (2017) when 16' beam size of OVRO-LWA at 73 MHz is taken into account.) **As convincing as V2021's results sound, when Hodgson et al. (2022) tried to reproduce the result using the same stacking technique with MWA phase 2 data, they found no statistically significant excess emission.** This result was even more surprising because MWA phase 2 offers twice the resolution of phase 1, which should lead to a lower confusion level, and thus a deeper survey. Therefore, the fate of first high-significance SCW detection currently hangs in balance.

If V2021's result is true, it has far-reaching theoretical consequences. The strength of the radio excess observed by V2021 was 30-40 times higher than what they obtained by running state-of-the-art cosmological simulations. Their observations put the strength of filamentary magnetic field as 20-60 nG, which would require a higher primordial seed magnetic field than expected from those simulations. Such a discrepancy in radio brightness would suggest that one (or more) of the models of intercluster magnetic fields, accretion shocks, or primordial magnetogenesis is severely lacking.

Given the immense scientific payoff of a detection, we believe it is of utmost importance to follow-up V2021 and Hodgson et al. (2022) observations with a fresh set of data that could provide an independent set of constraints. A non-detection would be equally important as it would allow the community to start examining why V2021 were able to detect the signal in 5 maps from 3 distinct instruments.

For our analysis, we would continue using the image stacking method, not only to enable direct comparison with previous results, but also because stacking method has a track-record of demonstrated success outside of radio astronomy in several fields. For example, stacking method has been used to obtain confirmed detection and/or measurements of: thermal Sunyaev-Zeldovich effect in filaments De Graaff et al. (2019), and mass of filaments using weak lensing Clampitt et al. (2016).

2 Technical Justification

V2021's stacking method involves subtracting a model of a physically close pair of Luminous Red Galaxies (LRGs) from an image of the pair, and then averaging several such images. Thus, the primary requirement for stacking analysis is a catalogue of LRG images. For our analysis, we plan to use the expanded LRG catalogue used in Hodgson et al. (2022), containing 1.4 million LRGs (shown in fig. 2). LOFAR is currently the only operational radio telescope capable of high-resolution (< 1 arcmin) interferometry at very low frequencies (< 80 MHz). SCWs typically appear as long extended arcs of emission, with a well-defined edge along the accretion shock, suitable for detection with high-resolution interferometers. V2021's numerical simulations put the width of these shock fronts as approx. 3'. With LOFAR's 38 Low Band Antennas (LBAs), and approx. 100 km baselines, it is possible to resolve the SCW emission. In fact, the two claims of intercluster bridge detection were also made with LOFAR data Botteon et al. (2020); Govoni et al. (2019). Other available telescope that operate in this frequency range have poor resolution at low frequencies (around 70 MHz, OVRO-LWA has 15' and LWA1 at 1-2 degree resolution), and hence are unsuitable for our analysis.

We propose co-observing our LRG field in shared-risk mode with LOFAR Low Band Antenna Sky Survey (LoLSS). LoLSS aims to cover the entire northern sky in 3170 pointings with approx. 15" resolution and 1 mJy beam^{-1} sensitivity de Gasperin et al. (2021). The current and planned operational status of LoLSS, and the LRG catalogue (from Hodgson et al. (2022)) that we plan to use is shown in figure 2. LOFAR's Low Band Antenna (LBA) array has the capability to observe in multi-beam mode. Total bandwidth available in a single LBA observation is 96 MHz, which is split among 4 beams, each with 24 MHz bandwidth. 3 of these beams can image 3 fields on the sky in parallel, while 1 beam is locked to a bright calibrator. All the 24 MHz bands for LoLSS are fixed to 42-66 MHz, where LBA is expected to be most sensitive, and each pointing will be observed for 8 hours. **From figure 2, in order to use the full LRG catalogue (in grey), we require imaging between $120 \leq RA \leq 240$ and $0 \leq \delta \leq 30$ in LoLSS 2023 run. The required patch would be covered in approx. 600 pointings, for a total observation time of (600/3) pointings per beam x 8 hours per beam per pointing = 1600 hours, or roughly 2 months. Therefore, we expect to obtain the data and perform our analysis before LoLSS ends.**

We will split the 24 MHz band into four equal sub-bands during imaging to account for typical flux density changes of sources and beam attenuation. However, final stacking will be done with the mean image made with full 24 MHz bandwidth. Imaging will be performed with publicly available LOFAR data reduction pipeline[2], which uses WSClean with robust Briggs weighting. Assuming that SCW emission follows a spectral index of approx. $-1.5 \leq \alpha \leq -1$, the emission at 54 MHz (center frequency of the band) will be 1.5-2 times brighter than what V2021 observed at 73 MHz with OVRO-LWA. Thus, if SCW is indeed present, it's signature would be loud and clear (SNR details at the end.) Furthermore, we'll be able to put tighter constraint on SCW spectral index (we'll have a total of 6 well-spaced data points including V2021) if we do detect a signal.

