Giant Metrewave Radio Telescope detection of associated H\textit{i} 21 cm absorption at $z = 1.2230$ towards TXS 1954+513

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1 INTRODUCTION

"Associated" H\textit{i} 21 cm absorption studies have been used to probe physical conditions in neutral atomic hydrogen (H\textit{i}) in the environments of active galactic nuclei (AGNs) for more than four decades (e.g. Roberts 1970). Such studies allow one to trace the presence and kinematics of, as well as physical conditions in, H\textit{i} in AGN environments as a function of redshift and AGN type. For example, comparisons between the H\textit{i} 21 cm absorption redshift with the AGN emission redshift allow one to determine whether the detected absorption arises from gas outflow or infall, and thus to study the fuelling of the active nucleus or the effects of AGN feedback (e.g. Morganti et al. 2005b). One can also use such observations, especially with Very Long Baseline Interferometric (VLBI) techniques, to study the kinematics of circumnuclear disks around AGNs (e.g. Conway & Blanco 1995; Peck & Taylor 2002), interactions between the active nucleus, the radio jet and the ambient gas (e.g. Morganti et al. 2005a), and even to infer the presence of binary supermassive black holes in active galaxies (e.g. Morganti et al. 2009). The detectability of such associated H\textit{i} 21 cm absorption in different AGN types can also be used to test AGN unification schemes (e.g. Barthel 1989).

More than a hundred radio-loud AGNs have been searched for associated H\textit{i} 21 cm absorption, from local systems out to very high redshifts, $z \approx 5.2$ (e.g. van Gorkom et al. 1989; Vermeulen et al. 2003; Gupta et al. 2006; Carilli et al. 2007; Curran et al. 2008; Gerèb et al. 2015; Aditya et al. 2016). More than 50 associated systems have so far been detected in H\textit{i} 21 cm absorption till now, with the vast majority at low redshifts, $z \lesssim 0.7$ (e.g. Vermeulen et al. 2003; Gupta et al. 2006; Gerèb et al. 2015), and, indeed, only four confirmed detections at $z > 1$ (Uson et al. 1991; Moore et al. 1999; Ishwara-Chandra et al. 2003; Curran et al. 2013). While this might suggest redshift evolution in the neutral gas content in AGN environments, the heterogeneity of most target samples, with typically a mix of compact and extended background radio sources,
has meant that it has been difficult to separate the AGN characteristics from the above redshift evolution. It has also been pointed out that H\textsubscript{i} 21 cm absorption has never been detected in the environment of an AGN with a rest-frame ultraviolet (UV) luminosity \( \geq 10^{29} \text{ W Hz}^{-1} \), at either low or high redshifts (Curran et al. 2008). These authors argue that the above luminosity may be a threshold above which neutral gas does not survive in AGN environments.

The two main problems with using H\textsubscript{i} 21 cm absorption to probe the redshift evolution of AGN environments have been the lack of searches for H\textsubscript{i} 21 cm absorption at high redshifts, \( z > 1 \), and the heterogeneity in the target samples at all redshifts. We have hence been using the Giant Metrewave Radio Telescope (GMRT) to carry out a search for redshifted H\textsubscript{i} 21 cm absorption in a large, uniformly-selected sample of compact sources, the Caltech-Jodrell Flat-spectrum (CJF) sample (Pearson & Readhead 1988; Taylor et al. 1996). Our pilot study of a subset of this sample yielded the first statistically significant evidence for redshift evolution in the detectability of associated H\textsubscript{i} 21 cm absorption in a uniformly-selected sample (Aditya et al. 2016). However, the data are also consistent with a scenario in which AGNs with a high UV or radio luminosity have a lower H\textsubscript{i} 21 cm absorption strength, as suggested by Curran et al. (2008).

In the present Letter, we report a new detection of redshifted H\textsubscript{i} 21 cm absorption from our GMRT survey of flat-spectrum radio sources, at \( z \approx 1.2230 \) towards TXS 1954+513, the first case of associated H\textsubscript{i} 21 cm absorption in a UV-luminous quasar.

