Current status and future of cosmology with 21cm Intensity Mapping

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21cm Intensity Mapping (IM) has been proposed about 15 years ago as a cost effective method to carry out cosmological surveys and to map the 3D distribution of matter in the universe, over a large range of post EoR redshifts, from z=0 to z=6. Since then a number of pathfinder instruments have been built, such as CHIME or Tianlai. Several other ones will be commissioned in the next few years (HIRAX, CHORD, BINGO), while even larger arrays, with several thousand antennae are being considered for the next generation experiments. We will briefly review the 21cm cosmology of the Epoch of Reionisation (EoR), and we will then focus on IM for late time cosmology. After presenting some of the promises of this technique to constrain the cosmological model, dark energy and inflation, we will review some of the instrumental and scientific challenges of IM surveys. The second part of the paper presents an overview of the ongoing and future experiments, as well as recent results by GBT, CHIME and Tianlai.

1 Introduction

Although the 21cm cosmology is mostly concerned with probing the dark ages and EoR, this paper is rather focused on late time cosmology, and mapping the cosmic matter distribution using the 21cm radio emission or absorption of neutral hydrogen gas (HI) through Intensity Mapping (IM). This technic refers to the detection of underlying structures formed by 21cm sources such as galaxies, without requiring detection of individual sources. A brief overview of EoR science with 21cm is presented in this section, while the idea and instrumental concepts behind Intensity Mapping would be developed in the following sections.

Observations revealing the evolution of the universe during the dark ages and the reionisation era are crucial for understanding the formation of structures in the universe. Dark ages refers to the period extending from Cosmic Microwave Background (CMB) last scattering era, at a redshift $z \sim 1100$ to the cosmic dawn, which corresponds to the birth of first stars and galaxies. The intense and energetic (UV, X) radiation from these first sources initiated the process of ionising the neutral gas, marking the start of the Epoch of Reionisation (EoR). The 21cm hyperfine transition of atomic hydrogen (HI) is one the only spectral features that can be used to probe this era, as the universe contains no sources, but only gas, mostly hydrogen at high redshifts ($z \gtrsim 30$). The HI gas leaves an imprint on the cosmic background radiation (CMB) if the spin temperature $T_s$ differs from the CMB temperature $T_{CMB}(z)$ at the corresponding redshift. The redshifted H1hyperfine transition, at a frequency of $\nu_21/(1+z)$ with $\nu_21 \simeq 1420.4MHz$ will appear as an emission, respectively an absorption feature, if the spin temperature $T_s(z)$ is higher, respectively lower, than $T_{CMB}(z)$.

The history of the evolution of the spin temperature during the dark ages and EoR is rather complex. $T_s$ tracks at first $T_{CMB}$, then decouples around $z \gtrsim 150$ and decreases due to collision coupling with the gas kinetic temperature $T_K$. The $T_s \leftrightarrow T_{CMB}$ equilibrium is restored around $z \sim 50$, when the atomic collision rates becomes ineffective to maintain $T_s \leftrightarrow T_K$ coupling, due to gas dilution by the expansion. After the for-
mation of the first stars and galaxies, the spin temperatures gets coupled to the gas temperature again in the UV photon bath at $z \sim 30$, through the Wouthuysen-Field effect.

The measurement of the 21 cm emission temperature and its anisotropies as a function of redshift would therefore allow to precisely identify the different stages of the universe’s evolution during the dark ages and EoR ($10 \lesssim z \lesssim 100$). In addition, the temperature anisotropies trace the distribution of matter in the linear regime over a broad range of wave modes (k-scales) at these redshifts, whereas non linearities affect a significant fraction of k-scales at later cosmological times ($z \sim 1$).

Although a number of dedicated instruments have been built over the last twenty years to observe the EoR 21cm signal, no undisputed observation has yet been reported. This is explained by the many challenges that needs to be overcome: the redshifted 21cm feature is located in the frequency range $10 - 50$MHz for redshifts $30 \lesssim z \lesssim 150$, which suffers from significant ionospheric absorption and diffraction as well as from major terrestrial, man-made disturbances (RFI). Moreover, the 21cm cosmological signal is very faint, in absolute terms, and completely buried in the foregrounds, specially the Galactic synchrotron and radio source emissions, which dominate this signal by 4 to 5 orders of magnitude. In addition, the reionisation history is very poorly constrained, making the experimental adventure quite risky, given the limited bandwidth that can be covered by any given instrument.

