PROBING THE DARK AGES AND COSMIC DAWN WITH NEUTRAL HYDROGEN[1]

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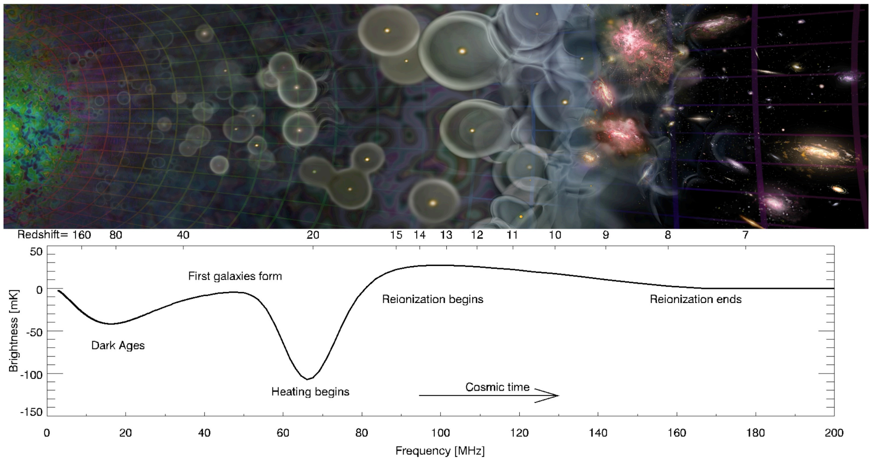
The *New Worlds, New Horizons* Decadal Survey identifies "Cosmic Dawn" as one of the three science objectives for this decade. This epoch is the final unresolved frontier of cosmology, defining a complex and rich target for observations and a research area that is likely to remain vibrant well into the next decade.



(*Top*) Schematic of the evolution of the Universe. The CMB is formed at the extreme left, and today ($z = 0$) is at the extreme right. The yellow dots with surrounding spheres represent the first stars and their Stromgren spheres. As the first galaxies form, these Stromgren spheres begin to overlap and the Universe reionizes. (*Bottom*) Illustration of the redshifted neutral hydrogen spectral feature, as a function of redshift (top axis) and frequency (bottom axis). While the exact shape of this H I spectral feature depends on the detailed evolution of the Universe, the existence of a such a signal is a robust prediction of our cosmological model; the schematic shape shown here represents one model and is likely to be relatively generic.

Following recombination ($z \approx 1100$), neutral hydrogen (H I) became the dominant baryonic component of the intergalactic medium (IGM). The highly redshifted H I hyperfine line is the *only* electromagnetic probe of the Universe before the formation of the first stars and would allow the cosmological investigation of the formation of the first gravitationally bound systems over the largest volumes of any approach. Multiple epochs accessible via the H I line can be identified (see figure), which are only poorly constrained by current observations:

Dark Ages ($z > 35$): Before the first stars formed, the gas is expected to have cooled rapidly relative to the CMB, causing the H I feature to appear in absorption. Observations of the feature at these redshifts probe the gravitational collapse of the first structures and are exquisitely sensitive to any energy injection into the IGM (e.g., decaying dark matter).

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First Stars ($35 > z > 20$): After the first stars appeared, their UV radiation couples to the H I line through the Wouthuysen-Field effect. This coupling creates a large absorption H I feature, which can be used to probe the spectra of the first stars, potentially distinguishing between Pop II and Pop III stars.

First Accreting Black Holes ($20 > z > 15$): Hot accretion disks around the first stellar remnants (e.g., black holes) emit X-rays, which efficiently heat the cold H I gas. Observations of the H I feature during this period are sensitive to the properties of the black holes and the metallicity of their progenitors, offering further insight into primordial star formation.

Epoch of Reionization ($15 > z > 6$): Eventually, UV photons from stars and black holes started ionizing the gas in giant bubbles within the IGM. Rapid destruction of the neutral gas then eroded the H I feature; the topology of these bubbles constrain the nature of the first galaxies, including those too faint to be detected through other means.

