SKA Observations of the Cosmic Web

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The Square Kilometer Array will be the first telescope capable of directly mapping the full extent of the cosmic web that characterizes the large scale structure of the Universe. The approach highlighted here is to map the cosmic web via the detection of diffuse synchtrotron emission associated with the growth of the large scale structure in the Local Universe. As matter collapses onto the filaments of the web it will be shock accelerated to extremely high energies. In the presence of even extremely weak magnetic fields these accelerated particles will emit large scale, diffuse synchrotron emission. The tremendous sensitivity of the SKA over a wide field and at low frequencies will allow us to fully map the cosmic web in the local Universe.

1. Introduction

One of the fundamental problems in modern cosmology is the fact that stars, neutral atomic and molecular gas, and the diffuse hot gas within clusters of galaxies account for only a third of the baryon density in the local Universe as predicted from Big Bang nucleosynthesis (Fukugita, Hogan, & Peebles 1988) and fluctuations in the microwave background (Spergel et al. 2003). Some fraction of the missing baryons lies in the Lyα forest at low redshift (e.g. Penton, Shull, & Stocke 2000), but much is believed to reside in a warm (T$\sim 10^5 - 10^7$K), low density intergalactic medium (Cen & Ostriker 1999, Dave$'$ et al. 2001, Cen et al. 2001, Tripp, Savage, & Jenkins 2000). The simulations of Cen & Ostriker (1999),Dave$'$ et al. (2001), Kravtsov, Klypin, & Hoffman (2002), and Klypin et al. (2003) predict that *most* of the warm-hot intergalactic medium (WHIM) resides in the filamentary network that characterizes the cosmic web of the large scale structure of the Universe.

Mapping the cosmic web has long been the domain of optical redshift surveys, and filaments are traced by the redshift distribution of galaxies (e.g. Doroshkevich et al. 2004 and references therein). By all accounts, however, individual galaxies only represent the highest density peaks of the cosmic web and contain a relatively small fraction of the total number of baryons in at low redshift. The majority of the baryons in the web is contained in the WHIM.

Experimental confirmation of the existence and extent of the WHIM primarly comes from observations of O VI $\lambda\lambda 1032, 1038$ absorbers with the STIS (Tripp, Savage, & Jenkins 2000, Tripp & Savage 2000). The *FUSE* satellite has also revealed the presence of what is likely O VI absorption along a number of sightlines. But individual sightlines are limited in their ability to probe the full extent of the WHIM and the cosmic web. In addition, the interpretation of absorption line detections is heavily dependent upon assumptions about the ionization fraction, density, temperature, and abundance.

Our understanding of the cosmic web, its condition, extent, origin, and evolution depends upon our ability to directly measure physically important properties such as density, total energy, and magnetic field strength, and our ability to directly map the distribution of baryons in the cosmic web. The SKA will be the only instrument with which we can make these fundamental measurements.

2. The Warm/Hot Intergalactic Medium and the Cosmic Web

Our understanding of the physical properties of the WHIM and its tracing of the cosmic web is largely based on a number of cosmological hydrodynamic simulations. Cen & Ostriker (1999) and Dave$'$ et al. (1999) were among the first whose simulations showed that a sizeable fraction of the baryons in the Universe are in a warm (T$\sim 10^5 - 10^7$K) low density gas initially heated by shock heating of gas during its infall onto the filaments that mark the large scale structure of the local Universe. While the density of the WHIM is highest where the local density contrast is highest, most of the WHIM remains in the filaments (Dave$'$ et al 2001). The simulations from groups such as Kravtsov, Klypin, & Hoffman (2002) also indicate that the WHIM is most clearly associated with the large scale filaments within which most galaxies and groups of galaxies reside. This is shown in Figure 1 which is taken from Kravtsov, Klypin, & Hoffman (2002). The web-like pattern of the large scale structure of the local Universe is clearly seen in the predicted distribution of the WHIM (Kravtsov, Klypin, & Hoffman (2002).

The temperature and low density of the WHIM leave it nearly undetectable in emission. The most accurate measures of this component of the intergalactic medium come from ultraviolet spectroscopic observations of distant quasars and other AGN (Richter et al. 2004). Measures of the column density of OVI detected in absorption against background quasars suggest a column density of 10^{19} cm^{-2} for warm hydrogen. The observations, however, probe only individual sightlines and cannot accurately map the distribution and extent of the cosmic web. Furthermore, neither *HST* nor *FUSE*, nor the *JWST* have or will have the necessary sensitivity to accurately map the extent of the WHIM and the cosmic web via uv absorption lines.