Some experiments, such as PAPER 8, SCI-HI 9 or EDGES 10 have targeted the global spectrum measurement and the detection of the distortions in the spectral shape of radio emission, due to EoR 21cm signal 11. Although some authors have claimed a possible signal 12, the detection has not been confirmed. Other groups, have developed complex wide band interferometric instruments to detect the inhomogeneties of the cosmological 21cm signal and measure the associated power spectrum. LOFAR 13,14 and NenuFAR 15 have deployed antennae in Europe, LWA 16 is a large dipole array in New Mexico (USA), while MWA 17 or HERA 18,19 observe from Australia. Recent upper limits on the 21cm power spectrum from these experiments can be found in 20 for LOFAR, in 21 for MWA and in 22 for HERA. Detection of the 21cm EoR signal is also the main goal of the SKA-low instrument of the future SKA (Square Km Array) observatory 23.

An brief overview of post EoR ($z < 6$) 21cm Intensity mapping and its scientific promises and challenges is presented in section 2. The instrumental concepts suited for such surveys, as well as key technical issues are discussed in section 3. Ongoing and planned intensity mapping instruments and surveys and their latest results are presented in section 4. The last section, 5 gives an outlook and expectations for the near future.

2 21cm Intensity Mapping

The large scale distribution of matter in the universe is a powerful cosmological probe, used to reconstruct the universe expansion history, and to determine the statistical properties of the initial density fluctuations. Indeed, the quantum fluctuations, relics of the early universe inflationary phase are considered to be the seeds that generated the large structures, visible in the late universe, through the gravitational instability 24,25. The LSS statistical properties, mostly encoded in the shape of the spatial correlation function $\xi(r)$ or the power spectrum $P(k)$, depends on the cosmological model and its parameters. The evolution of large structures with redshift, the growth rate of the structures in particular, is sensitive to changes in gravity 26, as well as to the neutrino masses, which, depending on their masses, partially erase small-scale structures 27. The Baryon Acoustic Oscillations (BAO’s) correspond to a preferred structure scale in the distribution of galaxies, originating from the baryon-photon plasma oscillations, prior to the decoupling. The BAO peaks, when observed at different redshifts, can be used as a standard ruler to reconstruct the cosmic expansion history, through the measurement of the Hubble parameter $H(z)$ and angular diameter distance $d_A(z)$ 28.
Historically, most cosmological surveys have been carried out using optical instruments through spectroscopic or photometric observations. Recent constraints on cosmological parameters derived from eBOSS and DES optical surveys can be found in 29 and 30. However, mapping matter distribution in the universe in the radio wavelengths, through the observation of the redshifted 21 cm line of the atomic hydrogen (H\textsubscript{I}), is a complementary approach to optical surveys to constrain cosmology and dark energy. The 21 cm line is the only astrophysical spectral feature in the L band (~GHz). It can therefore be used to determine unambiguously the redshift of an astrophysical object. Nevertheless, the detection of galaxies at 21cm needs a very large collecting area. The ALFALFA survey\textsuperscript{31} carried out with the Arecibo antenna, one of the largest radio-telescopes in the world\textsuperscript{a}, with a primary reflector 300 m in diameter, detected objects up to a redshift of 0.2. SKA will be able to extend this limit and allow the observation of gas-rich galaxies up to $z \sim 0.5$.

