

## **Report of Science Working Group 3**

### **Early Universe and Large Scale Structure**

#### **SKA Science Workshop Bologna, 14-15 January 2002**

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The interests of this group were focused on the Epoch of Reionization, and since there were no participants present who specialize in “Large Scale Structure as measured by continuum or spectral line surveys”, the group discussed only the potential for using SKA for EoR studies.

#### ***The Scientific Discussion***

The discussion benefited greatly from the presence of two theorists - Iliev and Tozzi - who have been modeling the 21cm emission from this epoch. Tozzi (+ colleagues) has several papers in the literature on this topic, and Iliev et al are preparing a preprint for release in the near future. Their work is based on N-body codes that follow the evolution of dark matter halos and the development of large scale structure. They add gas to follow the behavior (concentration and ionization level) of the baryons. Radiation transfer, including ionizing flux, Lyman lines and the 21cm line, predicts the spectrum and spatial structure of the diffuse radio sky at long wavelengths. It is important in appraising the possibilities for probing this epoch with radio telescopes that the evolving structures give rise to both spectral and spatial features in the radio sky.

Observations to probe the epoch preceding the most vigorous reionization promises to be a rich field of study for the astrophysics of primordial gas as it becomes concentrated in the forming mini- or sub-halos that will eventually merge to form the galaxies of the present. There are several stages of formation of the proto-galaxy evolution that can be probed with radio observations in a redshift regime that is totally blocked from view at optical wavelengths.

The distinct pre-reionization stages are:

1. Collapse of mini-halos... dark matter halos at this stage have such low masses that the HI can be compressed and heated to the extent that the 21cm line from these concentrations are seen in emission. The gas density becomes high enough that the hydrogen spin temperature is collisionally coupled to the gas kinetic temperature, which has been heated by gravitational compression to above the background CMB temperature.

Individual halos are too small to be detected individually with a telescope of SKA

collecting area, but the precursor of eventual Large Scale Structure causes there to be sufficient clustering already at this time (redshifts around 10) that there is contrast between the regions where the mini-halo distribution is over- and under-dense. When spatially averaged to match radio telescope beams, the models predict fluctuations of a few milli-K on angular scales of 10 arcminutes. Toward higher resolutions, the brightness fluctuations are expected to rise steadily to of order 10 mK on angular scales of an arcminute and less. At these fine scales, the calculation enters a non-linear regime that the current level of modeling does not follow, but the implication is that the brightness will rise even more steeply.

During this period, the halos have formed no stars, and there are not yet objects that would be called galaxies or even protogalaxies. If there has been a Pop III generation of stars, it lived and died prior to this period, perhaps provided the base-level of metals that is observed throughout the Lyman alpha forest and in the lowest metallicity stars at  $z=0$ .

Note that the Universe is opaque to ionizing radiation and Lyman lines through this period, and until the Universe is fully reionized and transparent at redshifts below 6.

2. Reheating and the WF Effect... the onset of the formation of stars in the mini-halos as they merge and grow to form the first galaxies provides a radiative flux that reheats and eventually reionizes the IGM once the flux is able to escape from the over density of neutral gas that collected in the mini-halos. The neutral gas may be photoionized once star formation occurs or may be shock ionized during mergers.

The degrading of ionizing and Lyman series lines leads to a strong Lyman alpha flux, which is resonantly scattered in the neutral medium. In the Inter-Galactic Medium gas of low density, the Wouthuysen-Field effect causes the hydrogen spin to couple to kinetic temperature, which at this time has dropped by adiabatic expansion to below the CMB temperature. This leads to the exciting possibility of seeing vast volumes of IGM in absorption against the microwave background with apparent signal strength of some tens of mK, possibly on very extensive angular scales that it could be detected with very low resolution telescopes – or even as a global absorption signal, if the star formation is synchronized throughout the sky.

Note that without the resonantly scattered Lyman alpha flux or localized compression in DM halos, the spin temperature of the low-density neutral IGM remains tied to the CMB flux, and therefore there is no contrast between the IGM and the CMB until reheating occurs.

2.a. Localized WF Effect... there is the possibility that the first quasars would be capable of providing localized spin temperature coupling of a significant volume of their surrounding neutral IGM to the IGM kinetic temperature. This could give rise to detectable localized absorption features that drop below the CMB. These spectral features would have the widths corresponding to the Doppler and Hubble flow velocities of the affected volume.

The spatial structure would be ring-like with angular scales of arcminutes. Such structure would be highly diagnostic, pointing to the site of origin of the exciting flux, possibly in objects that are heavily obscured, even at infrared wavelengths.

3. Large scale reheating... continued growth of structure is expected to lead to large quantities of the neutral gas having spin temperatures above the CMB temperature, accompanied by continued growth in apparent structure in the radio sky as the redshift approaches the redshift of transparency at  $z=6.2$ .

The transition from neutral to ionization....

4. Whether or not there was a sufficiently abrupt IGM reionization that was synchronized throughout the Universe will determine whether a global signal will be detected in the spectrum of the radio sky.

