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Postprint on Observational Progress of Cosmic Dawn and the Reionization Epoch

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Abstract

The detection of cosmic dawn and reionization signals constitutes one of the primary scientific objectives of both currently operating and forthcoming low-frequency radio arrays (such as the Square Kilometre Array, SKA). The 21 cm radiation arising from the hyperfine transition of neutral hydrogen (HI) during the redshift $z = 6 - 27$ epoch represents the most direct and effective probe of the cosmic dawn and reionization eras. Through detection of the HI 21 cm signal, the formation and evolution of the universe's first generation of luminous objects can be delineated, thereby illuminating the cosmic history of the transition from darkness to light. This paper primarily reviews recent research advances in cosmic dawn and reionization detection, discusses pertinent issues including foreground removal and data processing methodologies, and summarizes progress in low-frequency radio telescopes for all-sky total power measurements and power spectrum measurements.

Full Text

Preamble

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Progress on the Exploration of the Cosmic Dawn and the Epoch of Reionization

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Abstract

The detection of cosmic dawn and reionization signals represents one of the primary scientific objectives for current and upcoming low-frequency radio arrays such as the Square Kilometer Array (SKA). The 21 cm radiation produced by the hyperfine transition of neutral hydrogen (HI) during the redshift range $z = 6-27$ serves as the most direct and effective tool for probing the cosmic dawn and epoch of reionization (EoR). By detecting the HI 21 cm signal, we can map the formation process of the first generation of luminous objects and thereby study the history of the Universe's transition from darkness to light. This paper reviews recent research progress in cosmic dawn and reionization detection, discussing challenges related to foreground removal, data processing methods, and advances in all-sky total power measurements and power spectrum measurements using low-frequency radio telescopes.

Keywords: cosmology; cosmic dawn and epoch of reionization; radio interferometric arrays

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1 Introduction

Approximately 380,000 years after the Big Bang, protons and electrons recombined to form neutral hydrogen atoms, allowing photons to travel freely and creating the cosmic microwave background (CMB). The Universe then entered a prolonged dark ages period until the formation of the first luminous objects. As the first stars and galaxies began to form, their ultraviolet radiation ionized the surrounding HI, illuminating the Universe and marking the beginning of the cosmic dawn and reionization epoch. The HI 21 cm signal is the most direct and efficient tool for probing this era. The 21 cm signals from the cosmic dawn and reionization period have been redshifted to meter wavelengths today, making them detectable in the low-frequency radio band.

Currently, two primary approaches exist for detecting the cosmic dawn and reionization through HI 21 cm signals. The first method is 21 cm tomography, which uses the CMB as a background radiation source and detects variations in CMB brightness temperature to obtain reionization signals and generate three-dimensional evolution maps of the intergalactic medium. The second approach is “21 cm forest” observations, which use bright radio sources at high redshift ($z > 6$), such as quasars or gamma-ray burst afterglows, as background illuminators to detect absorption line signals from HI along the line of sight. Different structures at various redshifts produce absorption lines at different frequencies

in the quasar spectrum, creating a “forest” -like spectral pattern. Unlike tomography, the 21 cm forest signal is more sensitive to the temperature of the intergalactic medium and can more effectively extract information about cosmic temperature evolution.

As predicted by Gunn and Peterson, the detection of neutral intergalactic medium (IGM) absorption in $\text{Ly}\alpha$ toward two quasars at $z > 6$ revolutionized our understanding of cosmic reionization. The 21 cm forest method can provide information about small-scale structures such as individual dark matter minihalos, low-mass galaxies, and even early H II regions around stars. Through large-scale numerical simulations, Carilli et al. found that high-redshift sources in dense regions of the $\text{Ly}\alpha$ forest produce identifiable absorption features in the spectra of radio-loud quasars, though they could not resolve gas cloud collapse at the smallest mass scales that represent the most abundant clumps in the high-redshift IGM. Furlanetto and Abraham complemented these results through semi-analytical exploration of the statistics of these compact absorption systems, enabling better measurement of physical quantities through radio absorption spectroscopy. Xu et al. calculated the absorption signals from individual minihalos and dwarf galaxies, including their internal and surrounding gas content, using high-redshift point sources as background. This paper focuses primarily on advances in the tomographic method.

