Blind Search for 21-cm Absorption Systems in New Generation Chinese Radio Telescopes

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Abstract Neutral hydrogen clouds are known to exist in the Universe, however their spatial distributions and physical properties are poorly understood. Such missing information can be studied by the new generation Chinese radio telescopes through a blind searching of 21-cm absorption systems. We forecast the capabilities of surveys of 21-cm absorption systems by two representative radio telescopes in China – Five-hundred-meter Aperture Spherical radio Telescope (FAST) and Tianlai 21-cm cosmology experiment (Tianlai). Facilitated by either the high sensitivity (FAST) or the wide field of view (Tianlai) of these telescopes, more than a thousand 21-cm absorption systems can be discovered in a few years, representing orders of magnitude improvement over the cumulative discoveries in the past half a century.

Key words:

1 INTRODUCTION

Neutral hydrogen (H I) clouds are known to exist in the Universe, however relatively few of them are discovered in the past half a century, and we poorly understand their spatial distribution and physical properties (Wolfe et al. 2005). In damped Lyman-α absorption (DLA) systems, the radio spectrum is also substantially absorbed by the H I hyperfine structure, whose rest frame wavelength is approximately 21 cm ($1420405751.7667 \pm 0.009$ Hz in frequency). These systems have at least 2×10^{20} cm^{-2} H I column density, thus being able to absorb the background with its cold H I in their cold neutral medium (CNM).

The 21-cm absorption systems are important in the study of the distribution, location, temperature and structure of neutral gas, and the evolution of neutral gas systems and galaxies over cosmic time scale. Due to the narrow intrinsic line width, the 21-cm absorption systems are proposed to be used to directly measure the cosmic acceleration (Darling 2012; Yu et al. 2014), via the Sandage-Loeb (SL) effect (Sandage 1962; Loeb 1998). The main source of uncertainty of such proposed measurements lies in our poor understandings of H I clouds (Yu et al. 2014). New surveys are required to improve our understandings of spatial distribution and physical properties of H I clouds. This can be done by the Chinese new generation radio telescopes – Five-hundred-meter Aperture Spherical radio Telescope (FAST) (Li & Pan 2016) and Tianlai 21-cm cosmology experiment (Tianlai) (Chen 2012). The single-dish FAST, like Arecibo[1], uses its gigantic single dish to achieve ultimate sensitivity, whereas Tianlai, designed like CHIME[2], has ultra wide field of view (FoV) provided by its using its cylindrical reflectors and arrays of receivers to quickly scan the northern hemisphere of the sky as the Earth rotates.

Considering their respective design and observing strategies, we forecast their capabilities of blind searching of 21-cm absorption systems. In section 2 we show the sensitivity estimation and related factors for FAST and Tianlai. We present our forecast in section 3 and section 4 respectively. Conclusions are made in section 5.

2 SENSITIVITY

To find possible 21-cm absorption systems, radio telescopes could be devised to scan the radio sources in NRAO VLA Sky Survey (NVSS)[3]. If we assume the distributions of radio sources and H I clouds are uncorrelated over the sky, the redshift distribution of the 21-cm absorption systems $n_{\rm system}$ would be

$$n_{\rm system}(z) = n^*_{\rm H\,I}(z)\int_z^\infty n_R(z')\mathrm{d}z', \tag{1}$$

where n_R is the redshift distribution of radio sources over the sky (given by equation (26) of de Zotti et al. (2010)), and $n^*_{\rm H\,I}(z)$ is the number of occupation of H I clouds per any given line of sight. Note that, unlike n_R and $n_{\rm system}$, $n^*_{\rm H\,I}(z)$ is not an integration of volume so we do not need a volume filling factor in equation 1. However, this spacial distribution of H I is poorly understood and is to be studied in upcoming surveys. Recent studies show that the number density of absorbers to be $\mathrm{d}n_{\rm H\,I}/\mathrm{d}z = n^*_{\rm H\,I}(z) = 0.045 \pm 0.006$ per line of sight at low and medium redshift (Wolfe et al. 2005; Zwaan et al. 2007), so we apply this value in the following forcast. Equation 1 gives the H I cloud occupation regardless of observabilty, based on which we calculate the detections considering sensitivities.

Observation sensitivity depends on the background fluxes and foreground absorptions (current section), as well as telescope configurations and observation strategies (section 3,4).

