The Metrewavelength Sky
ASI Conference Series, 2014, Vol. 13, pp 219 – 225
Edited by J. N. Chengalur & Y. Gupta

The dark ages, cosmic dawn and epoch of reionization seen at radio wavelengths

L. V. E. Koopmans*
Kapteyn Astronomical Institute, University of Groningen, The Netherlands

Abstract. A short review is presented of the Dark Ages, Cosmic Dawn and Epoch of Reionization (EoR), in particular focussing on (planned) studies via the redshifted hydrogen 21-cm hyperfine transition. Current constraints on the EoR and current interferometric experiments (with the GMRT, MWA, PAPER and LOFAR) to detect the 21-cm brightness temperature are discussed and a forward look it presented on the Square Kilometre Array (SKA) and how how it can revolutionize this field from statistical (e.g. power-spectra) to tomographic (e.g. image-cube) analyses.

Keywords : Cosmology – cosmic dawn – epoch of reionization

1. Introduction

The first $\sim 10^9$ years of the Universe, wedged in between the recombination era and the era where most of the Universe was nearly fully ionized again, is still largely unexplored. Hydrogen was largely neutral during this time, until reionization by the first stars, quasars, and possibly still unknown sources set in and (re-)ionized hydrogen once more. This early period is a treasure-trove for cosmologists and astrophysicists studying the structure of the universe and the earliest phases of star, galaxy and black-hole formation and the enrichment of the IGM/ISM. The initial conditions of baryonic structures that we see emerge at $z < 6$ in some cases (e.g. low-mass stars, the IGM, low-mass satellites) might be due to processes that ocured during the Cosmic Dawn and Epoch of Reionization (CD and EoR hereafter). Whereas great progress is being made through studies of high-redshift sources, e.g. Ly-alpha emitters, drop-outs, GRBs and quasars, the uv-radiation from these observed sources is not sufficient to explain the transition from a neutral to a fully ionized universe. The real sources of (re-)ionization are beyond the reach of present-day telescopes and potentially even

*email: koopmans@astro.rug.nl

beyond the reach of the JWST. This makes the complementary study of the neutral hydrogen itself very important, in particular at redshifts where these sources become rare, faint and potentially even redshifting out of the wavebands of IR telescopes. A second advantage of observing neutral hydrogen is that is can be done over wider fields of view (tens of square degrees) with radio-interferometers, unlike the small FoVs (few square arcminutes) of IR telescope. In this short review I will outline the main phases during the CD/EoR (Section 2), provide an overview of current constraints on the EoR (Section 3) and shortly review the four current interferometric EoR detection experiments (Section 4). I then look forward to the planned Square Kilometre Array (SKA) and how it could revolutionize the study of the CD/EoR via 21-cm tomography (Section 5). I close with some general statements (Section 6).

2. HI in the dark ages, cosmic dawn and epoch of reionization

Radio-telescopes measure the sky's intensity distribution (or its Fourier transform), which at high z can be expressed in terms of a brightness temperature $T_{\rm b}$ as (e.g. Madau et al. 1997):

$$\delta T_{\rm b} = 27 x_{\rm HI}(1+\delta_{\rm b})\left(\frac{\Omega_{\rm b}h^2}{0.023}\right)\sqrt{\left(\frac{0.15}{\Omega_{\rm m}h^2}\frac{(1+z)}{10}\right)}\left(\frac{T_{\rm spin}-T_{\rm CMB}}{T_{\rm spin}}\right)\left[\frac{\delta_r v_r}{(1+z)H(z)}\right]\ \mathrm{mK} \tag{1}$$