However, the HI 21 cm signal from the cosmic dawn and reionization epoch is extremely faint, with maximum brightness temperature fluctuations of only about 0.01 K relative to the CMB—four to five orders of magnitude weaker than foreground contamination from Galactic radiation and extragalactic radio sources. Consequently, the weak cosmic signal is overwhelmed by powerful foreground emission, and removing foreground contamination to better than five orders of magnitude remains challenging in current low-frequency radio data processing. Additionally, the low-frequency radio band suffers from numerous anthropogenic interferences, such as television stations, mobile phones, and broadcast communications, making radio-quiet regions suitable for low-frequency radio telescopes extremely rare. In summary, practical detection faces numerous difficulties and challenges, including foreground identification and removal, high-dynamic-range wide-field imaging, calibration and ionospheric correction, instrumental effect removal, and massive data processing.

Current research on cosmic dawn and reionization detection encompasses three main directions: all-sky total power measurements, statistical power spectrum measurements, and direct imaging observations of reionization regions. All-sky total power measurements are conducted with single antennas, while power spectrum measurements and imaging studies rely on low-frequency radio interferometric arrays. These arrays represent pathfinders for the future SKA, which will leverage its sensitivity and resolution advantages to conduct power spectrum measurements and direct imaging studies of the cosmic dawn and reionization epoch.

Over the past decade, numerous low-frequency detection facilities have been

constructed internationally, advancing research in cosmic dawn and reionization detection. All-sky total power measurement experiments include EDGES, BIGHORNS, SCI-HI, LEDA, SARAS, DARE, PRIZM, ASSASSIN, DAPPER, and DSL. Low-frequency radio arrays for statistical measurements include 21CMA, GMRT, MWA, LOFAR, PAPER, and HERA. Future SKA will possess the capability for both statistical measurements and direct imaging of reionization regions. This paper reviews recent progress in cosmic dawn and reionization detection.

The structure of this paper is as follows: Section 2 provides an overview of observational and data processing issues in cosmic dawn and reionization detection; Section 3 introduces current progress in low-frequency experiments; Section 4 presents conclusions and future prospects.

2 Overview of Cosmic Dawn and Reionization Detection

2.1 The 21 cm Signal

The HI 21 cm radiation originates from hyperfine structure transitions in neutral hydrogen. The electron spin in HI can be either parallel or antiparallel, and transitions between these states produce 21 cm wavelength radiation. The spontaneous hyperfine transition probability is extremely small—for a single hydrogen atom, the time between spontaneous transitions is approximately 10 million years. Photons from the first luminous objects heat the surrounding HI, inducing hyperfine transitions.

The HI 21 cm line is a spectral line with a specific frequency that corresponds to different redshift epochs depending on the observation band. Due to cosmic expansion, 21 cm signals from the cosmic dawn and reionization period have been redshifted to meter wavelengths, i.e., the low-frequency radio band. Therefore, we can study the formation of the first luminous objects and probe the cosmic dawn and reionization epoch by detecting HI 21 cm signals in the low-frequency radio band.

The 21 cm signal from hyperfine transitions can be described by the brightness temperature $\delta T_b(r, z)$ as follows:

$$\delta T_b(r, z) = T_0(z)[1 + \delta m(r)][1 - x_i(r)]$$

where δm is the matter density, x_i is the ionization fraction of the gas ($x_i = 1$ for fully ionized, $x_i = 0$ for fully neutral), and $T_0(z)$ is expressed as:

$$T_0(z) = 26 (T_S - T_\gamma) / T_S * (\Omega_b h^2 / 0.023) * (0.15 / \Omega_m h^2) * (1 + z / 10)^{1/2} \text{ mK}$$

