21 CM COSMOGRAPHY, AN LRP WHITE PAPER

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ABSTRACT

21cm cosmology is a new field, which has gained theoretical attention, and is just opening up to observations. It has the potential of mapping the neutral hydrogen in the universe, initially up to the Epoch of Reionization, and ultimately much further. This opens up substantial improvements in dark energy constraints through measurements of Baryon Acoustic Oscillations at various redshifts, and probes dark matter and gravity through measurements of lensing. High redshift 21cm observations will image the epoch of reionization by detecting bubbles of ionized hydrogen in the largely neutral gas at $z \sim 10$. A new initiative, CHIME, to measure the BAO scale through cosmic time could allow Canada to emerge as a leader in this nascent field.

Subject headings: cosmology — 21 cm radio astronomy — intensity mapping — large scale structure — dark energy, dark matter — reionization

1. INTRODUCTION

Hydrogen is the most abundant element in the universe. Atomic hydrogen has a hyperfine spin flip transition at 1420MHz in the rest frame which can be collisionally or radiatively excited. Even though this transition is forbidden, it can be the dominant radiation mechanism in neutral hydrogen gas. The universe is nearly transparent to these redshifted 21 cm photons along almost all lines of sight at any redshift up to $z = 100$. This makes cosmological mapping of the universe using 21 cm radiation an attractive opportunity. Because 21 cm radiation is an isolated narrow spectral feature, redshifts are obtained in any detection, and images can be made in three dimensions.

Different approaches to understanding the high redshift 21cm universe have been proposed, each addressing different aspects. Some require very high point source sensitivity and resolution, for example the imaging of spiral arms or 21 cm evolution across galaxy types. This is the area of the future Square Kilometre Array (SKA[6]). Others map larger scale features of the cosmic matter distribution using a variety of existing facilities or purpose-built instruments.

Until recently, the study of this line had focused on the detection of gas in individual galaxies. Due to the inverse square law and cosmological redshifting, the highest redshifts for direct detection had been $z < 0.3$.

Although our galaxy is often bright compared to the cosmic features of interest, the galactic spectrum is smooth at wavelengths longer than 21 cm and spectral variations in flux are easily interpreted as extragalactic structure along the line of sight(de Oliveira-Costa et al. 2008).

We will review the prospects for using 21 cm emission to probe the epoch of reionization (EOR) and the so-called dark ages which preceded that, and also efforts to map the early assembly of galaxies. Then we will describe *intensity mapping* and a new initiative, the Canadian Hydrogen Intensity Mapping Experiment (CHIME) which capitalizes on new theoretical and observational developments including recent substantial advances in information technology. CHIME provides a unique opportunity for Canadian leadership in this exciting field.

2. THE EPOCH OF REIONIZATION

Despite the sensitivity challenge, several initiatives aim to search for the epoch of reionization (EoR) in the 21cm line. Because the hydrogen in the universe was once dominantly atomic, the emission flux was higher than at present, and so the era of $z \sim 10$ is thought to be accessible with existing radio telescopes (GMRT[7], for example) and several others under construction (LOFAR[8], MWA[9], Paper[10], PaST/21CMA). Exploring this regime is one of the key science goals of the SKA.

The expected scenario for re-ionization of the universe is that the first radiation-emitting objects to collapse ionize spherical bubbles around themselves. These bubbles grow and eventually percolate to form an essentially fully ionized plasma. What controls the formation of these first bubbles? When does this occur? What is the mass distribution?

Measurements of the size and distribution of these ionized bubbles as a function of redshift will have a huge impact on our understanding the very beginnings of star formation in the universe. This requires maps at redshifts near 10, corresponding to frequencies from 100 to 150 MHz. Considerable effort has gone into calculating how these maps might look (Shapiro et al. (2008), Razoumov and Sommer-Larsen (2007), Trac and Gnedin (2009), Thomas et al. (2009)) and how to extract physical parameters from them. The primary challenge is the removal of galactic synchrotron foregrounds, and manmade interference.

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Canada is involved through the GMRT-EoR project, headed by Pen at CITA, with an international collaboration including nodes at UBC, Pittsburgh, and in India. It is currently the most advanced group in the EoR search(Iliev et al. 2008), which combines CMB techniques, developed by Hirata, Sigurdson, Sievers, Chang. Much of the data pipeline infrastructure is similar to that needed by Intensity Mapping, discussed in the subsequent section. It is expected that EoR will make its initial detections in this decade, and Canada is well positioned in this field.