***Conclusions and Answers to General Questions for the Sub-Groups:***

SKA Science Level:

We decided that EoR Science is 'Level 1' since it is unique to radio astronomy. To take full advantage of the scientific opportunities a collecting area of at least a square kilometer is required. The LOFAR telescope, which is being designed to operate in the relevant frequency range from 100 to 220 MHz, will not have sufficient sensitivity to fully capitalize on the science. In this sense, it can be viewed as an 'exploratory' instrument.

***Observation Parameter Space***

Here follow some estimates of signal strength for emission at different resolutions and redshifts. More detailed plots will be soon available in the preprint of Iliev et al.

Redshift	Frequency	Resolution	Aperture	Signal <sup>a</sup>	Noise <sup>a</sup>
	MHz	arcmin	km	$\mu\text{Jy}$	$\mu\text{Jy}$
7	180	3	2	3 - 5	0.5
9	140	3	2.5	2 - 10	0.7
9	140	1	7	0.2 - 1	0.7

<sup>a</sup> for a bandwidth of 1 MHz and integration time of 600 hours.

Here the signals are taken to be the 3 sigma fluctuations that occur in a few percent of the pixels in a map of a large region of sky. The noise level is the rms fluctuations due to receiving system noise level, which at these wavelengths is dominated by the noise from the sky itself.

The implication is that this project would need to have a square kilometer of collecting area within a central patch that is less than 10 km in diameter.

### *Adequacy of Strawman Specification*

NOT ADEQUATE.

Strawman does not provide sufficient collecting area confined to central patch to achieve the necessary surface brightness sensitivity.

### *Simulations*

Simulations are required to improve the theoretical predictions of the nature of the signals, how the signals depend on cosmological model, and what are the most relevant astrophysical dependencies.

On the observational/technical side, simulations and further study are required to verify that the telescope can be calibrated. Relevant effects are loss of phase coherence due to variable ionosphere refraction and subtraction of a wide range of confusing foregrounds (including emission from the diffuse Galactic Interstellar Medium and from the full sky of discrete extragalactic radio sources).

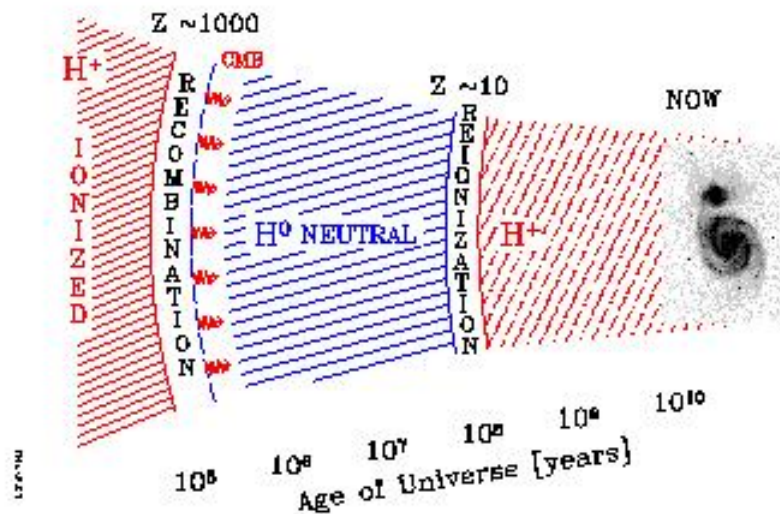


Figure 1: The T-I Diagram (Tozzi & Iliev, private communication, January 2002), an illustration of the astrophysical signatures in the radio sky, prior to and during Reionization. The time sequence follows (1) the condensation and heating of neutral gas into low mass Dark Matter halos near the end of the Dark Age but prior to the

ignition of the first stars in protogalaxies, (2) the consequences of Reheating of the IGM, prior to Reionization, and (3) the final reionization of the IGM, leading to optical transparency and the beginning of the Observable Universe accessible to optical wavelengths at the far right of the diagram. The vertical axis gives theoretical predictions of the magnitude of the brightness temperature fluctuations in milli-Kelvin; for the mini-halos prior to Reheating, the magnitude of the fluctuations will be a strong function of size scale, and the T-I diagram indicates larger rms fluctuations on angular scales of 0.1 arcmin than for 1 to 10 arcminute scales. There is a possibility of a very strong absorption feature developing on wide angular scales during the reheating phase, as the IGM hydrogen spin temperature is coupled to the gas kinetic temperature by resonant scattering of the Lyman-alpha flux generated by the first protogalactic stars (the Wouthuysen-Field Effect); this could give rise to a global spectral signature of absorption against the Cosmic Microwave Background, if there is widespread synchronization of protogalaxy formation. A related absorption signature may appear on smaller angular scales of a few arcminutes around the first Active Galactic Nuclei. Throughout the Reheating period, the hyperfine level populations of the neutral IGM may be progressively coupled to the cool gas kinetic temperature on larger scales, prior to the wave of ionization that will spread through the diffuse IGM and lead to an abrupt decline as the Universe becomes fully ionized and transparent to ionizing radiation.