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AN APPROXIMATION TO THE DETECTION OF THE 21CM LINE OF THE REIONIZATION EPOCH WITH THE MIA INTERFEROMETER

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RESUMEN

Las propiedades del Universo entre la emisión del fondo cósmico de microondas (CMB) y la formación de las galaxias más distantes, aún no han sido observadas. En esos tiempos se produce el amanecer cósmico. Este es el nacimiento y formación de las primeras estructuras, estrellas, agujeros negros supermasivos (AGN-SMBH), así como el subsequente cambio en las propiedades del medio intergaláctico (IGM) de frío y neutro a caliente y ionizado durante la época de reionización. Importantes radiotelescopios medirán las propiedades del IGM en grandes escalas (SKA-LOW, SKA-MID, CONCERTO, COPSS, SPHEREx, CHIME, etc.) en el futuro próximo. Estudiamos la posibilidad de observar la época de reionización utilizando las antenas del proyecto MIA (Multipurpose Interferometric Array).

ABSTRACT

The Universe's properties between the emission of the cosmic microwave background (CMB) and the formation of the most distant galaxies are not yet observed. In those times, the cosmic dawn occurs. This is the birth and formation of the first structures, stars, and supermassive black holes (AGN-SMBH). As well as the subsequent change in the properties of the intergalactic medium (IGM) from cold and neutral to hot and ionized during the reionization epoch. Significant radio telescopes will measure the properties of the IGM on large scales (SKA-LOW, SKA-MID, CONCERTO, COPSS , SPHEREx, CHIME, etc.) in the near future. We study the prospect of observing the reionization epoch using the MIA (Multipurpose Interferometric Array) antennas.

Key Words: Extragalactic astronomy: Intergalactic medium — Observational astronomy: Interferometry — Cosmology: Observational cosmology — Cosmology: Radiative transfer — Cosmology: Large-scale structure of the universe: Low-density-fields

1. GENERAL

The Cosmic Dawn (CD) and the Epoch of Reionization (EOR), when the first stars formed out of the primordial gas, and first light pervaded the universe, are observationally unexplored epochs in cosmology (Choudhury 2022). This reionization epoch holds information about the structure formation process in the early universe, the nature and formation of the first astrophysical objects, and the thermal evolution of intergalactic medium (IGM) at high redshifts (Ferrara & Pandolfi 2014). One of the most promising probes for studying these epochs is the redshifted 21 cm line from the hyperfine transition of the neutral hydrogen. The power spectrum of the fluctuations of this 21-cm Epoch of Reionization signal is measured employing radio interferometers.

The 21 cm cosmology has the potential to enhance our understanding of our Universe significantly. By searching for absorption or emission of the redshifted 21 cm line, one can observe neutral hydrogen, which can be used as a tracer of matter or as an indirect probe of other properties of our Universe, such as its ionization state or temperature. The 21 cm hydrogen line is a “forbidden” transition; thus, the likelihood of an individual atom making the transition is low. However, the sheer abundance of hydrogen in our Universe compensates for this, which results in an observable signal. In addition, the weakness of the transition means that the transition is optically thin. This enables a complete three-dimensional spectral line mapping, with the redshift providing line-of-sight distance information. The result will be a dataset with unprecedented reach in volume.

Extremely high redshifts are, in principle, acces-

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sible because one only requires neutral hydrogen, which exists before forming the first luminous objects. Moreover, even after luminous objects are formed, only the brightest ones will be seen by traditional observations. Observations in 21 cm cosmology typically do not resolve such individual bright objects, instead averaging over the extended IGM that fall inside single, relatively large pixels.

Without resolving individual objects, instrument specifications tend to be driven by length scales dictated by cosmology. While these length scales are generally large, it should be noted that the 21 cm line also enables one to access scales much finer than most other cosmological probes. This result arises from the relative ease with which spectral resolution can be obtained in radio astronomy.

2. LINE INTENSITY MAPPING (LIM)

LIM is an emerging approach to surveying the Universe, using relatively low aperture instruments to scan large portions of the sky and collect the total emission of spectral lines from the galaxies and the intergalactic medium. Mapping the intensity fluctuations of a series of lines offers a unique opportunity to probe redshifts well beyond the reach of other cosmological observations, access regimes that cannot be otherwise explored, and exploit the enormous potential of cross-correlations with other measures. This promises to deepen our understanding of various issues related to the formation and evolution of galaxies, cosmology, and fundamental physics.