3. INTENSITY MAPPING

For purposes of mapping cosmological structure and power spectra, the scales of interest extend to those larger than the non-linear growth scale. The traditional measure of fluctuations has been in using σ_8, the variance of mass in $8\,h^{-1}$Mpc radius spheres, and many interesting processes take place on much larger scales than that. Even an an $8\,h^{-1}$Mpc radius sphere contains many galaxies; optical probes of large scale structure rely on counting the galaxies in a given volume. Not only must the radiation from individual galaxies be detected, but it must be detected at high significance (signal to noise of 5) to ensure that the galaxy in truth exists. The different biases associated with different types of galaxies must be understood if one is to use these data to infer a mass distribution. Despite these challenges a lot has been learned about cosmic structure for these sorts of surveys. (Eisenstein et al. (2005), Percival et al. (2007))

An alternative approach, referred to as *Intensity Mapping*, simultaneously collects radiation from all the galaxies in the pixel volume without making individual detections. This greatly increases the amount of signal available. Additionally there is no need to make high significance detections since the density is proportional to the amount of collected radiation from all objects, not just the brightest detected galaxies. Hydrogen intensity mapping measures mass distributions via a census of neutral hydrogen without resolving structure into individual galaxies. Just as for the CMB, optimized surveys of this sort have a signal to noise of approximately one per voxel, allowing much higher angular and spectral resolution for a given raw sensitivity.

To detect emission requires a certain minimum aperture at fixed integration time. The aperture also determines the angular resolution. In the optical, any aperture sufficient to detect a high redshift galaxy is also sufficient to resolve it. In the radio, a 100 m telescope is sufficient to detect large scale structure at $z > 1$, as has been demonstrated in pilot experiments using the Green Bank Telescope (GBT)(Chang, Pen, Bandura and Peterson "Detection of the Neutral Hydrogen Intensity Field at z=0.8", submitted to Nature). The HI structure was found to correlate with optical redshift surveys.

Direct measurements at these relatively large angular scales are challenging because the galactic synchrotron foregrounds are large. Since the 21 cm line is spectral in nature, one can subtract the smooth continuum foregrounds off. The resolution is 15', which is insufficient for resolving individual galaxies. In the optical, one must normally detect individual galaxies at high resolution, because the empty space between them still contributes to noise. In the radio, there is no added noise, since there is no resolution information. So detecting the large scale structure can be done without resolving individual galaxies (arc-seconds), or their separation (arc-minutes), just as detecting an optical galaxy does not involve resolving individual stars (pico arc-seconds) or their separation (nano arc-seconds).

3.1. *Chemistry of Galaxy Formation*

The vast majority of the 21 cm emitting neutral hydrogen resides in densely packed clumps where it is self shielded from ionizing radiation. These so-called Damped Lyman-α (DLA) systems are closely related to the formation and evolution of their host galaxies, and the detailed chemistry of these systems is one of the key observables when studying star formation over cosmic timescales.

Measurements of these systems generally employ absorption lines from distant quasars. Unfortunately such measurements are difficult in the redshift desert. In the radio, one can detect the 21 cm DLA gas, both in absorption against background radio sources, and in emission through Intensity Mapping. Because the location of radio sources is known, a low resolution survey is well suited to finding 21 cm DLA in the optical redshift desert. Direct comparison allows studies of the temperature of the absorbing gas, and potentially study their optical sizes by using optically obscured QSO's.

Using velocity distortions, a measurement of the mean neutral hydrogen density could be performed (Masui et al. 2010). This is one of the key parameters in such studies and has only been measured up to a factor of 3. An understanding of its evolution over time would further our understanding of feedback mechanisms in the accretion of fuel onto star forming galaxies.

3.2. *The very distant universe*

In principle, 21 cm is observable up to $z < 100$, at which point our ionosphere becomes opaque. It has been thought that this range could open the opportunity for ultra-high precision cosmology, including the direct measurements of primordial inflationary non-Gaussianity, gravity waves, and other fundamental effects(Pen 2004; Loeb and Zaldarriaga 2004). Intensity Mapping is a first step in this long term programme.