Most of the cosmological information of large structures (LSS) is found at scales larger than a few Megaparsecs (Mpc). Therefore, the detection of individual galaxies is not mandatory for LSS studies. This is the essential idea behind the Intensity Mapping technique, which seeks to measure the aggregate 21 cm radiation of all the galaxies (a few hundred) contained in universe cells with a volume of a few hundred Mpc\textsuperscript{3}. A cosmological survey becomes then possible with more modest instruments\textsuperscript{32,33,34,35}, with a collection area of about few times $10^4 m^2$. However, the LSS cosmological signal has an average surface brightness of less than 1 mK, and is therefore totally overwhelmed by foreground emissions, mainly from the Milky Way synchrotron emission and radio sources. These foreground emissions, with a temperature of $T_{\text{fgnd}} \sim 2 - 5 K$ in the coldest parts of sky around 1 GHz, are in general about few thousand times brighter than the cosmological H\textsubscript{I} emission, while the instantaneous receiver noise is still about ten times larger with $T_{\text{sys}} \sim 50 K$. The reduction of fluctuations from instrumental noise ($T_{\text{sys}}$) is achieved through long integration time, a few hours for each direction of the sky.

Extraction of the cosmological 21cm signal in the presence of these foregrounds is among the main IM scientific challenges. Several methods of separating the signal from the foreground emissions have been proposed which are all based on the smooth variation of the foreground brightness with frequency\textsuperscript{35,36}.

Since the early works on 21cm Intensity Mapping as a tool for cosmology, many authors have studied the science reach of such surveys, either generically\textsuperscript{37,38}, or targeting specific existing instruments such as FAST\textsuperscript{39}, or the SKA\textsuperscript{40}.

The white paper\textsuperscript{41} present the science goals of an ambitious 21cm Intensity Mapping survey covering a broad redshift range, up to $z \sim 6$ with a very large dish array radio interferometer like PUMA\textsuperscript{42}. Figure 1, adapted from \textsuperscript{41}, shows the precision that could be reached on the determination of the transverse and longitudinal BAO scales as a function of redshift, as well as for the structure growth rate $f\sigma_8$, assuming that the instrument can be built and operated, with map making and foreground subtractions reaching the projected performances. Thanks to the very large surveyed volume, such an IM experiment would significantly outperform surveys by the latest optical instruments (Rubin/LSST, DESI, WFIRST, Euclid). Radio observations can also be used to search for non-gaussianities and inflationary features in the reconstructed 3D LSS maps.

3 Instrumental concepts and challenges

As already mentioned in section 2, the relatively low radio brightness of H\textsubscript{I} clumps and galaxies limits the possibility of their detection to the vicinity, in cosmological sense, of our galaxy, with the available radio instruments. A galaxy with an H\textsubscript{I} mass of $10^{10} M_\odot$, which is already a quite massive hydrogen cloud, would have a 21cm brightness $S_{21} \approx 10 \mu Jy$ if located at a redshift

\textsuperscript{a}The Arecibo 305 m telescope is being decommissioned, following damages to its structure \url{https://www.nsf.gov/news/news_summ.jsp?cntn_id=301674}
\[ P_{21}(k) \sim \langle T_{21} \rangle^2 \times P_{LSS}(k) \]
\[ \langle T_{21} \rangle \simeq 0.042 \text{mK} \frac{\Omega_{HI} H_0}{10^{-3} H(z)} (1 + z)^2 \]

The cosmological information encoded in the LSS is statistical in nature, so a reasonably large volume of the universe needs to be surveyed to extract the information with low enough statistical errors. Instruments suitable for 21cm Intensity Mapping thus needs to have a large instantaneous field of view (\( \text{FOV} \gtrsim 10 - 100 \text{deg}^2 \)) and a large bandwidth (\( \Delta \nu \gtrsim 100 \text{MHz} \)), to be able to survey a large fraction of the sky with large integration time, over a significant redshift range.

Progress in the L-band analog electronics have made room temperature RF amplifiers quite competitive with low noise cryogenic electronic used in the large radio telescopes. Noise temperatures below \( T_{\text{noise}} \lesssim 30 \text{K} \) can indeed now be reached by room temperature receivers. Large bandwidth interferometers with large number of feeds have become viable and cost effective, thanks to advances in digital electronic and computing (multi core CPU and GPU’s), combined with progress in room temperature RF analog electronic.

