The Gateway to Cosmic Dawn: A Low Frequency Radio Telescope for the Deep Space Gateway

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Introduction: If the Deep Space Gateway (DSG) is placed in low lunar orbit, it will experience a uniquely radio-quiet environment when Earth-based Radio Frequency Interference (RFI) is blocked by the Moon above the lunar farside [1]. To take advantage of this opportunity, we suggest fastening a dual-polarization low-frequency (20 MHz $\leq \nu \leq$ 100 MHz) radio antenna and receiver to the DSG. The primary scientific goal of this instrument would be to measure the never-before-observed sky-averaged (global) highly redshifted ($13 \leq z \leq 70$) spectrum arising from the 21-cm hyperfine line of neutral hydrogen. NASA's 2013 Astrophysics Roadmap [3] advocated for a small antenna in lunar orbit to measure the 21-cm signal and the 2010 Astrophysics Decadal Survey [4] pinpointed understanding Cosmic Dawn—the time of the birth of the first compact objects and a key knowledge gap addressed by the 21-cm signal—as one of its top 3 recommended priorities.

Accessible Science: Since the global 21-cm signal is a measure of the effect of the hyperfine transition of neutral hydrogen on the surrounding radiation field, it contains a history of all effects which change the relative number of neutral hydrogen atoms in the upper and lower energy states—or, equivalently, effects which change the excitation (or "spin") temperature of the transition. Because the frequency behavior of the 21-cm signal is determined entirely by how much the 21-cm photons have been redshifted since being emitted or absorbed, the spectrum can be transformed directly into redshift space, and thus can be interpreted as a history of radiation backgrounds which will fill in the gaps of our knowledge of the Universe's history (see Figure 1).

Spin Temperature Coupling Mechanisms: The three mechanisms known to couple to the spin temperature are (see [2] for a review): 1) the strength of the Cosmic Microwave Background (CMB), 2) collisions of hydrogen atoms with other atoms, which are determined by the kinetic temperature of the gas, and 3) the Wouthuysen Field (WF) effect—an effect where hydrogen gas is excited by stellar Lyman-α radiation and de-excites into either state of the hyperfine transition.

First Compact Sources Abundance and Properties: While the effect of CMB photons is essentially known, the other two effects are modulated by the strengths of local radiation backgrounds created by compact sources, specifically the X-ray background which heats the gas and the Lyman-α background which triggers the WF effect. The sensitivity of the spin temperature to these local sources leads to a 21-cm signal which, when averaged across the entire sky, contains information about the distributions of properties of the first stars and black holes. Since the amount of these sources depends on the amount of matter available after recombination, the 21-cm signal also probes parameters of the standard ΛCDM model, especially at low frequencies.

Exotic Physics: Since anything which heats the Universe's hydrogen gas would affect the spin temperature and, hence, the global 21-cm signal, some exotic physics mechanisms could be probed with the signal. One example of such a mechanism is the existence of dark