Tracking the evolution of the Universe during these epochs is already underway—the *Hubble* Space Telescope is providing constraints on the nature of galaxies in the Epoch of Reionization, the *Fermi* Gamma-Ray Telescope has identified gamma-ray bursts at $z > 6$, and the *James Webb Space Telescope* is likely to probe even deeper in redshift. However, a complete understanding of the evolution of the Universe over these epochs requires tracking all of its constituents, including the H I gas from which the first stars formed. Ground-based efforts to detect the H I line features are underway, but, at the highest redshifts, measurements from the ground are fundamentally limited by the ionosphere, interference, and instrument stability. The excellent characteristics of a space platform are essential to study at the highest redshifts, which are the strongest probes of cosmology and new physics.

Technical Capabilities

At these redshifts, the H I feature appears at meter wavelengths: for reference, at $z = 20$, the transition is observed at 67 MHz (λ4.5m), and, at $z = 70$, at 20 MHz (λ15m). Two measurement approaches exist. The **sky-averaged spectrum** is the most basic quantity (lower panel, figure). The different eras described above imprint distinct features on this spectrum, and its shape can be used to determine the timing of major events during the evolution of the Universe. This measurement potentially can be accomplished with a single, small antenna. The **power spectrum of H I fluctuations** allows the growth of structure to be tracked. It is therefore much more powerful than the sky-averaged spectrum, but it is also more difficult to measure because the signal from each structure is extraordinarily small. This measurement requires significant sensitivity on a range of angular scales.

The Table summarizes key technical capabilities for both measurement approaches. The challenges of obtaining sufficient sensitivity at the highest redshifts ($z > 30$) suggest that fluctuation power spectra at these redshifts are likely to be well in the future, thus the frequency range is somewhat more restricted for the power spectrum requirements. Finally, we emphasize that the values shown here are *notional* and are likely to be guided by on-going experiments and telescopes on the ground, and potentially by discoveries at other wavelengths.

	Sky-Averaged Spectrum	**H I Fluctuation Power Spectrum**
Spectral coverage	15 MHz–120 MHz	40 MHz–120 MHz
Spectral resolution	0.5 MHz	0.1 MHz
Angular resolution	≥ 5°	3 arcminute
Field of view	2π	10 deg^2
Sensitivity	3 mK	1 mK

New Technologies

Previous concept studies have identified a number of technologies that would enhance future Dark Ages-Cosmic Dawn missions (Lazio, Hewitt, et al., “The Lunar Radio Array,” Astrophysics Strategic Mission Concept Studies), and there has been an Explorer-class concept (Dark Ages Radio Explorer) developed for measuring the sky-averaged spectrum at redshifts $z \approx 20$.

The most demanding aspect of both measurement approaches is **calibration and system engineering** related to the control of systematics, rather than specific detector or signal processing technologies. The latter are both currently under development for various ground-based experiments and telescopes. For both measurement approaches, the expected signal is in the range of 10^{-4}–10^{-7} weaker than the Galactic synchrotron emission and other foregrounds. Even small changes in the performance of the instrument could obscure or vitiate the measurement.

Need for a Probe-class Mission

A measurement of the *sky-averaged* H I spectral feature at $z \approx 20$ can likely be performed with an Explorer-class mission. Fully exploiting the H I line will require obtaining higher angular resolution, probing deeper in redshift, or both. In turn, multiple antennas will be needed in order to obtain adequate sensitivity in a reasonable amount of time, sufficient angular resolution, or both. We use a previous study of an interferometric array conducted under the Lunar Sortie Science Opportunities (LSSO) program and the MoonRise mission as our “analogs.”

MoonRise has been a proposed New Frontiers (Planetary Sciences) mission to study the far side of the Moon. Its total payload is of order 1000 kg, with an estimated cost of less than $1B. Therefore, we use 1000 kg as the target mass budget for a future Cosmic Dawn Probe. The LSSO concept study considered an array of tens of antennas (~ 50), for which the mass budget was approximately 500 kg. While further study is required, the combination of MoonRise and the LSSO concepts indicate that a Cosmic Dawn Probe, consisting of tens of antennas could be implemented within the current specifications for Probe-class missions.