NVSS contains 2 million sources (with declination $\delta > -40°$, cover 82% of the sky) stronger than 2.5 mJy at ν =1.4 GHz (Condon et al. 1998) and their flux distribution $n_R(F)$ is given by Condon (1984). The observed flux is already lowered by the 21cm absorption if there is any on the line of sight, so the actual signal to noise of the absorption line is higher. Due to the limited knowledge of absorption system properties we ignore this factor for now. Redshifted H I clouds absorb lower frequency bands where the radio sources are typically brighter by $\nu^{-0.7}$ (Condon et al. 1998), or $(1+z_{\rm H\,I})^{0.7}$. The error of the measurement ΔF is given by[4]

$$\Delta F = T_{\rm sys}A_{\rm eff}^{-1}/\sqrt{n_{\rm pol}\Delta\nu\Delta t}, \tag{2}$$

where $T_{\rm sys}$ and $A_{\rm eff}$ are system temperature and effective receiving area, and $T_{\rm sys}A_{\rm eff}^{-1}$ is just the system equivalent flux density (SEFD). $n_{\rm pol}$ is the number of polarizations, $\Delta\nu$ is the line width and Δt is the integration time. $\Delta\nu = (u_{\rm width}/c)\nu_{\rm obs}$, where $u_{\rm width}$ is the equivalent line width of the H I absorber. The properties of 21-cm absorbers are primarily derived from followup studies of optical absorbers. The discovery rate from the cross correlation is a lower bound on the expect number of absorbers, since high column density systems in the CNM may systematically obscure potential background optical sources

[1] https://www.naic.edu
[2] http://chime.phas.ubc.ca
[3] http://www.cv.nrao.edu/nvss/
[4] https://science.nrao.edu/facilities/vla/docs/manuals/oss/performance/sensitivity

(Yu et al. 2014). There are only 3 blind radio detections, and a survey may discover more systems which are optically obscured. They would likely be cold and at high column density. For sensitivity purposes, we treat all sources as $u_{\rm width} = 2~{\rm km~s^{-1}}$ (Wolfe et al. 1982, 2005). $\nu_{\rm obs}$ is the observation frequency. For redshifted 21-cm absorption systems, $\nu_{\rm obs} = 1420~{\rm MHz}/(1+z_{\rm H\,I})$. The integration time $\Delta t = (n_{\rm obs} \times 24~{\rm h})\tau$, where $n_{\rm obs}$ is the number of days an object is scanned, and $\tau = \lambda_{\rm obs}/2\pi D \cos\delta$ is the fractional time the object transits the FoV ($\lambda_{\rm obs} \ll D$ or $\delta \nrightarrow \pi/2$). For 21-cm absorption systems $\lambda_{\rm obs} = 21~{\rm cm}\times(1+z_{\rm obs})$. ΔF is redshift- (frequency-) independent, as $(1+z_{\rm obs})$ terms from integration time and line width cancel out in the equation (2).

In the forecast we count $> 10\sigma$ detections, i.e., the absorption line depth is at least $10\Delta F$. The optical depth of H I absorbers are also poorly understood. Recent discoveries of 21-cm absorption systems have about $r = 20\%$ fractional depth (Allison et al. 2015; Zwaan et al. 2015), and we apply this value. Thus, all systems with $rF > 10\Delta F$ are counted. Note that there is no confusion in the spectral domain – When the system temperature is not dominated by sources, the noise in each pixel is not affected by the number of sources. So only sources with absorbers contribute to the signal, and nothing contributes to the noise. Thus being confusion limited makes no difference.

3 FAST ESTIMATION

FAST has a primary dish of 500 meter in diameter. The effective antenna aperture of FAST is 300 m, in diameter for any zenith angle up to 26° and decreases to 200 m for a maximum zenith angle of 40° (Li & Pan 2016). The 19-beam feed-horn array at L band will be the primary survey instrument for FAST. For a single day it can scan total of 0.5° in declination δ. FAST survey strategy scans each object only once ($n_{\rm obs} = 1$), and with its high sensitivity, even faint sources are identified in a single day. We assume a one-month survey by FAST around the celestial equator for simplicity. FAST observes 1.02 to 1.42 GHz (redshift $z_{\rm H\,I} < 0.39$), so objects on celestial equator have average transit time $\Delta t \simeq 12$ sec. Taking $\Delta\nu \simeq 9$ kHz, $n_{\rm pol} = 2$ (dual polarized system), $T_{\rm sys} \sim 20$ K and $A_{\rm eff} \sim 7 \times 10^4$ m^2, we get SEFD ~ 1 Jy for FAST, then we have $\Delta F \simeq~ 2.3$ mJy. Taking into account the $\nu^{-0.7}$ flux boost at lower frequencies, $rF > 10\Delta F$ requires $F \gtrsim 0.11$ Jy on 1.4 GHz.