where T_S is the HI spin temperature, T_γ is the CMB temperature, h is the Planck constant, Ω_b is the baryon density, Ω_m is the total matter density, and z is redshift. Assuming T_S is coupled to the gas temperature T_{gas} throughout the IGM and that the gas temperature is much higher than the CMB temperature, this assumption holds once a sufficient Ly α background is established to couple

the spin temperature to the gas temperature and early X-ray sources provide the required heating. When the HI spin temperature exceeds the CMB brightness temperature, 21 cm emission occurs; when it is lower, 21 cm absorption occurs. Thus, we can detect HI emission and absorption signals by measuring brightness temperature fluctuations relative to the CMB.

2.2 Radio Foreground Removal

Extracting the cosmic dawn and reionization signal requires accurate removal of radio foreground contamination from the Milky Way and extragalactic sources. Foregrounds include the radio halo, Galactic synchrotron radiation, Galactic free-free radiation, and extragalactic radio sources. Among these, diffuse Galactic radiation (synchrotron and free-free) and extragalactic point sources dominate, accounting for approximately 71% and 27% of foreground contamination at 150 MHz, respectively.

Recent international research has focused heavily on foreground removal. Current methods typically exploit the spectral smoothness of radio foregrounds in frequency space, employing techniques such as smooth functions, polynomial fitting, principal component analysis (PCA), singular value decomposition (SVD), and Karhunen-Loève transforms. However, removing foregrounds to better than five orders of magnitude remains difficult, especially given instrumental systematics that can cause polarization leakage into the unpolarized 21 cm signal and frequency-dependent gain variations, complicating signal extraction.

Diffuse radiation from the Milky Way—synchrotron and free-free emission—exceeds the reionization background signal by five orders of magnitude. Since Galactic radiation is assumed to have a smooth spectrum in frequency space, it can be removed through fitting. Extragalactic radio sources represent another major foreground component. While regular point sources can be subtracted using Gaussian fitting, extended sources with large-scale diffuse structures pose significant challenges. These include massive galaxy clusters and filamentary large-scale structures that exhibit diffuse emission at low frequencies, with morphologies similar to reionization background scales, complex non-Gaussian distributions, and steep spectra that make them stronger at low frequencies. The MWA GLEAM survey at 70–230 MHz has detected over 200 such diffuse sources, and more will be identified as telescope performance and data processing methods improve. These sources include radio halos, minihalos, and relics, which are 2–3 orders of magnitude stronger than the HI 21 cm signal from the cosmic dawn and reionization epoch.

Current fitting methods for diffuse sources include multi-Gaussian fitting and shapelets. Shapelets are orthogonal basis functions composed of weighted Hermite polynomials, widely used in astronomical applications such as modeling three-dimensional dust distribution, weak gravitational lensing measurements, and gravitational lens imaging. In cosmic dawn and reionization detection, foreground removal must be performed not only in image space but also in UV space

for non-gridded data to directly extract power spectra, making diffuse source fitting a persistent challenge.

2.3 Data Processing

The extreme faintness of cosmic dawn and reionization signals demands high precision at every stage of observation and data processing. Current SKA pathfinder telescopes, limited by sensitivity and resolution, focus primarily on statistical measurements, while future SKA will enable both statistical measurements and imaging. However, SKA's improved sensitivity and resolution will generate enormous data volumes, posing hardware and software challenges for wide-field, broadband, high-resolution, multi-beam observations.

A major challenge in low-frequency radio detection is radio frequency interference (RFI) removal. With technological development, RFI has become a primary obstacle, and radio-quiet regions are scarce. RFI identification and removal are therefore critical in low-frequency data processing. RFI appears in various forms: strong interference at specific frequencies from TV stations, satellites, aircraft, and radar; and broadband interference at specific times from lightning and power lines. No universal removal method exists, necessitating effective automated identification and removal techniques for large data volumes.