There has been a surge of interest in LIM recently, with an impressive list of experimental projects pursuing various spectral lines along the electromagnetic spectrum, from radio to ultraviolet. Simultaneously, the theoretical framework of line modeling intensities and the study of line intensity maps have developed enormously. The spectral lines are associated with the cooling of gases, and star formation in galaxies, ranging from rotational carbon monoxide (CO) transitions observed in the sub-mm through fine-structured bright lines as [CII] in the far infrared to the $H\alpha$ and $Ly\alpha$ hydrogen lines in the optical and ultraviolet. The 21 cm HI line at high redshift is generated by the neutral hydrogen pervading the intergalactic medium in the early Universe.

2.1. *21cm HI line*

The 21 cm line is the hyperfine transition of atomic hydrogen. The parallel alignment of the electron and proton spins is a slightly higher energy state than the anti-parallel alignment. As an atom transitions from one state to another, it emits (or absorbs) a photon of 21 cm wavelength. To study this line, we use the spin-temperature T_s that describes the relative occupancy of the two spin states:

$$\frac{n_1}{n_0} = 3 \cdot \exp(-\frac{h\nu_{21}}{k_b T_s}),$$

where the factor of three comes from the relative degeneracy of the states, n_1 is the number of atoms in the excited hyperfine state, n_0 is the number in the ground hyperfine state, h is Planck's constant, k_b is Boltzmann's constant, and $\nu_{21} \simeq 1420.406$ MHz is the rest frequency of the 21 cm line. The physics of the spin temperature T_s throughout the history of the Universe is complex.

The critical thing to note is that we observe the contrast between the Cosmic Microwave Background (CMB) and the spin temperature. Where the spin temperature is higher than the CMB temperature, T_γ, the IGM emits photons, and an excess above the CMB temperature is seen; when it is lower than T_γ, the photons are absorbed from the CMB, and we see a deficit compared to what we expect. The differential brightness temperature δT_b of the 21 cm line is given by:

$$\delta T_b = [\frac{(T_s - T_\gamma)}{(1+z)}](1 - e^{\tau_{21}}).$$

We have additionally defined $\tau_{21}(z)$ as the optical depth across the 21 cm line at redshift z, which is given by:

$$\tau_{21} = [\frac{3\hbar c^3 A_{10}}{16 k_b v_{21}^2}][\frac{x_{HI} n_H}{(1+z)\frac{dv_{||}}{dr_{||}}}](\frac{1}{T_s}),$$

where $dv_{||}/dr_{||}$ is the gradient of the proper velocity vk along the line of sight distance r_k, x_{HI} is the fraction of neutral hydrogen atoms, $n_H = n_H^0(1+z)^3(1+\delta)$ is their number density, $\hbar = \frac{h}{2\pi}$ is the reduced Planck's constant, c is the speed of light, and $A_{10} = 2.85 \times 10^{-15}\mathrm{s}^{-1}$ is the spontaneous emission coefficient of the 21 cm line. This optical depth is typically 4%. We may Taylor expand our expression for δT_b to arrive at:

$$\delta T_b = [\frac{3\hbar c^3 A_{10}}{16 k_b v^2}][\frac{x_{HI} n_H}{((1+z)^2\frac{dv_{||}}{dr_{||}}})(1 - \frac{T_\gamma}{T_s}).$$

One thing to note is that in the high spin temperature limit, the observed brightness temperature is independent of the spin temperature. This can be understood from the fact that all spin microstates are equally occupied at high temperatures. Thus,

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the observed brightness depends only on the spontaneous emission rate from the high energy state (A_{10}).

2.2. *The Cosmic Dawn ($30 \leq z \leq 15$)*

The Cosmic Dawn is typically defined as the time when the first stars (or other radiating sources) were formed. Ly_α emission from these sources efficiently coupled the spin temperature to that of the cold gas (Wouthuysen-Field effect), leading to neutral hydrogen seen in absorption. At the same time, however, the gas was supposedly heated via X-ray heating. This gas-heating and the parallel process of coupling the spin and gas temperature led to a rapid rise in the brightness temperature of neutral hydrogen until it is finally seen in emission around $z \sim 15$. When these processes occurred is unknown, and redshifts indicated here are merely indicative numbers currently expected from nominal models. Processes that can be studied during the Cosmic Dawn (CD) are the formation of the first (population III or pop-III) stars, the first black holes, X-ray heating sources, weak-field (W-F) coupling, bulk-flows, etc.