This equation contains several terms set by either cosmology (i.e. the global baryonic density and its spatial fluctuations, $\Omega_{\rm b}$ and $\delta_{\rm b}$, respectively; the total mass density and the Hubble constant $\Omega_{\rm m}$ and $H(z)$ or h, respectively), by (g)astro-physics (i.e. the spin-temperature $T_{\rm spin}$ of HI, the CMB temperature $T_{\rm CMB}$) and by Doppler effects ($\delta_r v_r$; e.g. due to peculiar motions and bulk-flows of the gas). Via the brightness temperature and different measures of it, e.g. variance, higher-order statistics, power-spectra, n-point correlations, tomographic cubes (i.e. images), HI-absorption spectra, cross-correlation, etc., one can address questions about the physics and sources responsible for processes during the CD/EoR such as (X-ray) heating, (Wouthuysen-Field) coupling, feedback, recombination, ionization, photon sinks, bulk-flows, light-cone effects, redshift-space distortions, metalicity, etc, and the sources ultimately responsible for (re-)ionization (e.g. stars, AGN), and connect these to stellar, ISM/IGM, galaxy and structure formation and evolution in the Universe at z<6 (see e.g. Barkana et al. 2001; Furlanetto et al. 2006; Morales et al. 2010; Pritchard et al. 2012; Mellema et al. 2013, for general reviews and detailed references). The three main phases that can be identified (although their definitions are not very strict and physical processes can overlap between eras) are the following – **Dark Ages (z ∼ 200 – 30):** After recombination hydrogen was largely neutral with its spin-temperate coupled – via trace electrons – to the cold gas-temperate, and it can therefore only be seen in absorption again the CMB. At the end of the Dark Ages (DA hereafter) the density of trace electrons, however, dropped sufficiently to make the coupling of the spin and gas temperature inefficient. The spin temperature starts to follow the CMB temperature again and $T_{\rm b}$ approaches zero from below. This phase is thought to just preceed the formation of the first radiating objects (see below) and lasted probably only briefly or might not even have been fully reached (i.e. $T_{\mathrm{b}} \sim 0$ mK). Processes that can be studied through measurements of T_{b} during the DA are the dark-matter power-spectrum evolution and its annihilation physics, baryonic bulk-flows (Tseliakhovich et al. 2010) and the physics of gravity and general relativity. The physics during this era can be large understood through linear theory (Lewis et al. 2007) and deviations of observation from ΛCDM predictions will immediately indicate new physics. Studying the DA however will remain out of reach for the near future and requires space-based radio telescopes since the 21-cm emission will have been redshifted to near or below the ionospheric cutoff. **Cosmic Dawn (z ∼ 30 – 15):** The Cosmic Dawn (CD) is typically defined as the time when the first stars (or other radiating sources) were formed. Ly-alpha emission from these sources efficiently coupled the spin temperature to that of the cold gas (via the Wouthuysen-Field effect), again leading to HI seen in absorption. At the same time, however, the gas itself was heated supposedly via X-ray heating. This gas-heating and the parallel process of coupling the spin and gas temperature led to a rapid rise in the brightness temperature of HI until it is finally seen in emission around $z \sim 15$. One should note that many of these processes are still ill-understood and all these effects (heating, coupling, etc) could shift around in redshift substantially, especially between the CD and EoR. Hence when these processes exactly occurred is not known and redshifts indicated here are merely indicative numbers currently expected from theory. Processes that can be studied during the CD are the formation of the first (pop III) stars, the first BHs, X-ray heating sources, W-F coupling, bulk-flows, etc. **Epoch of Reionization (z ∼ 15 – 6):** While heating and W-F coupling change the spin-temperature of the HI, the same radiation field (i.e. uv-radiation) starts to ionize HI leading to the percolation of bubbles around the first mini-haloes containing (pop-III/II) stars and possible intermediate mass black holes, i.e. mini-quasars. As time progresses and the universe becomes more non-linear (on small scales), more stars and quasars are formed. Recombination, although possibly having considerable impact, can not stop or balance ionization and by $z \sim 6$ the entire universe, apart from pockets of neutral HI (mostly in galaxies), will be ionized once more. Processes that can be studied during the EoR are the ionizing sources, such as pop-III and II stars, mini-quasars, feedback to the IGM and the transition from to the visible universe as currently seen in deep infrared observations.