Better insight into the true distribution of the WHIM and the cosmic web requires the ability to probe a large volume, not just individual sightlines. The best approach would be to map the cosmic web *in emission.* The cosmological simulations predict a temperature of $10^5 - 10^7$ K (e.g. Dave$'$ et al. 2001) with a peak energy between 0.5 and 0.8 keV (Phillips, Ostriker, & Cen 2003). While such energies can be probed via X-ray and far-ultraviolet *absorption* lines (again requiring individual sightlines), neither *XMM* nor *CXO* has the surface brightness sensitivities at these energies to detect the X-ray continuum radiation from the cosmic web.

The Square Kilometer Array will provide the best probes of the WHIM and the cosmic web. One approach highlighted in this volume is to map the distribution of low column density neutral hydrogen (Braun, this volume). Another, discussed here and in Lazio & Cordes (this volume), will be to use giant pulses from Crab-like pulsars in nearby galaxies to measure the dispersion measure across the local filaments and voids of the cosmic web. While this technique is limited to a relatively small number of sightlines determined solely by the number of giant pulses within a given galaxy, it offers the advantage of directly measuring the electron density of the baryons in the cosmic web, something ultraviolet and x-ray absorption line studies can only infer. A third approach will be to utilize the tremendous sensitivity and large field of view of the SKA to map the cosmic web via imaging of diffuse synchrotron emission arising from the infall of baryons onto the large scale structure of the Universe.

3. The Local Large Scale Structure

Optical redshift surveys, most recently, the Sloan Digital Sky Survey, have long revealed the complex filamentary network that characterizes the large scale structure of the Universe. The vast majority of galaxies reside in filaments and walls, the former having dimensions of many tens of Mpc in length and 1-2 Mpc in thickness (e.g. Ratcliffe et al. 1996, Doroshkevich et al. 2004). The Local Group in which the Milky Way resides, is believed to lie along an extended filament that originates near the Ursa Major group and includes both the IC 342 and M81 groups, and a second primary filament that includes the Sculptor group and originates near the Virgo cluster (Peebles et al. 2001). More broadly, the Virgo Cluster resides in the center of the Local Supercluster (LSC), a collection of galaxies, groups, clusters, filaments, and voids within 50-100 Mpc of the Local Group (Tully & Fisher 1987).

Galaxies, however, simply represent the highest density knots of the cosmic web as most of the baryons resides in a diffuse component that follows the distribution of dark matter. A simulation of the local large scale structure of the nearby Universe is shown in Figure 2 which is taken from Klypin et al. (2003). The contours represent the density of matter, with the lowest contour being the mean density of the Universe in the present epoch. The individual points represent the dark matter and the arrows represent the magnitude and direction of the infall of matter onto the growing structure. The distribution of baryons mimics the structure we see in these simulations. What is evident in this and other simulations of the web is the diffuse WHIM accurately traces the cosmic web as defined by the distribution of dark matter.