The confusion noise estimate for LOFAR LBA, as estimated from VLSS source counts, is given roughly as:

$$\sigma_c = 29 \left(\frac{\theta}{1"}\right)^{1.54} \left(\frac{\nu}{74}\right)^{-0.7} \mu Jy\ beam^{-1} \tag{1}$$

where θ is the synthesized beam FWHM and ν is the observation frequency. This estimate has been found to be a reliable estimate of confusion noise in several LBA runs Heald et al. (2015); Stewart et al. (2016). For our case, with a θ of roughly 15" at 54 MHz, we expect σ_c to be roughly 2 mJy. As for thermal noise, we know that noise in synthesized image (Stokes I) formed using dual-polarization dipole antennas is given as:

$$\Delta I = \frac{2k_B T_{sys}}{\eta A_e \sqrt{2N(N-1)\Delta\nu t_{int}}} 10^{29}\ mJy\ beam^{-1} \tag{2}$$

where T_{sys} is the system temperature (dominated by sky temperature at low frequencies), $\Delta\nu$ is the bandwidth of observation, t_{int} is the integration time, η is a combination of various efficiency factors. T_{sys} for high galactic latitudes is given as:

[2]https://github.com/revoltek/LiLF

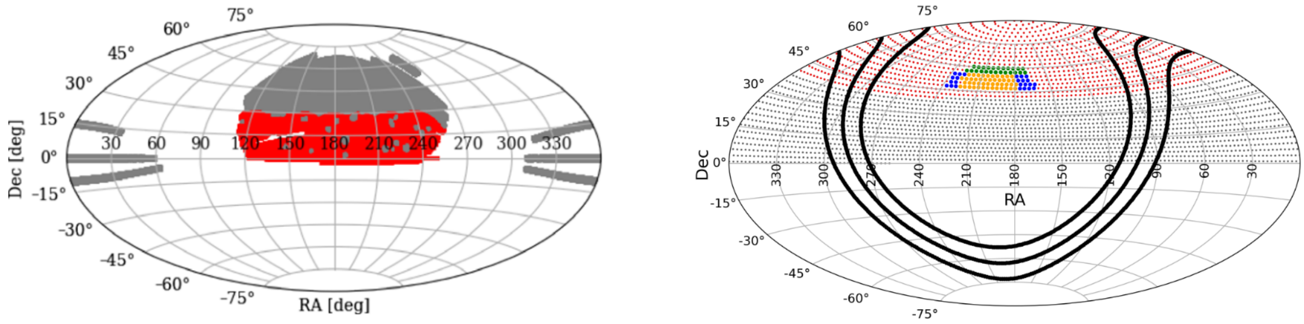

Figure 2: (Left) from Hodgson et al. (2022) shows the catalogue of 1.4 million LRG in gray and ones used by them in red. (Right) from de Gasperin et al. (2021) shows the 3170 discrete pointings of LoLSS. The area in red was observed in 2022, the area in grey is scheduled for 2023 run, the small multi-color area was observed as a test run in 2021.

$$T_{sys} \approx 300 \left(\frac{\nu}{150\ MHz} \right)^{-2.6} K \tag{3}$$

Thus, at $\nu = 54$ MHz, for a multi-frequency synthesis image formed using the entire 24 MHz bandwidth, effective area[3] 400 m^2, and 8 hours of integration time, we get a noise of approx. 1.5 mJy beam^{-1}, which matches well with LoLSS goal de Gasperin et al. (2021). Therefore, LoLSS will be at or near the confusion limit. At this point, 1.5-2 mJy beam^{-1} might seem like a high noise level given SCW's low brightness, but stacking will reduce the noise further.