3. Current observations of the epoch of reionization

Although rapidly improving, current constraints on the EoR are sparse and those from the CD and DA are fully absent. Our current understanding of these periods largely comes from theoretical considerations combined with a handful of observations. Current observation are: – **(a) Gunn-Peterson Troughs:** Observations of high-z quasars, currently out to $z \sim 7.1$ (Mortlock et al. 2011) shows progressively more absorption of quasar emission blue-ward of Ly-alpha, with the damping wing of Ly-alpha in general considerably suppressing even emission redward of the central wavelength of Ly-alpha. The optical depth due to neutral hydrogen suggests that ionization was completed by $z \sim 5-6$ but that around $z \sim 7$ the universe could potentially have been neutral at the $\sim$ 10% level. **(b) Gamma-Ray Bursts:** GRBs have now been observed out to $z \approx 8.2$ (Tanvir et al. 2009) potentially even higher. They are tracers of the star-formation rate at the high-mass end of the stellar mass function, although it would require correction for selection effect (e.g. orientation) and knowledge of the IMF shape to turn these into constraints on the UV-radiation field responsible for ionization of HI. **(c) IGM Temperature:** Temperature measurement of the IGM at higher redshift ($\sim 4-5$) combined with the notion that gas cools adiabatically suggest that reionization happened below $z \sim 8-9$ (Bolton et al. 2010), although the errors are large. At that redshift the gas would have been $\sim 30,000$ K expected just after ionization. This is a constraint on the EoR that is often forgotten, but is quite important. In the case of re-heating of the gas, however, those limits could shift to higher redshifts, but it's not clear what mechanism could do that. **(d) CMB Scattering:** Scattering of CMB photons of electrons after/during ionization leads to a measurable polarized signal in the CMB on large scales. Current observations suggest that ionization peaked around $z \approx 10 \pm 4$ (e.g. Dunkley et al. 2009), in general agreement with the above-mentioned constraint from the IGM temperature. In combination with the G-P optical depth this suggests an extended period of ionization with a long tail toward lower redshifts ending around $z \sim 6$. **(e) High-z galaxies:** Through drop-out techniques deep HST observations have started to reveal galaxies potential out to $z \sim 12$ (e.g. Ellis et al. 2013). Below this redshift the LF is evolving very rapidly potentially with a break at ~ 8 below which evolution occurs still fast but slightly slower. However, the LF needs to be extrapolated by ~7 magn. to have enough ionizing photons and even for JWST these faints sources will be a challenge. Overall observations seem consistent with reionization occurring around $z \sim 10$ and having a tail of maybe ~10% neutral hydrogen down to $z \sim 7$, but the population responsible for the bulk of re-ionization has not been discovered yet.

4. Current interferometric HI-detection experiments

In this section a short review is given of the four main active interferometric experiments to detect the redshifted 21-cm: – **GMRT:** Deep observations to detect HI at $z > 6$ were done first with the Giant Metre-Wave Telescope in India, near Pune. Based on 40 hrs data from December 2007 on a field centered on PSRB0823+26 [FWHM=3.1 degree primary beam, 20 arcsecond resolution, frequency range of 139.3–156.0 MHz (64×250kHz with 64 sec time resolution)], i.e. $z = 8.1 - 9.2$ gave, a first firm constraint on the HI power-spectrum , i.e. a 2-σ upper limit at $(248\ \mathrm{mK})^2$ at $k = 0.50$ $h\,\mathrm{Mpc}^{-1}$ was given by Paciga et al. (2011). **PAPER:** The Precision Array for Probing the Epoch of Reionization consisting of two array deployments, one at NRAO Greenbank with 32 elements and one at the Karoo in SA with 64 elements. The array performs drift-scans over a wide FoV (~60°). Based on 275 hrs of data taken with the 32-element array between 12/2011 and 2/2012, in the range 100 to 200 MHz (2048 channels, 10.7 sec integrations), a 2−σ upper limit of $(52\ \mathrm{mK})^2$ for $k = 0.11$ $h\,\mathrm{Mpc}^{-1}$ at $z = 7.7$ was published by Parsons et al. (2013). **MWA:** The Murchison Widefield Array is situated in the western Australia and consists of 128 tiles (of 4×4 dipoles) in a compact configuration (up to 2.8 km baselines). Using a 32-tile prototype array, 22 hrs of data was obtained in 3/2010, on a field (FoV~25°) centered at R.A.(J2000) = 10h20m0s and Decl.(J2000) = -10°0'0". A set-up of 3×30.72 MHz bands, centered at 123.52, 154.24 and 184.96 MHz respectively, covering the redshift range $6.1 < z < 12.1$. In total 5 hrs was spent at 123.52 MHz and 154.24 MHz, and 12hrs at 184.96 MHz. Upper limits on the power spectrum at z=6.2–11.7 were obtained. The lowest limit is (300 mk)^2 at the 95% confidence level at a comoving scale $k = 0.046\,\mathrm{Mpc}^{-1}$ at $z = 9.5$ (Dillon et al. 2013). **LOFAR:** The Low Frequency Array is situated in the Netherlands (core plus 14 remote stations) extending in to Europe (8 stations). The core has baselines up to ~3 km and consists of 48 high-band antenna stations, made up of 24 tiles of 4 × 4 dipoles each. The FoV per station is $\sim 4°$ at 150 MHz. Based on 114 hr of analyzed data on the NCP in the frequency range 115–189 MHz (stored at 12-kHz, 3-sec resolution, but currently analyzed at 180 kHz resolution), an upper limit a factor ~5 from the nominally expected HI brightness-temperature variance at $z \approx 8-9$ has been reached, integrated over $k \approx 0.03 - 0.2\,\mathrm{Mpc}^{-1}$. A more detailed power-spectrum analysis is ongoing (Zaroubi et al. 2014, in prep.). All experiments have made tremendous progress in their attempts to *statistically* detect HI at $z > 6$, overcoming a considerable challenges. Although no detection has been claimed yet, success is expected in the coming years. However, all current arrays lack sufficient sensitivity to *directly* image HI brightness temperature fluctuation expected to be at the few-mK level. This requires considerably more collecting area.

