THE PRIMEVAL STRUCTURE TELESCOPE

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The PrimevAl Structure Telescope (PAST), will be used to locate and study the era the of the first luminous objects, the epoch of reionization. The first stars ionized the gas around them producing a pattern of ionization that reflects the large scale density structure present at the time. The PAST array will be used to sense and study this ionization, by mapping the brightness of 21 cm neutral Hydrogen Cosmic Background (HCB) at redshift from 6 to 25. The HCB disappears on ionization, allowing the study of large scale structure and of star formation at this very early epoch.

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1. Introduction

The PrimevAl Structure Telescope (PAST) will be used to study the history of the Universe from age 100 million to 1 billion years. This period had been called "the dark ages", since no stars were thought to exist during this period. Recent observations, described below, lead us to consider whether the dark ages were in fact luminous. Evidence has come to light that the first stars formed early. With PAST we will examine this exciting period of cosmic history and define the era of the first stars. Note that we use the term "stars" here to represent any strong source of Ultraviolet radiation, even though these objects may bear little resemblance to today's stars.

The most intriguing and unexpected result to come from the new Wilkinson Microwave Anisotropy Probe is the hint that the Universe may have been ionized very early, at age $\sim$ 200 My. Kogut et al. (2003) report that the CMB scattered-fraction is surprisingly high, about 17 %. This implies early reionization, and requires a considerable release of energy at a redshift in the range 10-25. The WMAP data don't give any hint what the source of that energy might be, but if the energy source was gravitational or nuclear, if ionizing radiation was produced in compact objects, we can watch the resulting patchy ionization unfold using the PAST radio array. PAST will map early ionization by detecting the presence or absence of neutral hydrogen hyperfine emission. We will use the HI emission to map the ionization-front structure in the as-yet-undetected Hydrogen Cosmic Background (HCB).

Eventually, we anticipate that billions of primeval ionized bubbles can be imaged, each with a measured redshift. Then, as has been done with distant galaxies, ionized bubbles can be used to study concentrations of intervening matter through the technique of weak lensing mass imaging. [2] Combining this mass-imaging-via-lensing of intermediate redshift structure with three-dimensional direct imaging of high redshift ionization, PAST and successor telescopes can examine broad ranges of the history of cosmic evolution. Because of the unprecedented high redshifts of the objects to be found with PAST an ionized-bubble-lensing program has the potential to tightly constrain the cosmic evolution of Dark Energy.

The PAST will be a sparse array consisting of up to 10,000 log periodic antennas. The telescope will span several square kilometers. The system will be built almost entirely of inexpensive, commercially-available, off-the-shelf components. Details are presented below.

2. Ionization History of the Universe

The early universe was ionized by the Cosmic Microwave Background (CMB), and we also know that the universe is ionized today. The current source of ionizing flux is the cosmic distribution of stars and quasars. Before the WMAP ionization result, many cosmologist accepted the simplest ionization history that fit the data. This history has three eras: ionized at first because of the hot CMB–at $z \sim 1000$ neutral hydrogen forms and the IGM remains neutral until redshift ~ 8–then the first stars and quasars ionize the IGM. The IGM remains ionized today. However, if the WMAP result is right, that story is incorrect or incomplete. [3] [4] [5] One possibility is that the first stars formed at redshift ~ 15 and the universe has been partially ionized since. Another possibility is that the first stars came and went, at even higher redshift. In either scenario, or even if the WMAP result is in error, PAST can detect the transitions between neutral and ionized states using the technique explained below.

3. 21 cm Emission

There should be a ~ 20 mK VHF cosmic sky glow attributable to warm neutral hydrogen. [6] [7] [8] [9] [10] [11] The nuclear spin flip hyperfine transition of neutral hydrogen occurs at 1420 MHz, i.e. 21 cm in the rest frame. In the young universe, as clouds of neutral gas began to gravitationally collapse, kinetic temperatures rose to the range 10^3 to 10^4 K. As soon as a few of the first stars turned on, the photons they produced were sufficient to excite the hydrogen atoms from the ground state to the 2p state. The atoms returned to the ground state, but in either the singlet or triplet state. This coupled the spin temperature to the gas kinetic temperature and emission from the IGM became visible against the CMB.[13 14]

The 21 cm emission is from virialized clumps of mass $10^4 - 10^6 M_\odot$ [12], which some call minihalos. These clumps are much too small to be resolved spatially with PAST. They are spread out in redshift, and there are many in the observation beam, so the line emission of the many clumps forms an effective continuum in the reception frame.

