PROBING THE DARK AGES AND COSMIC DAWN

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The *New Worlds, New Horizons* Decadal Survey identifies "Cosmic Dawn" as one of the three science objectives for this decade. The **Epoch of Reionization** is a science frontier discovery area, and "**What were the first objects to light up the Universe and when did they do it?**" is a science frontier question in the Origins theme. NASA Astrophysics should aim to track the evolution of the Universe through as much of the Dark Ages and Cosmic Dawn as possible.

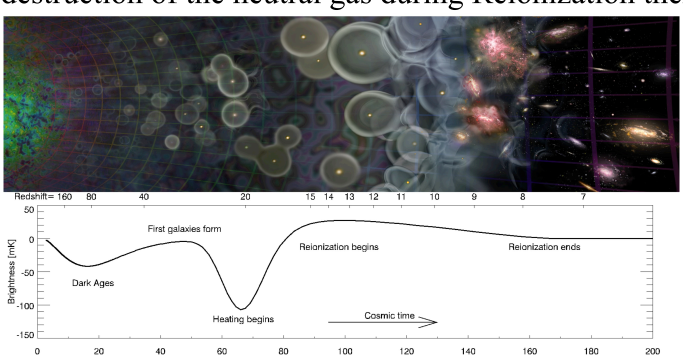
Following recombination ($z \approx 1100$), the Universe entered a largely neutral state in which H I was the dominant baryonic component of the intergalactic medium (IGM). The highly redshifted 21 cm hyperfine transition of H I provides unique information about the state of the IGM and large-scale structures during the formation of the first stars and potentially can probe the IGM *prior* to their formation. Multiple epochs can be identified, only poorly constrained by current observations:

Dark Ages ($z > 35$): Before the first stars formed, the hydrogen gas was influenced only by collisions and absorption of CMB photons. The gas cooled rapidly as the Universe expanded, and the resulting cold temperatures cause the 21 cm signal to appear in absorption. Any additional heating (e.g., dark matter decay) will affect the characteristics of the signal substantially.

First Light & First Stars ($35 > z > 20$): After the first stars appeared, absorption and re-emission of their UV photons through the Wouthuysen-Field mechanism "turned on" the 21 cm signal. The IGM gas remained quite cold, however, resulting in deep 21 cm absorption.

First Accreting Black Holes ($20 > z > 15$): Black holes likely formed, e.g., as remnants from the first stars. Accreting gas would be shock heated, radiating at X-rays wavelengths, and began to heat the extremely cold gas (~ 10 K). This heating transformed the spin-flip signal from absorption into emission as the gas became hotter than the CMB.

Epoch of Reionization ($15 > z > 6$): Once the gas became hot, the emission saturated, until photons from these stars and black holes started ionizing giant bubbles within the IGM. Rapid destruction of the neutral gas during Reionization then eroded the 21 cm signal.



These observations must ultimately be space-based because the H I 21 cm line is redshifted to wavelengths at which ionospheric opacity is significant: at $z = 20$, the transition is redshifted to λ4m (67 MHz) and, at $z = 70$, to λ15m (20 MHz). Two measurement approaches exist. The **sky-averaged 21 cm spectrum** is the basic quantity. The different eras described above imprint distinct features—*turning points*—on this spectrum, and its shape can be used to determine the timing of major events in the Universe's evolution. This measurement can be accomplished potentially with a single, small antenna.

The **H I fluctuation power spectrum** tracks the growth of structure. It is therefore much more powerful than the sky-averaged spectrum but also requires significant sensitivity on a range of angular scales.

Dark Ages and Cosmic Dawn Roadmap

Way-station	Scientific Challenge
10 yr	Determine when First Light occurred by measuring the sky-averaged 21 cm spectrum over the redshift range of at least $10 < z < 35$
20 yr	Track the development of structures during First Light by measuring the H I fluctuation spectrum over at least $10 < z < 35$
30 yr	Track the evolution of the Universe during the Dark Ages by measuring at least the sky-averaged 21 cm spectrum at $z \sim 80$