

LETTERS

## Blind search for 21-cm absorption systems using a new generation of 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 of Chinese radio telescopes through a blind search of 21-cm absorption systems. We forecast the capabilities of surveys of 21-cm absorption systems by two representative radio telescopes in China – the Five-hundred-meter Aperture Spherical radio Telescope (FAST) and Tianlai 21-cm cosmology experiment (Tianlai). Facilitated by either the high sensitivity (FAST) or 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:** telescopes — surveys — cosmology: observations

### 1 INTRODUCTION

Neutral hydrogen (HI) clouds are known to exist in the Universe, however relatively few of them have been discovered in the past half a century, and we poorly understand their spatial distribution and physical properties (Wolfe et al. 2005). In damped Lyman- $\alpha$  absorption systems, the radio spectrum is also substantially absorbed by the HI hyperfine structure, whose rest frame wavelength is approximately 21 cm ( $1420405751.7667 \pm 0.009$  Hz in frequency). These systems have HI column densities of at least  $2 \times 10^{20}$  cm<sup>-2</sup>, thus they are able to absorb the

background with cold HI in their cold neutral medium (CNM).

The 21-cm absorption systems are important in the study of distribution, location, temperature and structure of neutral gas, and the evolution of neutral gas systems and galaxies over a cosmic time scale. Due to their narrow intrinsic line width, 21-cm absorption systems are proposed to be used to directly measure cosmic acceleration (Darling 2012; Yu et al. 2014), via the Sandage-Loeb effect (Sandage 1962; Loeb 1998). The main source of uncertainty in such proposed measurements lies in our poor understandings of HI clouds (Yu

et al. 2014). New surveys are required to improve our understandings of the spatial distribution and physical properties of HI clouds. This can be done by a new generation of Chinese radio telescopes – the 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<sup>1</sup>, uses its gigantic single dish to achieve an ultimate in sensitivity, whereas Tianlai, designed like CHIME<sup>2</sup>, has an ultra wide field of view (FoV) provided by its usage of cylindrical reflectors and arrays of receivers to quickly scan the northern hemisphere of sky as the Earth rotates.

Considering their respective design and observing strategies, we forecast their capabilities for 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 forecasts for both telescopes 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 same radio sources as targeted in the NRAO VLA Sky Survey (NVSS)<sup>3</sup>. If we assume that the distributions of radio sources and HI clouds are uncorrelated over the sky, the redshift distribution of 21-cm absorption systems  $n_{\text{system}}$  would be

$$n_{\text{system}}(z) = n_{\text{HI}}^*(z) \int_z^\infty n_R(z') dz', \quad (1)$$

where  $n_R$  is the redshift distribution of radio sources over the sky (given by eq. (26) of de Zotti et al. (2010)), and  $n_{\text{HI}}^*(z)$  is the number of HI clouds per any given line of sight. Note that, unlike  $n_R$  and  $n_{\text{system}}$ ,  $n_{\text{HI}}^*(z)$  is not an integration of volume so we do not need a volume filling factor in Equation (1). However, this spacial distribution of HI is poorly understood and should be studied in upcoming surveys. Recent studies show that the number density of absorbers is  $dn_{\text{HI}}/dz = n_{\text{HI}}^*(z) = 0.045 \pm 0.006$  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 forecast. Equation (1) gives the number of HI clouds regardless of observability, based on which we calculate the detections considering sensitivities.

<sup>1</sup> <https://www.naic.edu>

<sup>2</sup> <http://chime.phas.ubc.ca>

<sup>3</sup> <http://www.cv.nrao.edu/nvss/>

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

NVSS contains 2 million sources (with declination  $\delta > -40^\circ$ , covering 82% of the sky) stronger than 2.5 mJy at  $\nu = 1.4$  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 21 cm absorption if there is any in the line of sight, so the actual signal to noise of the absorption line is higher. Due to the limited knowledge about properties of absorption systems, we ignore this factor for now. Redshifted HI clouds absorb lower frequency bands where the radio sources are typically brighter by  $\nu^{-0.7}$  (Condon et al. 1998) or  $(1 + z_{\text{HI}})^{0.7}$ . The error of measurement,  $\Delta F$ , is given by<sup>4</sup>

$$\Delta F = T_{\text{sys}} A_{\text{eff}}^{-1} / \sqrt{n_{\text{pol}} \Delta \nu \Delta t}, \quad (2)$$