4. BAO AND CHIME – TESTING DARK ENERGY

Just at the turn of the millennium, it was observed that the well established expansion of the universe is accelerating (Astier et al. (2006), Nolta et al. (2004)). This phenomenon is consistent with a particular value of an ideal cosmological constant, Λ, but it remains without a convincing particular mechanism. Its origin is one of the most fundamental open questions in cosmology. The popular explanation is that over the last half of the universe's life, it has become dominated by some form of exotic energy with negative pressure that drives the expansion. This energy is popularly called *dark energy.*

One of the principal methods of learning about this acceleration is to probe the expansion history of the universe in detail. Precise measurements of how quickly the universe expands at different epochs will constrainmodels of dark energy. This can be done by measuring both a distance and a redshift to a source. Redshift is obtained automatically for 21 cm experiments.

A *standard ruler* can be used to infer the distance to a source If an object has a known physical size, then the angular size of the object on the sky can be used to determine its distance. Baryon Acoustic Oscillations (BAO) provide this characteristic length scale embedded in the distribution ofmatter in the universe. Acoustic signals in the plasma which filled the universe before recombination, $z \lesssim 1090$, travel at the sound speed, $c_s = c/3$. They reach a well understood physical size as the universe becomes transparent and the restoring force which drives these acoustic waves vanishes, just as the ring in a puddle a fixed time after the raindrop hits has a well understood radius. This process gives the Cosmic Microwave Background its characteristic shape (Komatsu et al. 2010) and has also been detected in the present day, low redshift, distribution of galaxies (Eisenstein et al. (2005), Percival et al. (2007)).

21 cm experiments are particularly suited for mapping out the distribution of matter and looking for the BAO. To achieve precision, maps of large volumes of space are required, which is difficult to achieve economically for optical experiments.

Just at the redshift range where cosmic acceleration begins to dominate, $1 < z < 2.5$, obtaining optical redshifts becomes nearly impossible. Not only does the luminosity distance increase rapidly, the strong spectral features of galaxies shift outside the transparent atmospheric window. Only above $z > 2.5$, Lyman alpha shifts into the visible, making optical redshift determination accessible again. This redshift range is referred to as the optical redshift desert. In the radio, the universe and our atmosphere remain optically thin, allowing a ready exploration of this crucial volume.

21 cm requires a low frequency, wide area, all sky survey. This is well aligned along Square Kilometer Array exploratory missions, and will enable an incremental understanding of instrumental issues, including calibration, sensitivity, receiver development, etc. Facilities could potentially be shared by other astronomical projects which have similar parameters. These include transient surveys (e.g. GRB afterglows, radio supernovae, RRAT's(McLaughlin et al. 2006) variable sources, etc), magnetic field rotation measures, and pulsar monitoring/searching.

4.1. *Lensing – testing modified gravity*

In addition to a dark energy mechanism, other possibilities for the cosmic enigma exist. Einstein's theory of General Relativity has been highly successful, but has not been rigorously tested on all scales. Indeed it has been suggested that the cosmic acceleration described in the previous section is the manifestation of the failure of GR on the largest scales in the universe. In order to pass precision tests of gravity in the solar system and near pulsars, all observationally allowed modified models contain a mechanism, restoring Einstein gravity in high density regions. Probes of the low density regimes of the universe are needed as these models generically affect the growth of large scale structure. One powerful technique is weak gravitational lensing, the bending of light from distant sources by the gravitational field of intervening matter. This directly measures the perturbations to the gravitational metric.

In order to probe the largest scales, a wide area survey covering most of the sky is desired (Masui et al. 2009). 21 cm intensity mapping provides a potential source. The maps of large scale structure from 21 cm intensity mapping will be distorted by the weak lensing from intervening structures. Statistical differences between the lensed and expected unlensed maps allows the lensing field to be reconstructed, providing a probe of the intervening matter (Lu et al. 2009).

Intensity mapping is sensitive to lensing on angular scales of degrees to tens of arc minutes. This is in stark contrast to optical surveys which are mostly sensitive to scales of arc minutes. While these larger scales will ultimately contain less information, they are largely free of complicated nonlinear and baryonic processes. These are also the scales at which we would expect modified gravity.