Current automated RFI identification methods include software packages like AOFLAGGER and FLAGCAL. AOFLAGGER, the default RFI detection pipeline for LOFAR, fits signals in time-frequency space with accuracy comparable to visual inspection. GMRT primarily uses FLAGCAL for RFI flagging and calibration of interferometric data, featuring a powerful estimation system and high-performance parallel computing capabilities.

Data calibration is another crucial step. Calibration removes instrumental effects and ionospheric influences to correct flux densities and positions of observed radio sources. For wide-field imaging, signals vary with direction, time, and frequency, making direction- and time-dependent calibration essential. Calibration involves amplitude and phase corrections through fitting a complex gain factor for each receiver unit, using antenna beam models, sky models, or specific calibrators. However, establishing accurate beam and sky models remains difficult, and calibration errors propagate to the final signal extraction.

CLEAN is a widely used imaging method. Software packages developed for low-frequency array data processing include WSCLEAN (w-Stacking Clean), which features w-term correction for wide-field imaging. Written in C++ using the C++11 standard library threading module, WSCLEAN enables multi-threading for reading/writing, gridding between different w-terms, FFT execution, and Högbom Clean iterations. It currently employs the Kaiser-Bessel window function, which is computationally efficient and similar to the prolate spheroidal wave function (PSWF).

For reionization power spectrum analysis, existing calibration and power spec-

trum computation software includes the Fast Holographic Deconvolution (FHD), ppsilon, and the Cosmological HI Power Spectrum Estimator (CHIPS). The FHD/ ppsilon pipeline is widely used in studies including MWA Phase I, MWA Phase II, PAPER, and planned HERA data processing, as well as simulation data. It combines precise spectral calibration with end-to-end model matching and error propagation, making it well-suited for reionization signal measurement. CHIPS, used by the MWA EoR project, processes calibrated data into power spectra. While inverse covariance weighting of thermal noise plus residual foregrounds would be optimal for extracting statistical information, this is difficult to implement. Inappropriate residual foreground models and incomplete knowledge of their covariance can lead to signal loss, so CHIPS primarily serves as an inverse variance estimator using baseline weights.

The 50–200 MHz band for high-redshift HI signals suffers more anthropogenic interference than higher frequencies, complicating removal and identification. The power-law nature of foreground sources makes them stronger at low frequencies, increasing contamination. Additionally, current low-frequency observations have lower resolution and image quality than other bands, limiting precise foreground source identification and accurate sky model construction. Since calibration depends on these models, errors propagate. Ionospheric effects at low frequencies also cause source position and brightness variations, complicating calibration for resolution-limited observations.

In reionization power spectrum detection, the ideal approach is constructing power spectra directly from raw data to avoid gridding errors. However, raw data volumes from low-frequency arrays are enormous, and long integration times are needed to extract faint signals. Calibration of raw data demands substantial computational and storage resources, creating a massive data processing challenge.

Future SKA will employ deep-field pointed observations and survey modes for cosmic dawn and reionization imaging and statistical measurements. Wide-field imaging requires w-term correction and image mosaicking while maintaining the high dynamic range needed for signal extraction. This represents another significant data processing challenge.

3 Progress in Cosmic Dawn and Reionization Detection

Over the past decade, numerous low-frequency detection facilities have been constructed internationally, yielding significant research progress in cosmic dawn and reionization detection.

3.1 All-Sky Total Power Measurements

All-sky total power measurements of the cosmic dawn and reionization epoch are typically conducted with single antennas, similar to CMB measurements. International experiments include EDGES, BIGHORNS, SCI-HI, LEDA, SARAS, DARE, PRIZM, ASSASSIN, DAPPER, and DSL.

The EDGES experiment in Western Australia aims to measure the all-sky total power of the reionization signal. It employs a specific method to study expected spectral differences by constraining experimental scope to test for discontinuities in the spectrum, which must arise from rapid transitions in redshifted 21 cm brightness temperature rather than smooth foregrounds. In 2010, Bowman and Rogers first constrained the reionization timescale. In 2018, they published results detecting an absorption trough near 78 MHz, extracting a potential HI 21 cm absorption signal from the cosmic dawn epoch. In 2017, Monsalve et al. constrained reionization models using high-frequency antenna data.