5. Observing the CD/EoR with the square kilometre array

The Square Kilometre Array[1] (SKA) is a global effort to build the next-generation interferometric radio array[2] with cores in South-Africa and Australia. "SKA-low", in the current baselines design, will cover 50-350 MHz with ~1024 stations (D~35 m each) out to ~70 km baselines, fully covering the (expected) CD/EoR redshift range of $z \approx 27-3$. SKA's enormous sensitivity (A/T~$1000\,\mathrm{m}^2/\mathrm{K}$) on short ($< 6\,\mathrm{km}$) baselines, ad planned FoV of at least 5°, allows major steps forward over all current arrays: **(1)** Determine the HI-T_b power-spectrum with high S/N on few arcmin scales and larger over the full redshift range $z \approx 27-6$. **(2)** Image the 1-mK HI brightness temperature fluctuations directly with a good S/N on scales of >5 arcmin over the reshift range of $z \approx 27-6$. Tomographic data-cubes can be constructed that contain much more information than do the power-spectra. **(3)** Potentially access the very small k modes through HI-absorption against high-z radio source (if they exist). Hence, SKA can address CD/EoR science via a broad range of observables: e.g. brightness-temperature variance, higher-order statistics, power-spectra, n-point correlations, tomographic cubes (i.e. images), HI-absorption spectra, cross-correlation etc.

[1] http://www.skatelescope.org/

[2] see also HERA: http://reionization.org/

These capabilities will transform CD/EoR research from currently statistical detection experiments, with exciting but still limited capabilities, to a research area where direct high-S/N imaging can be done. An extensive review of CD/EoR science capabilities of the SKA-low is given by Mellema et al. (2013).

6. Conclusions

Ground and space-based infrared telescopes have begun to explore sources in the EoR for the first time over the last year, potentially up to $z \sim 12$ already. Discovered sources include Ly-alpha emitters, drop-out galaxies, GRBs and quasars. Combined with the G-P, IGM temperature and Thomson scattering measurements places reionization around $z \sim 10$ possibly with a long tail below that redshift. All these studies are limited to very small FoVs (also with ALMA) and only address questions about radiating sources. Despite enormous progress, 7-mag deeper observations might be needed to reach the mini-haloes responsible for re-ionization, which is hard even for the JWST. Observing HI during the CD and EoR provides a complementary approach. Despite the current lack of direct detections of high-z HI, increasingly tighter upper limits from the GMRT, PAPER, MWA and LOFAR make this a very exciting time and promise a genuine detection over the coming years. With the planned SKA (and also HERA) high-z HI observations will move, in the next decade, from statistical detections to direct imaging, another revolution in the making.

Acknowledgements

The author thanks the MWSKY organizers for an extremely well-organized and exciting meeting.

References

Barkana R., Loeb A., In the beginning: the first sources of light and the reionization of the universe, Physics Reports, 349:125–238, July 2001

Bolton J. S., Becker G. D., Wyithe J. S. B., Haehnelt M. G., Sargent W. L. W., A first direct measurement of the intergalactic medium temperature around a quasar at z = 6, MNRAS, 406:612–625, July 2010

Dillon J. S., Liu A., Williams C. L., Hewitt J. N., Tegmark M., Morgan E. H., Levine A. M., Morales M. F., Tingay S. J., Bernardi G., Bowman J. D., Briggs F. H., Cappallo R. C., Emrich D., Mitchell D. A., Oberoi D., Prabu T., Wayth R., Webster R. L., Overcoming real-world obstacles in 21 cm power spectrum estimation: A method demonstration and results from early Murchison Widefield Array data, ArXiv e-prints, April 2013

Dunkley J., Komatsu E., Nolta M. R., Spergel D. N., Larson D., Hinshaw G., Page L., Bennett C. L., Gold B., Jarosik N., Weiland J. L., Halpern M., Hill R. S., Kogut A., Limon M., Meyer S. S., Tucker G. S., Wollack E., Wright E. L., Five-Year Wilkinson Microwave Anisotropy Probe Observations: Likelihoods and Parameters from the WMAP Data, ApJS, 180:306–329, February 2009