This HCB sky brightness should be present across the VHF spectrum for all redshifts at which the hydrogen was neutral. But ionized hydrogen lacks 21 cm emission, so at the redshifts corresponding to ionized eras, the sky will be dimmer. This ionization begins in patches across the sky because luminous object will form first in high density regions.

Neutral hydrogen 21cm emission from the IGM (the HCB) has been studied using cosmological hydrodynamic simulations. [15 16 17] Figure 1 shows the brightness temperature variations on the plane of the sky at various times calculated using such a simulation. By scanning through frequencies, these different redshifts (which correspond to different spatial slices) can be picked out, making 3-D tomography of the IGM possible.

The detailed structure of the HCB will be quite unlike that seen in the large-scale distributions of galaxies, the former being driven by the advance of ionization fronts and the latter by gravity. However, the power spectrum of the HCB has as its source the underlying density structure. So the HCB should be simple in its power spectrum, but HCB images will be rich with the details of star formation and ionization equilibrium.

The redshift of the Hydrogen Cosmic Background falls neatly between the redshift of the Cosmic Microwave Background ($z \sim 1100$) and the Cosmic X-ray Background ($z \sim 2$). Each background tells the story of its own era. The CMB and CXB have been studied in great detail, while the HCB remains undetected. We hope to begin studying it soon.

4. Science Goal Summary

The PAST array will be used to image the end of the dark ages. It will do so by imaging the neutral Hydrogen Cosmic Background to detect the ionized regions around the first luminous sources. This information tells us when and how rapidly the universe reionized, and how many times this process occurred. The images from PAST will allow study of star formation and large scale structure at as much as four times higher redshift than is currently possible. The reionization history is directly related to the cosmological Thomson optical depth reported by the WMAP team. PAST will independently measure this critical parameter. PAST will also produce

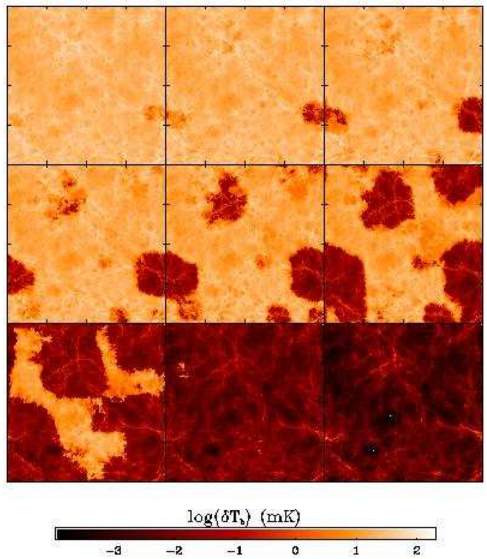

Fig. 1. **Simulated VHF sky images.** The nine panels show simulated sky brightness in redshifted 21-cm emission, separated in time, beginning in the upper left. Already in the first time slice the densest region, at the right of the panel, is losing brightness as the first stars are beginning to ionize the hydrogen gas. By the final panel the entire sky is dim–the IGM is ionized. Note the high contrast in the intermediate images. The typical patch size is expected to be around 5 arcminutes. In this particular model, the total redshift range of the transition corresponds to about 6 MHz in the received spectrum. Plot provided by S. Furlanetto

a new spectral survey of radio galaxies.

5. Competing Sources of Sky Brightness

The VHF sky is dominated by the glow of synchrotron emission from within the Galaxy. Even on the dimmest parts of the sky, near the Galactic poles, the sky brightness temperature is 1000K at 40MHz, declining to around 40 K at 210 MHz. Behind this blaze we will attempt to detect patches with temperature contrast 20 mK, with typical size 5 arcminutes, that evolve substantially within a one Megahertz frequency range. Fortunately, the low frequency synchrotron spectrum of Galactic emission is a featureless power law and the galaxy has little structure at 5 arcminutes angular scale. The spatial and spectral signatures of reionization patches in the HCB distinguish them from Galactic structure.

Extragalactic radio sources are a significant foreground. The brightest can be identified and cut, but a confusion contribution will always remain, creating a statistical patchiness across the sky. However, as seen in figure 2, even simple subtraction of the brightest sources from the sky images should allow detection of HCB structure. In addition, the sharp spectral signature of the ionization will be a powerful discriminant.