BIGHORNS features portability, simplicity, and low power consumption, enabling flexible site selection. In 2018, Choudhury and Datta used artificial neural networks (ANN) to detect the all-sky 21 cm signal from bright Galactic foregrounds (parameterized as a “tanh” model), demonstrating that 21 cm signal parameters could be accurately determined even with bright foregrounds represented by third-order or higher logarithmic polynomials.

SCI-HI used 4.4 hours of data with polynomial foreground subtraction to place a 1 K RMS residual limit in the 60–88 MHz range. LEDA used 19 minutes of effective measurement data to constrain the absorption trough between 50–100 MHz. SARAS, a single-antenna correlation spectrometer in India, provided absolute sky brightness and spectral indices for the 110–175 MHz band and more precise calibration for all-sky maps at 150 MHz. SARAS 2 excluded several reionization epoch all-sky 21 cm signal models simulated by Cohen et al.

Ground-based experiments, though located in remote, electromagnetically quiet sites, still suffer from anthropogenic interference and ionospheric absorption/refraction. Space-based observations, particularly using the Moon to block terrestrial interference, would significantly improve sensitivity and reliability. The DARE space mission proposes measuring the all-sky 21 cm signal from lunar orbit, tracking the formation of the first luminous objects through their impact on the interstellar medium during the dark ages and cosmic dawn. The PRIZM experiment, located on Marion Island in the sub-Antarctic with an exceptionally clean environment, measures all-sky average brightness including the expected redshifted 21 cm HI absorption feature from first-star formation. ASSASSIN aims to explore the redshifted 21 cm signal from cosmic dawn to the end of reionization. DAPPER, a lunar orbiter, will study the early Universe’s dark ages using specialized receivers and high-frequency antennas in the quiet lunar far-side environment. The DSL program, proposed by a China-Europe joint team in 2014, involves a linear array in lunar orbit for interferometric sky mapping to study low-frequency radio sources and Galactic interstellar medium. summarizes these experiments.

Current SKA pathfinder arrays employ either pointed or survey observation modes. China’s 21CMA array uses single-pointing antennas covering the north celestial pole region, enabling long-term data accumulation but limiting sky coverage and complicating calibrator selection and extended source removal.

For all-sky 21 cm signals, Jordan et al. (2017) developed a new model linking 21 cm signals to high-redshift galaxy luminosity functions through abundance matching. Calibrated against high-redshift galaxy luminosity function measurements and adjusted to match CMB Thomson scattering optical depth, the model peaks at 110 MHz. Without new physics, EDGES' detected signal cannot be explained. As shown in [Figure 3: see original paper], EDGES' all-sky signal shows an absorption trough consistent with cold pre-reionization IGM models but exhibits unexpected features: an absorption peak of ~ 0.5 K, far exceeding predictions, and a peak frequency of 78 MHz corresponding to higher redshift. Jordan et al. (2018) explained these differences through: (1) earlier absorption peaks from enhanced star formation efficiency in high-redshift dwarf galaxies, advancing Wouthuysen-Field coupling and X-ray heating; (2) parametric models of thermal history providing new IGM cooling channels to fit EDGES' deep trough; (3) possible additional radio backgrounds from star-forming galaxies beyond the CMB, which can be calibrated using empirical star formation rate-radio luminosity relations.

3.2 Power Spectrum Measurements

International SKA pathfinder low-frequency arrays including 21CMA, MWA, LOFAR, GMRT, PAPER, and HERA prioritize cosmic dawn and reionization power spectrum measurements as primary science goals. Power spectrum measurements follow two approaches: constructing the reionization background power spectrum after foreground removal, or directly constructing power spectra to identify reionization signal windows in power spectrum space while avoiding instrumental effects and foreground contamination.