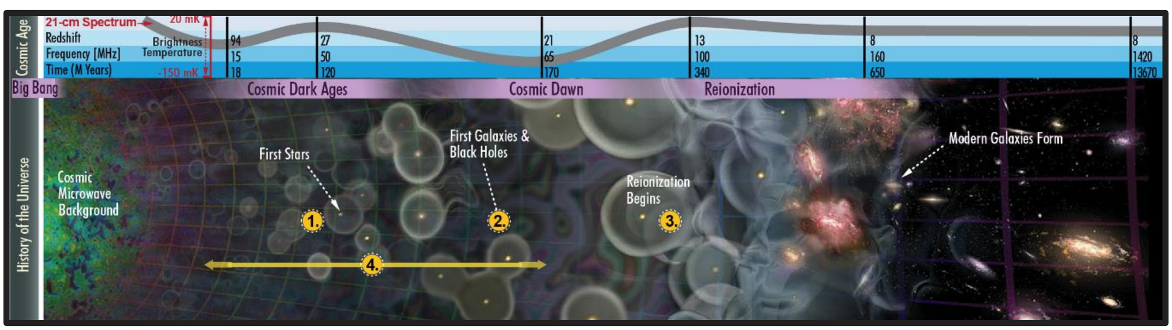

Figure 1: Schematic of the history of the Universe along with a fiducial 21-cm global signal. The first local maximum (1) comes at the end of the Dark Ages, when the first stars ignited, driving the signal into absorption via the WF effect. The local minimum during Cosmic Dawn (2) occurs when X-rays from black holes begin to heat up the gas. A local maximum occurs at the beginning of reionization (3) because the neutral hydrogen sourcing the signal begins to disappear. Note that this diagram does not include exotic physics such as self-annihilating dark matter, which would affect the signal most in the region marked (4). Given current uncertainties, the signal trough could be located anywhere between 50 and 150 MHz and can be anywhere between 50 and 300 mK deep.

matter which is its own anti-particle. Collisions between these particles would release heat into the Universe even before the first compact objects, changing the kinetic temperature of the gas.

Reionization: Because the 21-cm transition only occurs in neutral hydrogen, the strength of the 21-cm signal is proportional to the neutral fraction of hydrogen in the Universe. Current knowledge leads us to believe that the Universe was reionized sometime before z~6. The first measurements of the 21-cm signal should be able to better constrain this period.

Polarization Capability and Signal Extraction: The science objectives described above can only be completed if the global 21-cm signal can be differentiated from the Galactic foregrounds. This requires considerable effort as the foregrounds are 10^4-10^5 times larger than the signal. To mitigate this, the suggested antenna and receiver have the capability to measure all 4 Stokes parameters describing the incoming polarization (see Figure 2). This helps separate the signal from the foregrounds because the former appears only in the total power channels as it is unpolarized and isotropic while angular anisotropies of the latter interact with the large beam of the antenna to generate a projection-induced polarization signal. The data from this experiment would be analyzed using a data pipeline similar to that described in [5], which uses simulated training sets to help pick out this differential structure.

Requirements on the Deep Space Gateway: Once deployed, spacecraft maneuvers may be necessary to point the antenna in a particular direction (to within ~0.5°) but no further interaction with the crew is necessary. The ideal DSG orbit for the experiment is a low-inclination orbit about 100 km from the lunar surface which leads to an orbit period of about 2 hours. Due to the orders of magnitude difference between the Galactic foregrounds (~10^3−10^4 K) and the global 21-cm signal (~10−100 mK), in order for the thermal noise of the observations to be low enough to meet the science goals, the instrument must observe for a total of 800 hours when above the lunar farside and with the Sun out of view. A key requirement this experiment would impose on the DSG is a restriction on the EMI environment. In the 20-100 MHz range being measured, the instrument must be shielded from EMI at a level 50 dB better than the MIL-STD461F standard. Further requirements are listed in the Table 1.

Unique Utility of the Deep Space Gateway: The Deep Space Gateway offers opportunities to perform science which may be impossible to do from an Earth-based environment. For low frequency radio astronomy, the opportunity is especially fruitful because the lunar farside is the only place in the inner solar system free from human-generated RFI. We suggest that the Deep Space Gateway could also be the gateway to new knowledge of the first billion years of the history of our Universe.

Figure 2: The antenna for the low frequency radio telescope is a pair of wideband orthogonal bicones surrounded by a cylindrical sunshade (shown transparent here for clarity). The antenna rests on a deployable ground plane and is connected to a temperature-stabilized backend consisting of a pilot-tone calibrated receiver and a high-resolution digital spectrometer.

Table 1: Basic requirements placed on the Deep Space Gateway by the low frequency radio telescope described and shown in Figure 2.

DSG Requirement	Estimate
Mass	50 kg
Volume	64 m^3
Power	95 W
Data rate	1.6 Gb/orbit
Pointing accuracy	0.5°

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