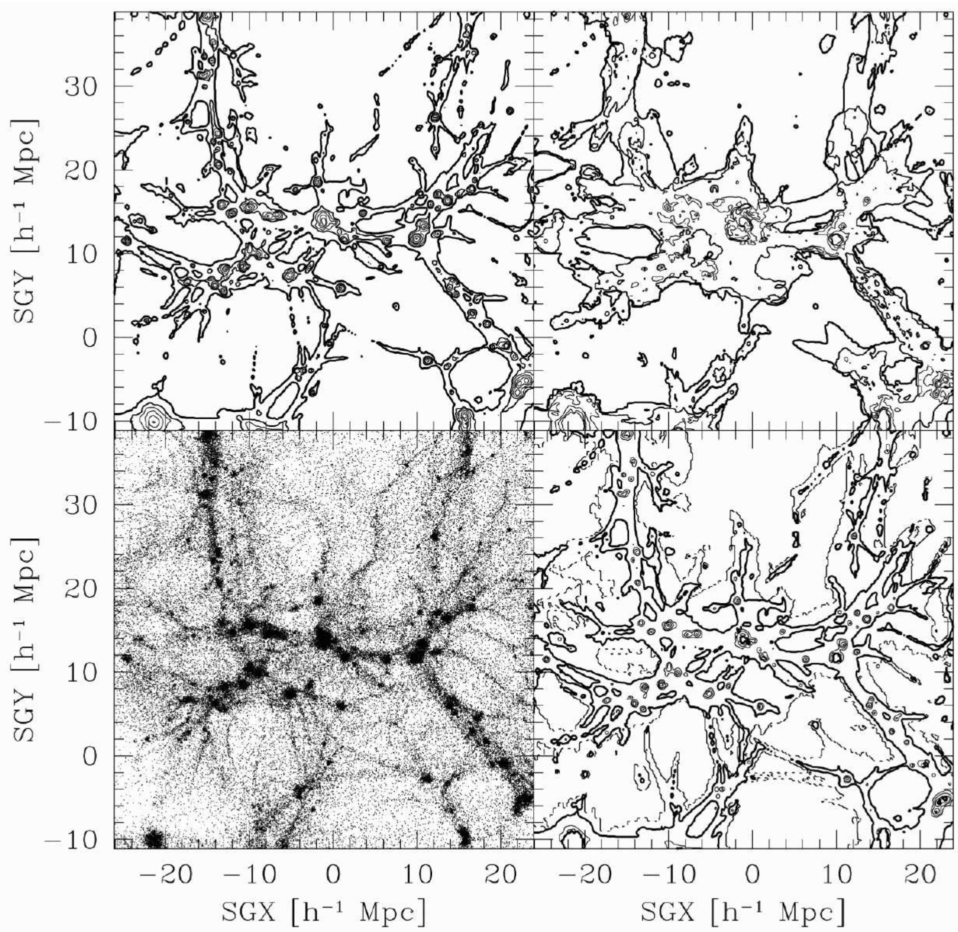

Figure 1. This figure is taken from Kravtsov, Klypin, & Hoffman (2002) and represents a slice of their simulation centered on the Virgo cluster. The upper left panel is the density field, upper right is the temperature, lower left is the distribution of dark matter, and the lower right is the projected density of the warm-hot intergalactc medium.