Recent observations from these arrays have enabled extensive statistical measurement research, summarized in . For foreground source characterization and accurate sky modeling, source catalogs have been compiled from low-frequency array data, including the 21CMA catalog and MWA GLEAM catalog.

In power spectrum measurements, Procopio et al. combined MWA GLEAM survey data with GMRT TGSS survey data at 150 MHz to build a model for compact foreground sources, improving calibration accuracy by up to 8% for the EoR1 field. Using this model, Beardsley et al. measured $\Delta^2 < 627 \text{ K}^2$ at $k = 0.27 \text{ h Mpc}^{-1}$, $z = 7.1$; Barry et al. obtained $\Delta^2 < 3.9 \text{ K}^2$ at $k = 0.2 \text{ h Mpc}^{-1}$, $z = 7.0$; Li et al. found $\Delta^2 < 2.39 \text{ K}^2$ at $k = 0.59 \text{ h Mpc}^{-1}$, $z = 6.5$; Trott et al. calculated average power spectra at $k = 0.07\text{-}3 \text{ h Mpc}^{-1}$, $z = 6.5\text{-}8.7$ using real-time calibration and CHIPS pipeline; Byrne discussed all-polarization diffuse sky maps for improved EoR calibration and foreground removal.

Patil et al. measured $\Delta^2 < 79.62 \times 10^{-3} \text{ K}^2$ at $k \geq 0.053 \text{ h Mpc}^{-1}$, $z = 10.1$. Mertens et al. obtained new upper limits on the 21 cm power spectrum at $z \geq 9.1$ from 141 hours of LOFAR data, implementing significant improvements in spectral smoothness gain calibration, Gaussian process regression foreground mitigation, and optimal weighted power spectrum inference. Bradley et al. used

21CMMC for forward modeling of 3D 21 cm signals to explore astrophysical parameter spaces beyond observational limits.

Ali et al. from PAPER measured $\Delta^2 < 22.42 \times 10^{-3} \text{ K}^2$ at $k = 0.15\text{-}0.5 \text{ h Mpc}^{-1}$, $z = 8.4$. Cheng et al. improved previous measurements through reliable reanalysis. Kolopanis et al. presented 21 cm power spectrum constraints from PAPER data, improving delay-based foreground filtering and empirical covariance estimation while addressing signal loss issues. Jacobs et al. published power spectrum measurements at 145 MHz covering most ionization band signal sources, making progress in foreground modeling. GMRT continues high-redshift HI power spectrum measurements; Paciga et al. used SVD foreground removal with minimal assumptions about foreground structure, quantifying for the first time signal loss from foreground filters and providing corrected power spectrum measurements, yielding a 2σ upper limit of $\Delta^2 < 2482 \times 10^{-3} \text{ K}^2$ at $k = 0.5 \text{ h Mpc}^{-1}$, $z = 8.6$.

[Figure 4: see original paper] compares recent low-frequency array power spectrum results with theoretical predictions. Matias et al.'s theoretical model predicts a 21 cm signal peak around 0.01 K, shown as a black dashed line.

3.3 Imaging Studies

Future SKA low-frequency arrays will not only measure reionization power spectra but also enable direct imaging of reionization signals, helping unveil the mysteries of cosmic reionization. Compared to power spectrum measurements, direct imaging of large-scale ionized regions during reionization can more directly extract physical information about ionized region sizes and characteristics. Deep imaging observations of five 20-square-degree fields represent one of SKA's primary science goals.

SKA is the world's largest radio telescope array, built through international collaboration across more than 10 countries. Located in radio-quiet regions in Australia, South Africa, and eight southern African countries, SKA comprises approximately 2,500 15-meter dish antennas covering 3,000 km, 250 dense aperture arrays (~60 m diameter) within 250 km (mid-frequency), and 1.3 million log-periodic antennas in sparse aperture arrays (low-frequency), providing square-kilometer equivalent collecting area and frequency coverage from 50 MHz to 20 GHz. SKA development includes a pre-construction phase (2012-2021), Phase 1 construction (SKA1, 2021-2028), and Phase 2 (SKA2, post-2028). A primary science goal is EoR imaging and CD/EoR power spectrum measurements using HI 21 cm signals. SKA1 low-frequency array is the only facility capable of EoR imaging among current pathfinders, representing a historic milestone. SKA1 low-frequency surveys will statistically measure 21 cm power spectra at redshifts 6-27, providing three-dimensional HI distributions with peak signal-to-noise ratios of ~100 at wavenumbers $k = (0.02\text{-}0.1) \text{ h Mpc}^{-1}$. SKA2 will dramatically improve angular resolution and sensitivity for more precise measurements across larger scales.