Interferometers are most often used to reach high angular resolution, thanks to long baselines, but at the expense of a sparse sampling of the angular wave-mode or (\( u,v \)) plane. High resolution is not needed for LSS mapping for cosmological purposes, while high sensitivity is crucial, given the low signal strength. Although large dishes equipped with a multi-feed or phased array in their focal plane are a possible option, densely packed interferometric arrays, using rather small reflectors (\( D \sim 5 - 10 \text{m} \)), operating in transit mode, are the type of instruments most widely considered for intensity mapping surveys. The small size of reflectors insures a large FOV \((\sim \frac{\lambda^2}{D^2}) \text{srad} \)), and the dense packing concentrates the sensitivity in the \( k_\perp \) range useful for LSS. Transit mode operation is well adapted for surveying large area of the sky, while reducing instrument complexity and cost. Initially, cylindrical reflectors, with their axis or the focal line oriented along the north-south direction were proposed \(^{43}\), and implemented in the Pittsburgh CRT (Cylindrical Radio Telescope) prototype and then in CHIME, as well as in Tianlai. It was then realised that packed dish arrays might have some advantages, despite a smaller FOV and
the need to change dish pointing in declination to cover a large enough sky area. PAON4 and Tianlai are early examples of dish based pathfinder instruments (see section 4).

Radio instruments are inherently diffraction limited with their angular resolution degrading at longer wavelengths, hence with redshift. The projected spatial resolution will in addition vary with redshift, depending on the cosmological distance scales, namely the line of sight distance $d_{\text{LOS}}(z)$ and Hubble parameter $H(z)$. Values of transverse and longitudinal spatial resolution of maps obtained with a radio array covering a $\sim 100 \times 100 \text{m}^2$ area and with a 250kHz resolution are gathered in table 1. The approximate level of instrument noise projected on sky for a $\sim 1600$ element arrays, covering a $200 \times 200 \text{m}^2$, surveying $\sim 5000 \text{deg}^2$ over a year is shown in the figure 2, computed according to the scaling formula in 35. One can see that the resolution, hence the projected noise level degrades quickly with increasing redshift. A few hundred element interferometer with a few thousands $\text{m}^2$ collecting area might be sufficient to detect the signal up to $z \lesssim 1$, while larger instruments, with $10^4$ feeds and $\sim 10^5 \text{m}^2$ are required to reach higher redshifts $z \sim 2 - 3$.

Reconstructing sky maps, from visibilities which are cross correlation signals measured by interferometers has been and is still a technical challenge and major efforts have been devoted to develop accurate and efficient map making methods and tools. The transit operation mode, with observations covering the full 24 hours of right ascensions, combined with the large covered sky area, has led to the development of mathematically rigorous and efficient methods to reconstruct sky maps from transit visibilities. These methods operate in the spherical harmonic ($\ell,m$) domain, and take advantage of the full 24 hours coverage to decompose visibilities into m-modes. The huge matrix representing the linear relation between time dependent visibilities and the sky can be written as a block diagonal matrix in this representation, making the numerical problem tractable 44,45.

As stated in section 2 the 21cm signal is several orders of magnitude fainter than the broad band emissions from the Milky Way the te radio-sources. The foreground subtraction or component separation is a major difficulty in Intensity Mapping surveys, probably more challenging than in CMB experiments. The different approaches relie all on the foreground brightness varying smoothly with frequency, behaving as power laws, while the signal that follows the matter density fluctuations is structured along the frequency, corresponding to the radial direction. The inherent frequency dependence of the interferometer beam makes the foreground subtraction even more difficult. This is usually referred to as mode mixing as the angular modes probed by a given baseline changes with frequency.

21cm Intensity Mapping shares many technical aspects, map making and foreground subtraction in particular with the search for the 21cm signal from the EoR 46. Although signal-foreground separation might be effective on a per visibility basis with filtering along the frequency axis 47,48 many authors have explored the methods where signal and foreground components are projected into different sub spaces or modes 44,49,45,50.
The power spectrum $P_{21}(k)$ in mK/(Mpc/$h_{70}$)$^3$ is plotted as a function of the comoving wavenumber $k$ in $h_{70}$Mpc$^{-1}$. The top scale shows the angular scales at $z \sim 1$ for the corresponding transverse $k_{\perp}$ wavenumbers. The expected projected noise level, due to the instrument noise for $T_{\text{sys}} \sim 50$K, in the white noise approximation, is also shown, at $z = 1$ and $z = 2$ for a survey of $\sim 5000$deg$^2$, with an array of $\sim 1600$ dishes, covering $\sim 200 \times 200$m$^2$. The noise level line extent shows the approximate accessible $k_{\perp}$ range.