2 THE TARGET: TXS 1954+513

TXS 1954+513 is classified as a blazar in the literature (e.g. Xie et al. 2007; Healey et al. 2008; Massaro et al. 2009), based on its optical, X-ray, and radio characteristics. Specifically, the optical spectrum shows broad emission lines (Lawrence et al. 1996), the source has a high X-ray luminosity (\( > 10^{43} \text{ erg s}^{-1} \); Britzen et al. 2007), the low-frequency radio spectrum is very flat (with a spectral index of \( \alpha = 0.01 \) between 1.4 GHz and 5 GHz), and the radio flux density varies on timescales of a few days (Heeschen 1984), all typical blazar properties.

The redshift of TXS 1954+513 has been estimated to be \( z = 1.2230 \) (Lawrence et al. 1996), based on the detection of a slew of both broad and narrow emission lines (including O\textsc{iii}3727, O\textsc{iii}4363, H\textsc{γ}, H\textsc{δ}, etc). The large number of detected lines allow an accurate estimate of the AGN redshift: Lawrence et al. (1996) estimate the redshift uncertainty to be \( \approx 0.0001 \) for this source.

Unfortunately, there are few optical photometric studies of TXS 1954+513 in the literature. Monet et al. (2003) obtain \( R= 17.34 \) and \( B= 18.87 \) from the second epoch of the USNO-B catalogue, with slightly different values (\( R= 17.47 \) and \( B= 18.44 \)) in the first epoch. This would imply a high inferred rest-frame 1216 Å luminosity (e.g. Curran et al. 2008). However, the errors on the above measurements are uncertain (Monet et al. 2003); we hence chose to also carry out optical imaging of TXS 1954+513 to obtain accurate photometry.

3 OBSERVATIONS, DATA ANALYSIS AND RESULTS

3.1 GMRT imaging and spectroscopy

The GMRT was initially used to search for associated redshifted H\textsubscript{i} 21 cm absorption towards TXS 1954+513 in 2014 April, using the 610 MHz receivers and the GMRT software correlator as the backend. A bandwidth of 16.7 MHz was used for the observations, centred at the expected redshifted H\textsubscript{i} 21 cm line frequency (\( \approx 638.96 \) MHz) and subdivided into 512 channels; this yielded a velocity resolution of \( \approx 15.3 \text{ km s}^{-1} \) and a total velocity coverage of \( \approx 7815 \text{ km s}^{-1} \) (covering redshifts \( z \approx 1.194 \) – 1.252). Observations of the standard calibrators 3C286 and 3C295 were used to calibrate the flux density scale and the system passband. No phase calibrator was observed as TXS 1954+513 is known to be relatively compact at low frequencies. The on-source time was \( \approx 60 \) minutes.

The spectrum from the original GMRT observations showed statistically significant evidence of a narrow absorption feature close to the expected redshifted H\textsubscript{i} 21 cm line frequency. We hence re-observed TXS 1954+513 in 2015 May to confirm the detection, again using the GMRT software backend as the correlator, but this time with a bandwidth of 4.17 MHz sub-divided into 512 channels, and centred at the redshifted H\textsubscript{i} 21 cm line frequency. This yielded a finer velocity resolution of \( \approx 3.8 \text{ km s}^{-1} \), allowing us to resolve out any narrow spectral components in the absorption profile. 3C286 was again used to calibrate the flux density scale and the system bandpass. The on-source time was \( \approx 90 \) minutes.
3.2 Nickel Telescope photometry

The field surrounding TXS 1954+513 was imaged through the B and R filters using the 1m Nickel telescope at Lick Observatory on UT 2016 Sep 14. Images of 600s and 1800s were obtained under clear but humid conditions. Images of the standard fields PG2213-006 and SA 111 (Landolt 2009) were taken directly after the science field for photometric calibration. Additional calibration frames (bias, dome flats) were also obtained. Image processing of the on-sky images proceeded in standard fashion (e.g. bias subtraction, flat field normalization) with custom scripts.

We measured the counts in 14″ diameter apertures around each calibration star and estimated the sky counts from a nearby, off-source aperture. The measured zero points corresponding to one count per second are $ZP_B = 22.1$ mag and $ZP_R = 22.7$ mag, for the B and R filters, respectively. Aperture photometry was then performed on TXS 1954+513; after applying the zero-point corrections, we obtained $B = 18.0 \pm 0.1$ mag and $R = 16.9 \pm 0.1$ mag, on the Vega magnitude scale. We estimate an uncertainty of 0.15 mag from calibration errors and photon statistics.