Given the extreme faintness of the 21 cm signal, long observations are required to reduce noise. Deep-field observations with SKA pathfinder arrays help characterize foreground properties, understand instrumental effects, improve data processing methods, and enable constraints on reionization detection windows in 2D power spectrum space—essential preparations for SKA low-frequency array observations. SKA is expected to obtain the first direct images of cosmic reionization at 100–200 MHz, unveiling its mysteries. For this challenging observation, Zheng et al. preselected the “quietest” and “cleanest” candidate fields for deep CD/EoR imaging from existing catalogs and observations.

summarizes SKA1 key technical parameters. [Figure 5: see original paper] compares sensitivity of current radio telescopes with similar frequency coverage to SKA, provided by the SKA Organization.

High-dynamic-range wide-field imaging represents a major challenge for future SKA low-frequency data processing. Hardware infrastructure costs for meeting SKA low-frequency imaging computational needs may account for half the total budget. Wide-field imaging faces difficulties in calibration, high dynamic range, bandwidth, antenna beam pointing, main lobe edges, ionospheric correction, and calibrator selection. The wide field contains numerous radio sources and atmospheric/instrumental effects that vary with direction, time, and frequency, making effective direction-dependent calibration crucial. Current peeling-based calibration methods are effective but require further development to reduce costs and improve accuracy. High-quality images are vital for modeling, calibration, signal extraction, and foreground removal. For wide-field telescopes like SKA, phase corrections must account for different antenna pointings, and integration time selection determines the signal-to-noise ratio and separation between bright calibrators without imaging contamination.

4 Summary and Outlook

Cosmic dawn and reionization detection studies the formation of the first luminous objects by measuring the 21 cm signal from HI hyperfine transitions. The extreme faintness of the HI 21 cm signal presents difficulties and challenges in foreground removal and all data processing stages. Detection approaches include all-sky total power measurements (single antennas), power spectrum measurements, and direct imaging studies (low-frequency arrays). Low-frequency arrays can conduct shallow surveys in drift-scan mode for wide-field imaging, statistically obtaining HI power spectra at 50–200 MHz (redshift 6–27). Power spectrum measurements follow two approaches: constructing reionization background power spectra after foreground removal, or directly constructing power spectra to identify reionization signal windows while avoiding instrumental effects and foreground contamination. Power spectrum measurement is a primary science goal for many SKA low-frequency pathfinder arrays, which currently lack direct imaging capabilities due to sensitivity and resolution limitations. Future SKA low-frequency arrays will conduct both power spectrum measurements and imaging studies, enabling direct mapping of reionization regions. Compared to

power spectrum measurements, direct imaging of large-scale ionized regions can more directly extract information about ionized region sizes and characteristics. This paper has discussed foreground removal, data processing methods, and research progress in all-sky total power and power spectrum measurements.

Improvements in low-frequency array sensitivity and resolution, along with advances in data processing capabilities from software and hardware development, continuously increase the likelihood of ultimately detecting cosmic dawn and reionization signals. Probing the cosmic dawn and reionization epoch is crucial for understanding how and when the first luminous objects formed, the scales and clustering of ionized regions, key physical processes during reionization, and the formation and evolution history of cosmic structure and galaxies. Power spectrum measurements and imaging studies of cosmic dawn and reionization signals will reveal the Universe's history from darkness to light and the evolution of cosmic structure from linear to non-linear regimes.

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