Stacking involves averaging uncorrelated patches of sky after subtracting an LRG model. Therefore, both instrumental (thermal) and confusion noise scale as $1/\sqrt{N}$ where N is the number of images stacked. Once we stack close to a million images of LRG pairs, we expect 1000 times smaller error, roughly in the range **2-3 μJy beam^{-1}** (accounting for increased noise due to miscalibration, ionospheric refraction, etc.) To see how good this sensitivity is, we consider once again the expected brightness of SCW reported by Vernstrom et al. (2017) of 0.01-0.3 mJy arcmin^{-2} at 180 MHz for MWA-I. Assuming a conservative spectral index of -1, and LoLSS beam size of 15" or 0.25' we expect the signal brightness to be approx. 0.002-0.05 mJy beam^{-1} at 54 MHz. **Therefore, assuming SCW is present, in the best case scenario, we'll be able to make a 15-25σ detection. Whereas in a much more modest scenario with 5x lower SCW brightness of 0.01 mJy beam^{-1}, we'll still be able to make a 3-5σ detection.**

References

Botteon, A, RJ Van Weeren, G Brunetti, F de Gasperin, HT Intema, E Osinga, G Di Gennaro, TW Shimwell, A Bonafede, M Brüggen et al. 2020. "A giant radio bridge connecting two galaxy clusters in Abell 1758." *Monthly Notices of the Royal Astronomical Society: Letters* 499(1):L11–L15.

Clampitt, Joseph, Hironao Miyatake, Bhuvnesh Jain and Masahiro Takada. 2016. "Detection of stacked filament lensing between SDSS luminous red galaxies." *Monthly Notices of the Royal Astronomical Society* 457(3):2391–2400.

de Gasperin, Francesco, WL Williams, P Best, M Brüggen, G Brunetti, V Cuciti, TJ Dijkema, MJ Hardcastle, MJ Norden, A Offringa et al. 2021. "The LOFAR LBA Sky Survey-I. Survey description and preliminary data release." *Astronomy & Astrophysics* 648:A104.

[3]https://science.astron.nl/telescopes/lofar/lofar-system-overview/observing-modes/lofar-imaging-capabilities-and-sensitivity/

De Graaff, Anna, Yan-Chuan Cai, Catherine Heymans and John A Peacock. 2019. "Probing the missing baryons with the Sunyaev-Zel'dovich effect from filaments." *Astronomy & Astrophysics* 624:A48.

Govoni, FEDERICA, E Orrù, ANNALISA Bonafede, M Iacobelli, Rosita Paladino, FRANCO Vazza, MATTEO Murgia, VALENTINA Vacca, Gabriele Giovannini, L Feretti et al. 2019. "A radio ridge connecting two galaxy clusters in a filament of the cosmic web." *Science* 364(6444):981–984.

Heald, GH, RF Pizzo, E Orrú, RP Breton, D Carbone, C Ferrari, MJ Hardcastle, Wojciech Jurusik, G Macario, D Mulcahy et al. 2015. "The LOFAR Multifrequency Snapshot Sky Survey (MSSS)-I. Survey description and first results." *Astronomy & astrophysics* 582:A123.

Hodgson, Torrance, Melanie Johnston-Hollitt, Benjamin McKinley and Natasha Hurley-Walker. 2022. "Searching for the synchrotron cosmic web again: A replication attempt." *Publications of the Astronomical Society of Australia* 39.

Stewart, AJ, RP Fender, Jess W Broderick, Tom E Hassall, T Muñoz-Darias, Antonia Rowlinson, John D Swinbank, Tim D Staley, Gijs J Molenaar, Bart Scheers et al. 2016. "LOFAR MSSS: detection of a low-frequency radio transient in 400 h of monitoring of the North Celestial Pole." *Monthly Notices of the Royal Astronomical Society* 456(3):2321–2342.

Vazza, Franco, Nicola Locatelli, Kamlesh Rajpurohit, Serena Banfi, Paola Domínguez-Fernández, Denis Wittor, Matteo Angelinelli, Giannandrea Inchingolo, Marisa Brienza, Stefan Hackstein et al. 2021. "Magnetogenesis and the Cosmic Web: A joint challenge for radio observations and numerical simulations." *Galaxies* 9(4):109.

Vernstrom, Tessa, Bryan M Gaensler, Shea Brown, Emil Lenc and Ray P Norris. 2017. "Low-frequency radio constraints on the synchrotron cosmic web." *Monthly Notices of the Royal Astronomical Society* 467(4):4914–4936.

Vernstrom, Tessa, George Heald, Franco Vazza, TJ Galvin, JL West, Nicola Locatelli, Nicolao Fornengo and Elena Pinetti. 2021. "Discovery of magnetic fields along stacked cosmic filaments as revealed by radio and X-ray emission." *Monthly Notices of the Royal Astronomical Society* 505(3):4178–4196.