2.3. *Epoch of Reionization (EoR) ($15 \leq z \leq 6$)*

While heating together with the W-F effect changes the spin temperature of the neutral hydrogen, the same radiation field (i.e. UV-radiation) starts to ionize hydrogen leading to the percolation of bubbles around the first mini-haloes containing pop-III stars and possible intermediate-mass black holes, i.e., mini-quasars. As time progresses and the universe becomes increasingly non-linear (on small scales), more stars and quasars are formed. Although recombination can have some impact, it can not stop or balance ionization in an expanding universe. By $z \approx 6$, the entire universe will be ionized once more, apart from pockets of neutral hydrogen (mostly in galaxies). Processes that can be studied during the Epoch of Reionization are the physics of the ionizing sources, such as pop-III and II stars, mini-quasars, feedback to the IGM, and the transition to the currently visible universe.

3. MULTIPURPOSE INTERFEROMETRIC ARRAY (MIA)

The MIA project involves implementing a multipurpose interferometer that will operate at low frequencies (between 50 MHz and 2 GHz), formed by an array of 5m diameter antennas. Its maximum angular resolution will be near a second of arc, making the instrument competitive with others of its type in other latitudes. The instrument's maximum baseline is expected to be 50 km. It will be located in a site with low radio interference, preferably in the western region of the Argentine Republic. Its construction was planned in three stages:

- MIA-Prototype: arrangement of 3 antennas with which the technological development begins and the technical training is carried out.
- MIA-16: 16-antenna interferometer.
- MIA-64: contemplates the expansion to 64 antennae.

Currently, the building of the MIA prototype is in progress.

3.1. *Simulations of the IGM at high redshift*

To estimate the cosmic dawn and the reionization epoch observations, we perform simulations for the 16 MIA prototype antennas. The study's primary motivation through simulations is to measure the absorption signal at 78 MHz claimed by the EDGES experiment (Experiment to Detect the Global EoR Signature) in Bowman et al. (2018).

This radio telescope is located at the Murchison Radio Astronomy Observatory in Western Australia. It is a collaboration between Arizona State University and the Haystack Observatory, with infrastructure provided by CSIRO (Commonwealth Scientific and Industrial Research Organization).

More recently, another experiment, the SARAS radio telescope in India, reported a null observation of the absorption signal detected by EDGES (Singh et al. 2022).

It operates in the 87.5 MHz–175 MHz band. Therefore, the cosmic dawn signal detection is still open, and the MIA interferometer could participate in such a search.

Considering a redshift between $16 < z < 22$, using 16 antennas of MIA with a bandwidth of 2 MHz for a hypothetical observation, we simulated the 21cm signal emission by hydrogen in a cosmological box of 400 Mpc under the standard LCDM cosmology (Planck Collaboration et al. 2020) with the 21cmTools (Giri et al. 2020) code. This code follows the growth of fluctuations, the gas cooling inside halos, the subsequent star formation, and the radiative transport of its photons that reionize the IGM.

Figure 1 shows an example of the simulated distribution of ionized hydrogen obtained for redshift z = 10. The presence of bubbles of ionized hydrogen around the very first luminous sources could be appreciated. The radiation from the 21cm line is computed on the combination of similar fields along the

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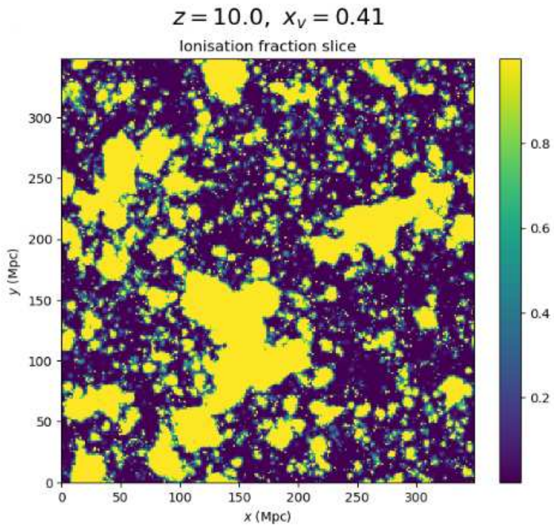

Fig. 1. Distribution of the fraction of ionized hydrogen (color scale) present in a 400 Mpc slab at redshift 10.0.

line of sight, i.e, from simulation outputs computed at different redshifts in the reionization epoch.