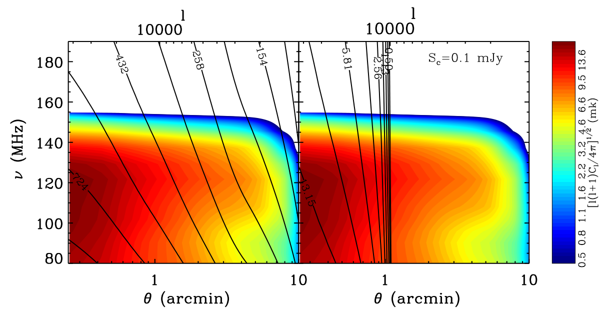

Fig. 2. **VHF Extragalactic Foreground.** The colored shaded area is the 21cm signal (power spectrum) from high redshift. THis is the HCB signal we seek. The case presented here is according to the model of Ciardi & Madau, 2003, Apj, 596. In this example, reionization occurs fairly smoothly - the signal is spread over a wide range of frequency space. The signal is strong at frequencies below the time of full reionization, which in this model occurs at z $\sim$ 12. With a slightly top-heavier IMF the same model can produce earlier reionization as well. The black lines are the contours (labeled with the respective values in mK) for a predicted radio-galaxies foreground. In the left panel no source subtraction has been made. The foreground signal is 50 higher than the 21cm signal PAST seeks. In right hand panel, sources with flux greater than 0.1 mJy were removed. The overall amplitude of the power spectrum/signal is significantly reduced and in particular the power in the smaller ℓ (large angles) drops out completely. This is because the power spectrum there is dominated by the few brightest sources, which are eliminated by using this cut. Note that no spectral information was used in making this cut, adding spectral modeling of sources will improve the removal efficiency. An efficient source removal scheme should leave angular scales of a few arcminutes free of point source contamination. Plot provided by T. Di Matteo.

Free-free emission from the high redshift ionized universe will also contribute to sky brightness. This emission is neither point-like nor smooth, but has spatial structure comparable to the neutral hydrogen transition.[18] The total amplitude on arcminute scales can be larger than the 21cm emission. However, because free-free and synchrotron spectra vary smoothly with frequency, we can distinguish these sources from the line emission we seek. In addition, the free-free emission from regions of early ionization can be used to study the ionization process. This is a signal, rather than a source of noise.

It is clear that in the face of such strong competing signals it will be essential to use both spatial and spectral discrimination to separate the ionization signal in the HCB from astronomical foregrounds. These requirements drive the design of PAST.

6. Instrument Design

The redshift range of interest is 6 to 25, so the frequency range of the telescope is about 200 MHz to 50 MHz.

The frequency resolution is set, not by astronomical requirements, but by the need to remove a few man-made lines from the spectrum. Although we will use an extremely quiet site for PAST our site tests so far still show a few man-made lines. These lines are narrow, generally a few kilohertz wide, and the spectral resolution has been chosen to allow their isolation and removal.

The spatial scale range to be covered is determined by the need to avoid extragalactic foregrounds, while still detecting the large scale structure that underlies the ionization pattern. This is illustrated in figure 2. We chose 3 arcminutes at 100 MHz as the resolution of the telescope.

The spatial resolution sets the longest baseline at around 3 km. This large size, combined with the relatively high contrast (20 mK) of ionization structure, immediately points us to a dilute array as the appropriate technology for this telescope.

We want even UV coverage to faithfully generate images. Also, over some particularly interesting range of frequency we may wish re-analyze our data by synthesizing frequency-independent beams. That can be done using wavelength-scaled apodization of the visibilities across the UV plane. This works best if there is dense, uniform UV coverage. To meet these requirements we will use about 20 interferometer elements, which we also call pods, providing 190 instantaneous baselines. Earth rotation will fill in the UV plane.

The effective area of the elements depends on the system temperature, integration time, and desired surface brightness sensitivity. For N$\sim$ 20, the elements must have effective diameters much greater than the wavelength. In other word the elements must have substantial antenna gain. We accomplish this by assembling the elements as phased arrays of log periodics. Each antenna within the elements will have selectable phase delay, allowing an electronically steered beam.

Conveniently, twice the top frequency, the Nyquist sample rate, is within the sample speed limit of a variety of off-the-shelf Analog to Digital Converters. We will use such ADCs to sample each element signal directly into a PC computer. The FX correlator for PAST will be built as a Beowulf network of such PCs. All components are commercial off-the-shelf items.

7. Sites

Sites we have visited and examined for PAST include, in China: Delingha Station, Urumuqi Station, Tung-guo, Ulasitai, and we have examined the South Pole. For now we will concentrate our development effort at Ulasitai(E 86° 41', N 42° 56'), because of the support available there. Ulasitai is accessible by road and rail year-round, has electrical power, and is a short distance from the VLBI site, Urumuqi Station where engineering assistance, test equipment and a machine shop are available for our use. We will make the final site selection after gaining more field

Table 1. Specifications of Planned PAST Instrument.