4 Past, ongoing and future experiments

We review here some of the experimental and observational efforts initiated in the last decade to explore and possibly establish the feasibility of observing large scale structures through 21cm intensity mapping. We start by mentioning some of the pioneering work performed using the GBT and Parkes radiotelescopes. We will then describe the dedicated pathfinder instruments, CHIME and Tianlai which have been specifically built to carry IM surveys, before presenting briefly few other projects, which are in the construction phase and will become operational in the coming years. Obviously, the list of projects mentioned here is incomplete.

The HI Parkes All Sky Survey (HIPASS)\(^5\) was carried out from 1997 to 2001 with the 64 meter Parkes Australian telescope, equipped with the 21cm multi beam receiver.\(^6\) It covers a large fraction of the southern, but also the northern sky, in the velocity range $-1280 < cz < 12700$km/s, or $z \lesssim 0.042$. A positive cross-correlation of 21cm signal from HIPASS data cubes with galaxies from the 6dF\(^5\) survey was reported in 2009.\(^5\)

The fully steerable 100m diameter Green Bank Telescope (GBT)\(^b\) has also been used to statistically detect the redshifted 21cm signal, in cross-correlation with optical surveys. Observations with the GBT have been carried out from 2010 to 2015, using the 680-920 MHz prime focus receiver covering the $0.6 \lesssim z \lesssim 1.0$ redshift range. A first cross-correlation detection from observation in DEEP2 fields\(^5\) was reported in 2010,\(^6\) confirmed with more data, using the WiggleZ\(^7\) survey in 2013.\(^8\) The detection of the cosmological 21cm autocorrelation signal has also been claimed using the same data set. More recently, using a subset of the GBT data, corresponding to about 100 hours of observations covering $\sim 100$deg$^2$ and the SDSS-IV eBOSS and WiggleZ spectroscopic redshift catalogs, the HI gas fraction at redshift $z \sim 0.8$ has been measured,\(^9\) more precisely the product of hydrogen mass fraction, its bias and galaxy-hydrogen correlation coefficient ($\Omega_{H_I}b_{H_I}r_{H_I} \sim 0.35 - 0.6 \times 10^{-3}$ at $z \sim 0.8$).

Tianlai (Cosmic Sound in Chinese) is an international project led by NAOC, with US, French and Canadian contributions and is exploring 21cm Intensity Mapping. The collaboration operates two pathfinder instruments which have been built and installed in a radio quiet area in north-western China, a cylindrical reflectors (TCI) and a dish array interferometer (TDA). The observatory is located at $(91^\circ48'E, 44^\circ09'N)$ and an altitude of $\sim 1500$m, near Hongliuxia, about 500 km east of Urumqi, in the Xinjiang province. The feeds have been designed to cover a broad frequency range (400-1430 MHz), although the current digitisation and correlator electronic can only handle a narrower 100 MHz frequency interval. The frequency band is tunable by adjusting the local oscillator and changing the analog filters. All observations have been performed in the frequency band 700-800 MHz up to now.

\(^b\)GBT: https://greenbankobservatory.org/
The TCI is composed of three cylinders, each 40 m long and 15 m wide. Only the central part of the focal line is currently instrumented with receivers. The three cylinders are equipped with a total of 96 dual polarisation feeds, representing 192 RF signals. The digital correlator computes 18528 visibilities from sampled signals, and channelised into 1024 frequency channels with 122kHz frequency resolution. Reference 61 present the basic system performance for the cylinder array.