4.2. *CHIME: capitalizing on Canadian Opportunities*

The challenges of 21 cm intensity mapping of BAO through the epoch where dark energy becomes dominant are well matched to Canadian resources. The Canadian Hydrogen Intensity Mapping Experiment (CHIME) is a proposal to pursue this opportunity, mapping 21 cm emission over half the sky and over the frequency regime from 350 to 850 MHz, corresponding to redshifts from 3 to 0.7. CHIME would consist of fixed cylindrical parabolic reflectors oriented NS populated with low noise room temperature receivers along the focal line. Digital FFTs would form one dimensional images from each cylinder. Correlations between the images from adjacent cylinders form the instantaneous beams and the instrument surveys half the sky every day as the earth turns. The full CHIME instrument will be 100m square and cost $\lesssim 20M\$$.

It has been shown in Chang et al. (2008) that 21 cm intensity mapping experiment compares favourably to future generations of dark energy experiments, but on shorter time scales and lower cost. A full sky survey at GBT would take centuries of GBT time with a single pixel, making a dedicated survey instrument more timely. Quantitative forecasts use the standard NSF-DOE Dark Energy Task Force (Albrecht et al. 2006). The Figure of Merit (FoM) forecasts for CHIME is 450, which compares very favourably to future DETF stage IV proposals. The forecast errors are shown in Figure 1.

HIA-DRAO is an excellent site for such an instrument. It is in a legally protected radio quiet site with world class expertise in low frequency astronomy and a mandate to support University research. They operate galactic survey instruments at 1400 and 408 MHz. This corresponds to z=0 and 2.5 for HI emission and brackets the band of interest in BAO Intensity Mapping. The presence of this facility makes a Canadian experiment possible. The current sensitivity at 408 MHz is not suitable for 21 cm science but does probe the same frequencies. The RF environment in the CHIME band has been measured to be excellent.

Intensity Mapping involves large angular scale mapping of low surface brightness features where statistical properties of the map are more important than individual features. This is closely related to CMB experiments, of course, since they are mapping the same BAO features, but at much higher redshift. Canada has substantial established experience in CMB experiments and map

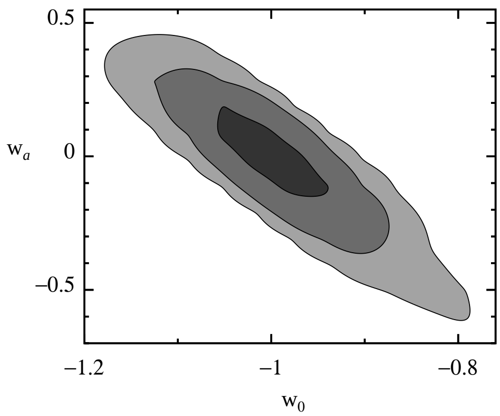

FIG. 1.— Sensitivity forecast of CHIME combined with Planck 2.5 yr 3 channel on the dark energy parameters w_0 (current equation of state) and w_a (derivative of w). Three contours are 68.3%, 95.4%, 99.7% CL respectively. The standardized Figure of Merit, defined as the inverse area in the $w_0 - w_a$ ellipse, is 450. This compares favourably to Phase IV experiments, which are all currently under discussion. If constructed early, CHIME could deliver the science before any substantial competition.

making, with participation in projects including WMAP, Boomerang, CBI, ACT and the SPT. Analysis of large data sets and massive linear algebra computations are a key component, which is well represented in Canada at CADC and CITA, including the recent buildup of High Performance Computing resources, such as SciNet. Interest also exists from other international groups, in the US(Peterson et al. 2006, 2009), China, and France.

For the purpose of an all sky survey, a transit cylinder telescope is able to map the whole sky with no moving parts. This provides substantial cost savings for the mechanical and electronics hardware. The enormous progress in digital processing now allows software beam forming and real time gain calibration. This enables an instantaneous wide field of view at only $N \log N$ correlation cost. Developments at DRAO and UBC for low frequency receivers and technologies are well aligned for this purpose.

The nature of wide band redshifted HI studies requires observations outside of protected radio bands. That means that it is most effectively carried out at very special places, of which DRAO is one, protected by terrain and zoning regulation from RF interference. DRAO has the basic infrastructure that such a telescope needs (land, access to power and internet, RF labs, and other facilities). 21 cm cosmology is a unique Canadian opportunity.

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