Using the simulation output and the radiometer equations (equation 6.82, Richard Thompson) for the spatial configuration shown in Figure 2 (for the case where the number of antennas is 16), we compute the time required for observing the 21cm signal. We consider the observation of each antenna at different redshifts between $10 \leq z \leq 20$. Then we add their integration times in such a way that we obtain a global 21cm HI signal. We also explored the possibility of increasing the array's sensitivity. In the case of 64 antennas, including a core of low-frequency antennas in the central region consisting of logarithmic-type antennas will be desirable.

It is important to recall that currently, we are not including realistic foregrounds, and therefore, our estimations should be considered as a lower value in such best case scenario. Furthermore, the MIA array location is still undefined. For this work, we assume it is located at the Auger site in Mendoza Province, Argentina, and the observations were made in the Austral summer to avoid the galactic center foreground emission using a beam of 18 arcsecs.

The times required for observing the 21cm signal at a minimum of a 37 signal-to-noise ratio aimed at observing redshift in the range $10 < z < 20$ are displayed in Table 1. A standard bandwidth of 2 MHz was assumed, and the detection of the 21cm line from the simulated IGM was performed using 16 antennas. The code used in this work can be accessed at the following repository https://github.com/3c279/code4mia.git.

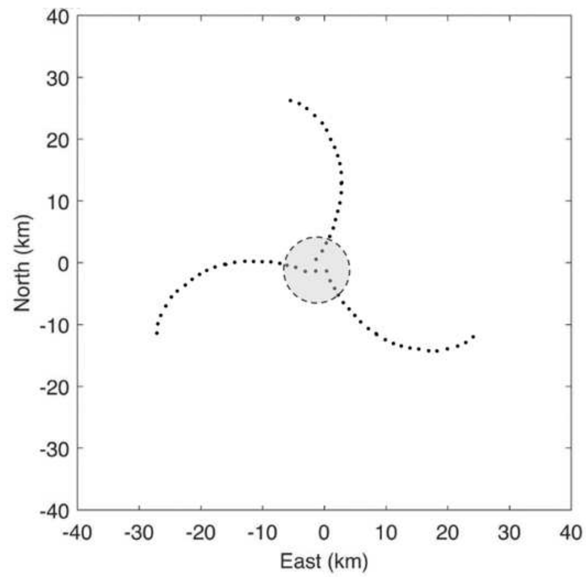

Fig. 2. Distribution of 64 MIA antennas on the Auger Observatory site assumed in this work, distances are in Km.

TABLE 1

INTEGRATION TIME

T_{sys}	z	t_{int}
75	10	2.5
75	14	2.7
75	17	3
75	20	5

Duration of observation run in months (t_{int}) to detect the global 21cm HI signal at different redshifts using 16 antennas.

4. DISCUSSION

The MIA project offers us a great variety of scientific objectives. For our particular case, we are interested in observing a redshift between $20 < z < 6$. We carry out several simulations of hydrogen distributions in the standard cosmological model, using the 21cmTools code adapted to an assumed MIA configuration in phase 2. For project configuration 2 (diameter of each dish is 5m), and considering a system temperature of 75 K, we obtain an average value of 1250 hours of observation for detection with a signal-to-noise ratio greater than 40 of the 21 cm line at redshift 16. For configuration in phase 3 (64 antennas), we expect a shorter observation time since the sensitivity of the radio telescope increases as the collecting area increases. Our estimations weren't performed for MIA operating in interferometric mode. Therefore, the figures reported in this work indicate the exposure time needed to measure the averaged signal in the beam. This constitutes a first approximation to the actual value, given that we are not considering the presence of the numerous galactic and extragalactic foregrounds involved in such measurements in our analysis. In future works, we plan to include such foregrounds and the signal analysis pipelines for MIA operating as an interferometer to produce spatially resolved maps of these important cosmological observations.

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