3.3 Data analysis and Results

The GMRT data on TXS 1954+513 were analysed in “classic” AIPS following standard procedures. The data were first carefully inspected, and edited to remove non-working antennas and time-specific intermittent bad data (e.g. due to radio frequency interference, RFI). The antenna band-passes were estimated from the data on the bright calibrators 3C286 and 3C295. An initial estimate of the complex antenna gains was obtained by assuming TXS 1954+513 to be a point source, and the gains were then refined via an iterative self-calibration procedure consisting of 4 rounds of phase-only self-calibration and imaging, followed by 2 rounds of amplitude-and-phase self-calibration and imaging. The amplitude-and-phase self-calibration step was followed by further data editing, based on the residuals after subtracting the continuum image from the calibrated visibilities. This iterative procedure was carried out until it yielded an image that did not improve upon further self-calibration and data editing. The final continuum image was then subtracted out from the calibrated spectral-line visibilities; any remaining continuum emission was removed by fitting a first-order polynomial to line-free channels in each visibility spectrum, and subtracting this out. The residual visibilities were then shifted to the heliocentric frame, and imaged to obtain the final spectral cube.

The final GMRT 640 MHz continuum image of TXS 1954+513, displayed in Fig. 1, shows a central core and two emission components extended in the north and south directions. A 3-component Gaussian model was fitted to the GMRT image (using the task jmfit) to measure the flux densities of the three components; this yielded flux densities of $(1254.1 \pm 1.2) \, \text{mJy (core)}$, $(403.4 \pm 1.6) \, \text{mJy (northern lobe)}$, and $(198.1 \pm 1.3) \, \text{mJy (southern lobe)}$. The core emission is marginally resolved, with a peak flux of $(1221.30 \pm 0.69) \, \text{mJy/Beam}$, the northern lobe is highly resolved, with a peak flux of $(247.90 \pm 0.66) \, \text{mJy/Beam}$, while the southern lobe is also marginally resolved, with a peak flux of $(184.00 \pm 0.69) \, \text{mJy/Beam}$.

The radio core dominates the emission, providing $\approx 70\%$ of the total flux density at our observing frequency of 640 MHz; as a result, the spectrum remains relatively flat at low frequencies, with a spectral index $\alpha \approx -0.2$ between 640 MHz and 1.4 GHz (Condon et al. 1998) obtained from the total flux densities at the two frequencies (assuming the flux density $S_\nu$ at a frequency $\nu$ to be given by $S_\nu \propto \nu^{-\alpha}$). The angular size of the source in the north-south direction is $\approx 20''$, i.e. $\approx 170 \, \text{kpc}$ at the AGN redshift of $z = 2.230$.

The three panels of Fig. 2 show Ht 21 cm spectra at the locations of the peaks of the three emission components of TXS 1954+513 (after subtracting out a 2nd-order or 3rd-order baseline fitted to line-free regions), with optical depth (in units of $1000 \times \tau$) plotted versus velocity (in km s$^{-1}$), relative to the heliocentric redshift $z = 2.230$. These were obtained from the second observing run in 2015 May, whose data have both a better spectral resolution and a higher sensitivity. Strong Ht 21 cm absorption is clearly visible in the spectrum through the radio core, shown in the left panel, while no Ht 21 cm absorption was detected in the spectra...
through the two lobes, shown in the middle and right panels of the figure. Note that the optical depth sensitivities of the spectra towards the peaks of the northern and southern lobes are sufficient to detect HI 21 cm absorption of the same strength as that of the main absorption component seen against the core, but not to detect the weaker absorption component. We can thus rule out the possibility that the “cloud” producing the strong HI 21 cm absorption covers both the core and either of the lobes, but cannot rule out the possibility that the gas producing the weaker HI 21 cm absorption might cover all three source components.