where  $T_{\text{sys}}$  and  $A_{\text{eff}}$  are system temperature and effective receiving area, and  $T_{\text{sys}} A_{\text{eff}}^{-1}$  is just the system equivalent flux density (SEFD).  $n_{\text{pol}}$  is the number of polarizations,  $\Delta \nu$  is the line width and  $\Delta t$  is the integration time.  $\Delta \nu = (u_{\text{width}}/c)\nu_{\text{obs}}$ , where  $u_{\text{width}}$  is the equivalent line width of the HI 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 expected number of absorbers, since high column density systems in the CNM may systematically obscure potential background optical sources (Yu et al. 2014). There are only three 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  $u_{\text{width}} = 2 \text{ km s}^{-1}$  (Wolfe et al. 1982, 2005).  $\nu_{\text{obs}}$  is the observation frequency. For redshifted 21-cm absorption systems,  $\nu_{\text{obs}} = 1420 \text{ MHz}/(1 + z_{\text{HI}})$ . The integration time  $\Delta t = (n_{\text{obs}} \times 24 \text{ h})\tau$ , where  $n_{\text{obs}}$  is the number of days an object is scanned, and  $\tau = \lambda_{\text{obs}}/2\pi D \cos \delta$  is the fractional time the object transits the FoV ( $\lambda_{\text{obs}} \ll D$  or  $\delta \rightarrow \pi/2$ ). For 21-cm absorption systems  $\lambda_{\text{obs}} = 21 \text{ cm} \times (1 + z_{\text{obs}})$ .  $\Delta F$  is redshift-(frequency-) independent, as  $(1 + z_{\text{obs}})$  terms from integration time and line width cancel out in 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 HI absorbers is also poorly understood. Recent dis-

<sup>4</sup> <https://science.nrao.edu/facilities/vla/docs/manuals/oss/performance/sensitivity>

coveries 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 m in diameter. The effective antenna aperture of FAST is 300 m in diameter for any zenith angle up to  $26^\circ$  and decreases to 200 m for a maximum zenith angle of  $40^\circ$  (Li & Pan 2016). The 19-beam feed-horn array at the  $L$  band will be the primary survey instrument for FAST. For a single day it can scan a total of  $0.5^\circ$  in declination  $\delta$ . The FAST survey strategy scans each object only once ( $n_{\text{obs}} = 1$ ), and with its high sensitivity, even faint sources can be identified in a single day. We assume there is a one-month survey by FAST around the celestial equator for simplicity. FAST observes 1.02 to 1.42 GHz (redshift  $z_{\text{HI}} < 0.39$ ), so objects on the celestial equator have an average transit time  $\Delta t \simeq 12$  sec. Taking  $\Delta\nu \simeq 9$  kHz and  $n_{\text{pol}} = 2$  (dual polarized system), and considering that FAST has SEFD of  $\sim 1$  Jy, 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 at 1.4 GHz.

A one month scan ( $n_{\text{obs}} = 30$ ) around the celestial equator by FAST will have  $N_R \simeq 10^4$  sources whose  $F \gtrsim 0.11$  Jy at 1.4 GHz. We further assume there is independency between  $n_R(F)$ ,  $n_R(z)$  and  $n_{\text{HI}}(z)$ . From  $n_{\text{system}}(z)$  by integrating Equation (1), there will be  $N_{\text{system}} \simeq 200/\text{month}$  absorption systems found in redshift range  $0 < z < 0.39$ .

### 4 TIANLAI ESTIMATION

Tianlai currently has an area of  $30 \times 12$  m with SEFD  $\simeq 300$  Jy. Different from FAST, however, Tianlai scans all sources in the northern hemisphere of the sky everyday, and one needs longer periods for integration to identify absorbers with fainter background sources. We forecast its capability during a one year survey to search for 21-cm absorption systems in the northern hemisphere.

Because Tianlai is located at latitude  $\phi_{\text{site}} = +44^\circ$  and its cylinders are fixed, only objects at the zenith ( $\delta =$

$\phi_{\text{cite}} = 44^\circ$ ) fully utilize  $A_{\text{eff}}$ . On the other hand, higher declination objects have longer integration time per day. Thus,  $\Delta F$  is a function of  $\delta$ ,

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

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

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

Note that the inner flux integration converges as  $F' \rightarrow +\infty$  because  $n_R(F) \sim F^{-2.5}$ . Additionally, even if  $\tau = \lambda_{\text{obs}}/2\pi D \cos \delta$  fails at  $\delta \rightarrow \pi/2$  (the north celestial pole  $\tau(\delta = \pi/2) = 1$  is always in the FoV), the outer declination integration also converges as  $\delta \rightarrow \pi/2$ , because the pole area is tiny and neglectable. For FAST, surveys at higher declinations would also use Equations (3) and (4), however the  $\cos(\delta - \phi_{\text{site}})$  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  $N_{\text{system}} \simeq 80 \text{ yr}^{-1}$  absorption systems found in redshift range  $0.58 < z < 0.78$ .

### 5 CONCLUSIONS

We forecast the capability of the FAST and Tianlai telescopes to search for 21-cm absorption systems. According to our assumptions, FAST is able to find  $\simeq 200$  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 of Tianlai will enable it to more effectively identify systems with higher signal to noise ratio over a wider sky area.

Regarding the quantitative forecasts of each telescope, although we take into account many detailed aspects affecting the result, major uncertainties are  $n_{\text{HI}}(z)$ ,  $u_{\text{width}}$  and  $r$ . These poorly understood parameters are conversely worth investigating from these proposed surveys. Modest changes in real-time analysis could allow further identification 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 HI 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 size of objects that generate 21 cm emission. For Tianlai, one can try to measure this size from very long baseline interferometry (VLBI).

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