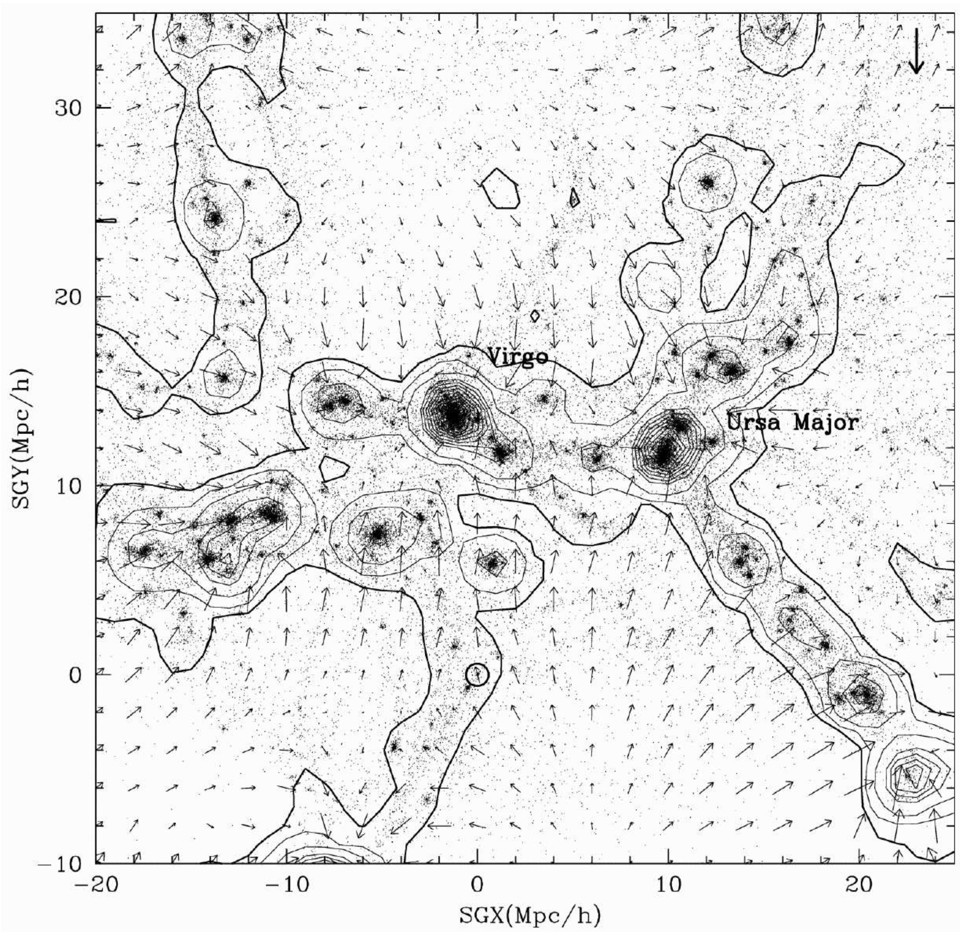

Figure 2. A schematic diagram showing the growth of the large scale structure in the nearby Universe taken from Klypin et al. (2003). The points are dark matter particles, the lowest contour is the average matter density of the Universe, and subsequent contours are overdensities of factors of 2, 4, 6, 8, etc. The arrows indicte the infall of matter onto the large scale structure.

4. Measuring the Electron Density in the Cosmic Web: Detecting Giant Extragalactic Pulsars

4.1. Motivation

The dispersion measure, DM, is a direct measure of the electron density along a given pathlength. It does not depend on temperature, abundance, or ionization fraction. The goal of this SKA program is to directly measure the electron density, n_e, of the IGM in the local cosmic web via the detection of giant pulses from extragalactic pulsars and the subsequent determination of the dispersion measure towards extragalactic pulsars.

4.2. SKA Observations

The SKA can detect giant pulses from pulsars in more than 30 bright galaxies within 7 Mpc of the Milky Way. As described by Lazio & Cordes (this volume) the sensitivity of the SKA will allow for the detection of giant pulses originating in galaxies as distant as the Virgo cluster. It will also be possible to detect giant pulses from extragalactic pulsars on the other side of the Local Void, allowing for measurements for the first time of the baryon density of voids in the cosmic web. The exploration of the WHIM and the cosmic web will be a natural extension of the pulsar survey described by Lazio & Cordes in this volume. The details of the observational program are fully described therein.

5. Mapping the Cosmic Web in Synchrotron Emission

What the cosmic web really traces is the infall of matter on a filamentary structure that reflects overdensities in the Universe. The formation of the large scale structure of the Universe is thought to be marked by large scale shocks as baryons accrete onto collapsing structures, resulting in the heating of the baryons to temperatures of $10^5 - 10^7$K. Typical shock velocities of 500-1000 km s^{-1} can be expected for reasonable cosmological properties (Keshet et al. 2003). Such infall velocities are sufficiently high that the infalling particles can be accelerated to total energies of $10^{18} - 10^{19}$ eV (e.g. Keshet et al. 2003, Ryu et al. 2003). In the presence of even a weak magnetic field in which the energy density of the magnetic field accounts for only 1% of the total post-shock energy density, the growth of structure should be accompanied by the emission of diffuse synchrotron radiation coincident with accretion shocks (Keshet et al. 2003, Loeb & Waxman 2000). Thus, the detection of diffuse synchrotron emission associated with these external shocks offers us the opportunity to accurately map the cosmic web, while at the same time measuring the electron density and energy distribution and inferring the strength of primordial magnetic fields associated with large scale structure.

6. SKA Observations of the Cosmic Web Via Synchrotron Emission

To date the only environment in which such synchrotron emission is detected is in the infall regions surrounding giant clusters of galaxies, where the emission is attributed to accretion shocks (e.g. Liang et al. 2000, Ensslin et al. 1998). One detection of diffuse synchrotron arising from the filaments of the cosmic web is associated with the growth of formation along a 6 Mpc filament anchored by two large clusters (Bagchi et al. 2002). The total radio power in this case is $\sim 10^{42}$ erg s^{-1} Mpc^{-2} with an estimated magnetic field strength of 0.3-0.5 μG (Bagchi et al. 2003).

Within the cosmic web, large clusters typically reside at the intersection of two of more filaments. They are the high density peaks in a broader web of lower density matter. The filaments themselves are traced by smaller structures, typically loose groups of galaxies very much like the Local Group. The shallower potential wells of groups result in lower infall velocities and subsequently lower shock velocities. Infall along a filament will be characterized by a lower velocity and weaker magnetic fields, but higher Mach numbers, than what is seen in either the immediate environment of a cluster or a galaxy group. Thus the total radio power generated by infall along filaments in the cosmic web will be significantly weaker than infall into a cluster. Comparison of the predictions of Keshet et al. (2003) with the results from

Bagchi et al. (2002) suggests that the anticipated flux density from filaments in the cosmic web will be 3-5 orders of magnitude less than what we find in the infall regions of galaxy clusters. Thus the complete mapping of the cosmic web will require the surface brightness sensitivity of the SKA.