One-month-scan ($n_{\rm obs} = 30$) around celestial equator by FAST will have $N_R \simeq 10^4$ sources whose $F \gtrsim 0.11$ Jy on 1.4 GHz. We further assume the independency between $n_R(F)$, $n_R(z)$ and $n_{\rm H\,I}(z)$, from $n_{\rm system}(z)$ by integrating equation (1), there will be $N_{\rm system} \simeq 210/{\rm month}$ absorption systems found in redshift range $0 < z < 0.39$.

4 TIANLAI ESTIMATION

Tianlai is currently 30×12 m area with SEFD $= T_{\rm sys}A_{\rm eff}^{-1} \simeq 300$ Jy. Different from FAST, however, Tianlai scans all sources in the northern hemisphere of the sky everyday, and one needs longer periods integration to identify absorbers with fainter background sources. We forecast its one-year-survey capability of searching 21-cm absorption systems in the northern hemisphere.

Because Tianlai locates at latitude $\phi_{\rm site} = +44^\circ$ and its cylinders are fixed, only objects at the zenith ($\delta = \phi_{\rm cite} = 44^\circ$) fully utilize $A_{\rm eff}$. On the other hand, higher declination objects have longer integration time per day. Thus, ΔF is a function of δ,

$$\Delta F(\delta) = \frac{T_{\rm sys}A_{\rm eff}^{-1}}{\cos(\delta - \phi_{\rm site})}\sqrt{\frac{\cos\delta}{n_{\rm pol}\Delta\nu\Delta t(\delta=0)}}, \tag{3}$$

where $\Delta t(\delta = 0) \simeq 1.17 \times 10^5$ sec is the total integration time (1-year survey) for objects on celestial equator, for Tianlai frequency range 800 to 900 MHz ($0.58 < z < 0.78$). The effective N_R is given by

$$N_R = \int_0^{\pi/2} 2\pi\cos\delta\left(\int_{10\Delta F(\delta)/r}^{+\infty} n_R(F'){\rm d}F'\right){\rm d}\delta. \tag{4}$$

Note that the inner flux integration converges as $F' \to +\infty$ because $n_R(F) \sim F^{-2.5}$. Additionally, even if $\tau = \lambda_{\rm obs}/2\pi D\cos\delta$ fails at $\delta \to \pi/2$ (the north pole $\tau(\delta = \pi/2) = 1$ is always in FoV), the outer declination integration also converges as $\delta \to \pi/2$, because the pole area is tiny and neglectable. For FAST, surveys at higher declinations would as well use equation (3,4), however $\cos(\delta - \phi_{\rm site})$ term affecting SEFD should be neglected.

For Tianlai, equation (4) gives $N_R \simeq 1.3 \times 10^4$, and applying it to equation (1) again we get $N_{\rm system} \simeq 80/{\rm year}$ absorption systems found in redshift range $0.58 < z < 0.78$.

5 CONCLUSION

We forecast the capability of FAST and Tianlai telescopes to search 21-cm absorption systems. According to our assumptions, FAST is able to find $\simeq 210$ systems per month whereas TianLai can find $\simeq 80$ systems per year. Comparing the results between two quite different telescopes – high sensitivity FAST and large FoV Tianlai, we find the former is more efficient in looking for fainter radio sources ($n_R(F) \sim F^{-2.5}$) for possible foreground absorptions. Future improvements in the sensitivity on Tianlai enable it more effectively looking for highest signal-to-noise systems over a wider sky.

Regarding the quantitative forecasts in each telescope, although we take into account many detailed aspects affecting the result, the major uncertainties are $n_{\rm H\,I}(z)$, $u_{\rm width}$ and r. These poorly understood parameters are conversely worth investigating from these proposed surveys. Modest real-time analysis changes could allow the survey of 21-cm absorption systems. The data would need to be recorded at sufficient spectral resolution. Spatial computational costs are in principle unchanged, but there could be additional overhead costs for the larger resulting data sets. Systematic surveys of H I clouds over a cosmic scale enable us to measure the 3D density of these systems. For objects detected by FAST, one can also try to measure the 21cm emission size. For Tianlai, one can try to measure the size from very-long-baseline interferometry (VLBI).

Acknowledgements HRY acknowledges General Financial Grant No.2015M570884 and Special Financial Grant No. 2016T90009 from the China Postdoctoral Science Foundation. HRY and ULP acknowledge the support of the National Science and Engineering Research Council of Canada.

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