The TDA is composed of 16 on-axis dishes, each 6 meter in diameter, arranged in a circular layout, with a central dish, surrounded by six dishes arranged as an hexagon, and then an outer ring with nine dishes. Although dishes are fully steerable, the array operates in transit mode, with all dishes fixed and pointed towards a given direction in the meridian plane. Each dish is equipped with a dual polarisation receiver, representing a total of 32 RF signals, sampled at 250 MSPS and 14 bits. A total of 528 visibilities (496 cross + 32 auto) are computed by an FPGA based correlator for 512 frequency channels with 244kHz resolution. A few thousand hours of observations have already been performed, with a significant fraction spent toward the NCP (North Celestial Pole). Indeed, one of the advantages of the dish arrays is their ability to be pointed toward a given declination band. By observing toward the NCP, it is possible to reach a high sensitivity over a small sky area. Detailed description of the Tianlai dish array and its performance, as well as preliminary results from deep observations toward the NCP can be found in reference 62.

Smaller instruments such as PAON4 63 and BMX 64 have also been built to explore specific technical aspects of dish arrays operating in transit mode. PAON4 is a small, 4-dish test interferometer located at the Nançay radio observatory in France, operational since end of 2015. It consists in four D=5 m diameter dishes, equipped with dual linear polarisation feeds, arranged in a triangular layout with a fourth dish in the center. PAON4 is being upgraded and will serve as the qualification instrument for the new IDROGEN digitisation and processing electronic system. These FPGA (Field Programmable Gate Array) based boards exploits the White Rabbit technology 65 for precise clock synchronisation and can digitise L-band signals at the receivers, without frequency shifting. They can transfer waveform signals, or frequency components as digital streams over high throughput (> 20Gb/s) ethernet optical links.

Figure 3 – Cross correlation of CHIME intensity maps with eBOSS galaxies and quasars. Top figures show the actual stacked signal in black, stacked on the positions of ELG’s with mean redshift \( \langle z \rangle = 0.96 \) (left), LRG’s with \( \langle z \rangle = 0.84 \) (center) and QSO with \( \langle z \rangle = 1.2 \) (right). The red curve corresponds to the best fit model and the bottom figures show the residuals, after best fit model subtraction. Adapted from 65.

\footnote{White Rabbit clock synchronisation over ethernet : https://white-rabbit.web.cern.ch}
The Canadian Hydrogen Intensity Mapping Experiment (CHIME) is a cylinder based interferometer designed and built for 21cm Intensity Mapping. It consists of four north-south oriented cylindrical reflectors, each 100m long and 20m wide, located at the DRAO observatory in Penticton, British Columbia (Canada). The instrument has a very broad bandwidth and covers the 400-800 MHz frequency range, corresponding to redshifts between 0.8 and 2.5. Each cylinder is fully instrumented and equipped with 256 dual polarisation feeds. The 2048 (4 × 2 × 256) analog signals are processed by an FX correlator. The F-engine uses FPGA custom designed electronics to perform digitisation and frequency decomposition into 1024 channels, each 390kHz wide. Correlations are computed for all $N^2$ feed pairs by the X-engine, which uses custom electronic for data exchange and 256 GPU nodes which perform the actual correlation computations. An overview of CHIME performance can be found in.

Thanks to their large FOV and bandwidth, Intensity Mapping instruments are also very efficient in detecting transient radio sources, such as FRB’s (Fast Radio Bursts) and pulsars. However, a specific backend is required to process the radio signals to search for fast transients. CHIME has proved to be a powerful radio burst and pulsar observation machine and has detected several hundred FRB’s over a one year observation period.

Despite CHIME successful operation, efficient data processing and impressive performance, the detection of the 21cm cosmological signal appears more challenging than anticipated. However, CHIME has published very recently, in February 2022, a sophisticated analysis showing convincing evidence for a correlation signal between CHIME intensity maps, and eBOSS galaxies and quasars at redshifts $0.78 < z < 1.43$. Maps were reconstructed from over 100 nights of CHIME observations, then stacked on the angular and frequency positions of eBOSS galaxies and quasars, after filtering and foreground subtraction. Figure 4, adapted from, shows the stacked signals as a function of the frequency shift, for ELG’s (Emission Line Galaxies), LRG’s (Luminous Red Galaxies) and quasars (QSO), together with the best fit model.

BINGO (Baryon acoustic oscillations from Integrated Neutral Gas Observations) is a single dish instrument being built in Brazil. It uses a off-axis 1600m$^2$, $D ∼ 50m$ primary reflector which illuminates a focal plane equipped with 28 horns through a secondary mirror. The whole optical setup is fixed and will observe a $15^\circ$ wide declination band centered on $\delta = 15^\circ$. The instrument covers the frequency range 980-1260 MHz corresponding to redshifts $0.13 < z < 0.45$.