Ellis R. S., McLure R. J., Dunlop J. S., Robertson B. E., Ono Y., Schenker M. A., Koekemoer A., Bowler R. A. A., Ouchi M., Rogers A. B., Curtis-Lake E., Schneider E., Charlot S., Stark D. P., Furlanetto S. R., Cirasuolo M., The Abundance of Star-forming Galaxies in the Redshift Range 8.5-12: New Results from the 2012 Hubble Ultra Deep Field Campaign, ApJL, 763:L7, January 2013

Furlanetto S. R., Oh S. P., Briggs F. H., Cosmology at low frequencies: The 21 cm transition and the high-redshift Universe, Physics Reports, 433:181–301, October 2006

Lewis A., Challinor A., 21cm angular-power spectrum from the dark ages, PhRvD, 76(8):083005, October 2007

Madau P., Meiksin A., Rees M. J., 21 Centimeter Tomography of the Intergalactic Medium at High Redshift ApJ, 475:429, February 1997

Mellema G., Koopmans L. V. E., Abdalla F. A., Bernardi G., Ciardi B., Daiboo S., de Bruyn A. G., Datta K. K., Falcke H., Ferrara A., Iliev I. T., Iocco F., Jelić V., Jensen H., Joseph R., Labroupoulos P., Meiksin A., Mesinger A., Offringa A. R., Pandey V. N., Pritchard J. R., Santos M. G., Schwarz D. J., Semelin B., Vedantham H., Yatawatta S., Zaroubi S., Reionization and the Cosmic Dawn with the Square Kilometre Array, Experimental Astronomy, 36:235–318, August 2013

Morales M. F., Wyithe J. S. B., Reionization and Cosmology with 21-cm Fluctuations, ARA&A, 48:127–171, September 2010

Mortlock D. J., Warren S. J., Venemans B. P., Patel M., Hewett P. C., McMahon R. G., Simpson C., Theuns T., Gonzáles-Solares E. A., Adamson A., Dye S., Hambly N. C., Hirst P., Irwin M. J., Kuiper E., Lawrence A.,Röttgering H. J. A., A luminous quasar at a redshift of z = 7.085, Nature, 474:616–619, June 2011

Paciga G., Chang T.-C., Gupta Y., Nityanada R., Odegova J., Pen U.-L., Peterson J. B., Roy J., Sigurdson K., The GMRT Epoch of Reionization experiment: a new upper limit on the neutral hydrogen power spectrum at $z \approx 8.6$, MNRAS, 413:1174–1183, May 2011

Parsons A. R., Liu A., Aguirre J. E., Ali Z. S., Bradley R. F., Carilli C. L., DeBoer D. R., Dexter M. R., Gugliucci N. E., Jacobs D. C., Klima P., MacMahon D. H. E., Manley J. R., Moore D. F., Pober J. C., Stefan I. I., Walbrugh W. P., New Limits on 21 cm EoR From PAPER-32 Consistent with an X-Ray Heated IGM at z=7.7 ArXiv e-prints, April 2013

Pritchard J. R., Loeb A., 21 cm cosmology in the 21st century, Reports on Progress in Physics, 75(8):086901, August 2012

Tanvir N. R., Fox D. B., Levan A. J., Berger E., Wiersema K., Fynbo J. P. U., Cucchiara A., Krühler T., Gehrels N., Bloom J. S., Greiner J., Evans P. A., Rol E., Olivares F., Hjorth J., Jakobsson P., Farihi J., Willingale R., Starling R. L. C., Cenko S. B., Perley D., Maund J. R., Duke J., Wijers R. A. M. J., Adamson A. J., Allan A., Bremer M. N., Burrows D. N., Castro-Tirado A. J., Cavanagh B., de Ugarte Postigo A., Dopita M. A., Fatkhullin T. A., Fruchter A. S., Foley R. J., Gorosabel J., Kennea J., Kerr T., Klose S., Krimm H. A., Komarova V. N., Kulkarni S. R., Moskvitin A. S., Mundell C. G., Naylor T., Page K., Penprase B. E., Perri M., Podsiadlowski P., Roth K., Rutledge R. E., Sakamoto T., Schady P., Schmidt B. P., Soderberg A. M., Sollerman J., Stephens A. W., Stratta G., Ukwatta T. N., Watson D., Westra E., Wold T., Wolf C., A γ-ray burst at a redshift of z 8.2 Nature, 461:1254–1257, October 2009

Tseliakhovich D., Hirata C., Relative velocity of dark matter and baryonic fluids and the formation of the first structures PhRvD, 82(8):083520, October 2010