The cosmic web has been envisioned as a network of filaments with a thickness of $\sim$5 Mpc wrapped around voids with diameters of 50-60 Mpc (e.g. Bharadwaj, Bhavsar, & Sheth 2004, Sheth et al. 2003). Simulations show that the coherent external shocks, those arising from the infall of baryons onto filaments, span 10-30 Mpc. The Local Supercluster is defined as a region within 50-100 Mpc of the Local Group, encompassing a number of clusters, groups, filaments, and voids. Klypin et al. (2003) simulated the structure of the Local Supercluster to match the observed distribution of galaxies and clusters, and the central 45 Mpc are shown in Figure 1. Given its sensitivity a key goal of the SKA can and should be to map the cosmic web in the Local Supercluster.

The energy distribution of the electron number density for shock accelerated particles corresponds to a synchrotron spectral index of ~ -1.25 (Liang, Dogiel, & Birkinsaw 2002). Thus, the key SKA observational program will be a low, multi-frequency survey designed to map diffuse synchrotron emission over large areas on the sky corresponding to specific filaments in the cosmic web.

6.1. The Filamentary Cosmic Web

One approach will be to use the redshift distribution of galaxies as a tracer of the local large scale structure. For example, Santiago et al. (1995) identified via an optical redshift survey a large scale filament stretching velocities of 5000-8000 km s^{-1}, Galactic latitude of $-30° < -20°$, and a Galactic longitude of $90° - 120°$. This filament extends nearly 50 Mpc in length, but is considerably narrower. The SKA program would be a multi-frequency campaign to map the 300 square degree section of the local cosmic web coincident with this filament to sensitivities of $\sim 10\mu$Jy. Clearly, such a survey would benefit from the largest available instantaneous field of view. The combination of the exquisite sensitivity over a wide field and at low frequency (150-300 MHz) of the SKA should reveal the presence of large scale accretion shocks along the filament as well as diffuse synchrotron emission throughout the filament - a direct detection of the WHIM and the cosmic web in emission.

6.1.1. Perseus-Pisces Supercluster

To further illustrate the power of the SKA to fully map the low redshift cosmic web we consider a test case of the Perseus-Pisces supercluster, a large swath of galaxies spanning nearly 100 square degrees on the sky. Optical redshift surveys suggest that the Perseus-Pisces supercluster is part of a large filament connecting to the Virgo cluster. As such it represents a laboratory in which we cannot only map the distribution of matter in internal shocks, those triggered by the re-acceleration of cosmic rays in the intracluster medium by radio jets, but also external shocks originating with the infall of material onto the large scale filament. The effect of internal shocks in Perseus-Pisces is evident in the morphology of the extended radio halo around the galaxy NGC 315 (Ensslin et al. 2001). The more diffuse, lower surface brightness synchrotron emission requires the sensitivity and wide field of view of the SKA.

6.2. Confusion

The most significant impediment to deep searches for diffuse continuum emission will be the confusion arising from a combination of the Galactic foreground synchrotron emission and the diffuse extragalactic background which is largely comprised of the unresolved emission from numerous point sources (di Matteo et al. 2002). Certainly by the time the SKA comes along we will know enough about the characteristics of the diffuse Galactic foreground emission to be able to account for its contribution to the detected signal. The unresolved point source population, however, will be a more difficult problem. The obvious solution will be to utilize the superior angular resolution and sensitivity of the SKA to identify and remove contaminating background sources. The nature of the backgrond depends fundamentally on the exact form of the faint end of the radio source count distribution (Fomalont et al. 1991). At low flux densities slightly extended background sources may well dominate other sources of confusion because of their finite angular size. Di Matteo et al. (2002) argue that the spectral index of the background continuum will be somewhat flat ($-0.2 - -0.8$). Comparison with the relatively steep spectral index of the cosmic web (-1.25) suggests that with multifrequency observations one will be able to mitigate the effects of confusion.

7. Conclusions

The SKA presents the opportunity to do what existing and planned facilities at other wavelengths cannot: map the extent and probe the conditions of the low redshift cosmic web. The majority of baryons in the local Universe reside in a diffuse warm-hot intergalactic medium that is distributed in a complex network of filaments.

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