HIRAX (Hydrogen Intensity and Real time Analysis eXperiment) is a packed array interferometer using $D = 6m$ dishes and shares many technological components with CHIME. The 256 dish array, represents a total collecting area of $\sim 7200m^2$ being built. It will be located at the South African Radio Astronomy Observatory in the Karoo desert, a few kilometers away from the MeerKat site (The South African SKA precursor).

CHORD (Canadian Hydrogen Observatory and Radio transient Detector) can be considered as a successor to CHIME, reusing many technologies developed for its predecessor, specially electronics and the FX correlator. But unlike CHIME, it will use 512 dishes, each 6m in diameter for the core array, representing a total collecting area of 14400m$^2$. The bandwidth will be slightly increased, covering the 300-1500 MHz band. Wide field of view outrigger stations located at large distances from the CHIME/CHORD instruments will also be built to enhance FRB localisation.

SKA, a very large general purpose interferometric radiotelescope, is being constructed by an international organisation. A review of the cosmological surveys planned for SKA Phase-I, and their forecasted performance in the redshift range $0 < z < 3$ can be found in. In addition to more traditional HI and continuum galaxy surveys at low redshifts $z < 0.35$, Intensity Mapping will enable to extend significantly the accessible redshift range, and even cover $3 < z < 6$ thanks to a deep survey over a $100deg^2$ field. Finally, one can mention the PUMA white paper, which is a proposal for an ambitious close-packed interferometer array with 32000 dishes, covering the frequency range 200-1100 MHz ($0.3 < z < 6$), as a stage II intensity mapping instrument.
5 Conclusions, discussion

21cm Intensity Mapping has emerged in the last decade as a novel, and possibly powerful method to map large scale structures at redshifts up to $z \sim 6$. Such surveys would be complementary to optical observations, and could be used to test and constrain the cosmological model, more specifically Dark Energy and Inflation. Densely packed interferometers with a large bandwidth of a few hundred MHz and large number of receivers (several hundreds to several thousands), observing in drift-scan or transit mode, without tracking, are the suitable instruments for such surveys. These instruments and projects share many technological issues, as well data analysis challenges, in particular calibration and foreground subtraction, with 21cm surveys for EoR, and more broadly, interferometers with large number of antennae. Few pathfinder and first stage instruments have been built to explore Intensity Mapping, and several others are planned or being constructed.

In the next few years, performance assessment and results from the ongoing and future IM experiments will shed light on some of the IM challenges. For example, it is important to show that it is possible to implement a cost effective design and construction process for a large number of antenna and receivers, as well as the associated electronics, while maintaining uniformity, construction quality and performance.

Precise array calibration is crucial to achieve large imaging dynamic range and to ensure foreground subtraction with the required precision. Among other aspects, it would be necessary to determine beam response for individual feeds, through a combination of electromagnetic simulations and on site beam measurements. Arrays with highly redundant baselines present many advantages for the calibration, whereas such arrays with many identical baselines, perform poorly in terms of mode mixing.

Structures in the instrumental frequency response, due to standing waves for example, should be minimized and precisely calibrated to be filtered out. Such frequency structures, if not corrected for, would indeed ruin the foreground subtraction. Another concern is the contribution of bright sources (sun, radiosources ...) through the far side lobes, which might be highly frequency dependent. It is also important to clarify the level of feed cross-couplings and correlated noise, which limits instrument sensitivity.

Faraday rotation causes linearly polarised sources to appear oscillating in frequency. The two linear polarisation measurements need to be combined during map making, to remove these oscillations, which in turn implies a good control of polarisation leakage and calibration. Also, some astrophysical effects such as self absorbed synchrotron might create higher order mode structures along the frequency axis, which would impact foreground subtraction.

Finally, I would like to mention that Line Intensity Mapping (LIM), using other atomic and molecular lines (CO, Carbon CII ...) is also considered for astrophysics and cosmology surveys \(^{75}\), although a discussion of LIM is well beyond the scope of this review.

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