Parameter	Goal (at 150 MHz)
Total antennae	10000
Effective Elements	20
Effective area	70,000 m^2
Sky brightness temperature	90 K
Instantaneous imaging field of view	2 sq deg
Angular resolution	3 arc minutes
Instantaneous frequency coverage	50 - 200 MHz
21 cm redshift range	6 +
Frequency resolution	4 kHz
Comoving radial spatial resolution	140 kpc
Comoving transverse spatial resolution	6 Mpc
Brightness temperature sensitivity	20 $mK/\sqrt{\text{day}}$

experience at several sites.

The most important reason that the telescope must be sited at a remote location is to avoid interference from television and FM radio transmitters. These transmitters operate throughout the frequency range of this telescope. Some emit Megawatts of VHF power. Each television signal occupies a band several megahertz wide. Transmitter spurious emissions are often much wider. Astronomical fringes, recorded on-site, using a PAST prototype correlator and two log periodic antennas are shown in figure 3.

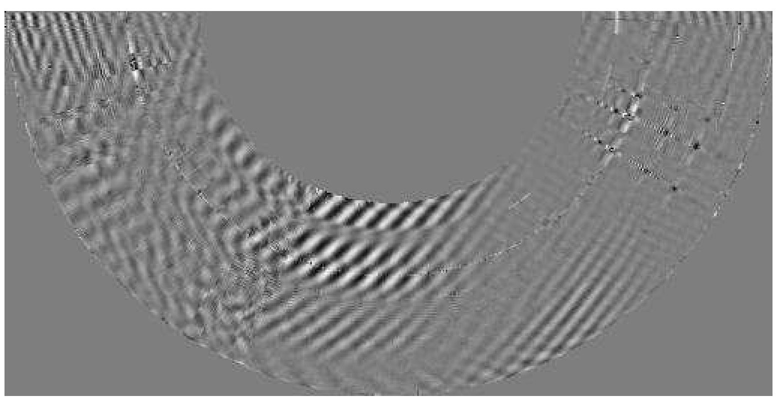

Fig. 3. **First PAST Interference Fringes** Two log periodics at 67 meters separation were sampled using a commercial off-the-shelf ADC installed in a PCI slot in a Pentium IV PC. Aliased sampling was used to measure a band of frequencies above the Nyquist frequency. The UV plane fringes shown here are the correlator output values for 16k frequencies from 100 to 200 MHz. The fringes in the image are due to bright sources in the Galactic plane, and this has been confirmed by fourier transforming this UV image to create a sky brightness image. The fringes are curved in the image, since no compensation for differential dispersion has yet been made. These are our first 12 hours of interference data.

8. References

1. Kogut, A., Spergel, D. N., Barnes, C., Bennett, C. L., Halpern, M., Hinshaw, G., Jarosik, N., Limon, M., Meyer, S. S., Page, L., Tucker, G. S., Wollack, E., Wright, E. L., 2003, *Astrophys. J. Supp.*, 148, 161
2. Pen, U., astro-ph/0305487
3. Cen, R.*Astrophys. J. Lett.*, 591, L5
4. J. Mackey, B. Volker, and L. Hernquist., astroph/0208447
5. V. Bromm, N. Yoshida 2003, and L. Hernquist, submitted to *Astrophys. J. Lett.*, astroph/0305333
6. Sunyaev, R.A., & Zeldovich, Ya. B., 1972, *Astron. & Astrophys.*, 20, 189
7. R. A. Sunyaev and Y. B. Zel'dovich 1975, MNRAS, 265, 365
8. C. J. Hogan and M. J. Rees 1979, *Mon. Not. R. astr. Soc.*, 188, 791
9. D. Scott and M. J. Rees 1990, *Mon. Not. R. astr. Soc.*, 247, 510
10. K. Subramanian and T. Padmanabhan 1993, *Mon. Not. R. astr. Soc.*, 265, 101
11. Madau, P., Meiksin, A., & Rees, M.J., 1997, *Astrophys. J.*, 475, 429
12. Iliev, I., Shapiro, P.R., Ferrara, A., Martel, H., 2002, *Astrophys. J.*, 572, 123.
13. Wouthuysen, S.A., 1952, *Astron. J.*, 57, 31
14. Field, G., 1959, *Astrophys. J.*, 129, 551
15. Gnedin, N. Y. & Shaver, P.A., 2003, *Astrophys. J.*, submitted, astro-ph/0312005
16. Furlanetto, Sokasian & Hernquist (2004), *Mon. Not. R. astr. Soc.*, 347, 187
17. Ciardi & Madau, P., 2003, *Astrophys. J.*, 596, 1
18. Oh, S.P. and Mack, K.J., *Mon. Not. R. astr. Soc.*, 346, 871