The root-mean-square noise on the spectrum through the core was measured (from line-free channels) to be \( \approx 2.3 \text{ mJy per } 3.8 \text{ km s}^{-1} \text{ channel} \). The integrated HI 21 cm optical depth of the absorption line detected against the core is \( (0.716 \pm 0.037) \text{ km s}^{-1} \), which implies an HI column density of \( N_{\text{HI}} = (1.305 \pm 0.067) \times (T_v/100 \text{ K}) \times 10^{20} \text{ cm}^{-2} \), for an assumed spin temperature of 100 K (this value was used for consistency with the literature; e.g. Vermeulen et al. 2003; Gupta et al. 2006). Note that the spin temperature of neutral hydrogen in AGN environments could be much higher than the assumed 100 K (e.g. Maloney et al. 1996); the above estimate of the HI column density is hence likely to be a lower limit.

The detected HI 21 cm absorption towards the core of TXS 1954+513 is relatively narrow, with a velocity width between 20% points of \( \approx 40 \text{ km s}^{-1} \). No evidence is seen for a wide absorption component. The peak of the absorption is blueshifted from the AGN redshift \( (z = 1.2230 \pm 0.0001; \text{ Lawrence et al. 1996}) \) by \( \approx 328 \text{ km s}^{-1} \).

4 DISCUSSION

A clear core-jet structure is seen on scales of tens of milli-arcseconds in the 1.6 GHz VLBI image of TXS 1954+513, with a single jet in the eastward direction (Polatidis et al. 1995). The one-sided nature of the jet indicates that it is likely to point close to our line of sight to the core. Interestingly, however, our GMRT 640 MHz continuum image shows that the radio structure is very different on arcsecond scales, with a core and two weaker lobes symmetrically extended in the north-south direction with a transverse angular extent of \( \approx 25'' \); this three-component north-south structure is also seen in the 1.4 GHz Very Large Array image of Xu et al. (1995). The arcsecond-scale structure is thus of the “core-dominated triple” type (e.g. Marecki et al. 2006). However, the milli-arcsecond scale core-jet structure is nearly perpendicular to the north-south arcsecond-scale structure. Such strong misalignments between the milli-arcsecond-scale and the arcsecond-scale radio structure have been observed earlier in a number of AGNs, especially BL Lac objects (e.g. Pearson & Readhead 1988; Wehrle et al. 1992; Conway & Murphy 1993), and, more recently, in a few core-dominated triples (e.g. Marecki et al. 2006). Models that can account for these misalignments include twisted radio jets, either due to interaction with the ambient medium or precession of the axis of the central super-massive black hole (e.g. Conway & Murphy 1993; Apply et al. 1996), and restarted AGN activity accompanied by a flip in the spin of the central black hole, possibly due to a galaxy merger event (e.g. Marecki et al. 2006).

We followed the prescription of Curran et al. (2008) to estimate the rest-frame UV luminosity of TXS 1954+513, using a power-law model to extrapolate from its measured R-band and B-band magnitudes to infer its flux density at 1216 × (1 + z) \( \mu \text{Jy} \) (\( z = 1.223 \)), and, hence, its luminosity at this wavelength. Our measured R-band and B-band magnitudes are \( R = 16.9 \pm 0.15 \) and \( B = 18.0 \pm 0.15 \). Extrapolating from these measurements, we obtain \( L_{\text{UV}} \approx (4.1 \pm 1.2) \times 10^{23} \text{ W Hz}^{-1} \); this is by far the highest UV luminosity at which associated HI 21 cm absorption has been detected at any redshift (e.g. Curran et al. 2008, 2010). This is also the first case of a detection of HI 21 cm absorption above the UV luminosity threshold suggested by Curran et al. (2010) of \( L_{\text{UV}} = 10^{23} \text{ W Hz}^{-1} \). Curran & Whiting (2012) use a simple model to argue that this is the UV luminosity threshold above which a quasar would ionize all the neutral gas in its host galaxy, for a range of gas densities. Our detection of HI 21 cm absorption shows that neutral hydrogen can indeed survive in AGN environments at high UV luminosities, \( \gg 10^{23} \text{ W Hz}^{-1} \).

The peak of the HI 21 cm absorption is blueshifted by \( \approx 328 \text{ km s}^{-1} \) from the AGN redshift of 1.2230, indicating that this is a case of gas outflow from an AGN. The detected absorption against the core of the GMRT 640 MHz image may arise against either the VLBI core or the VLBI-scale, eastward-pointing radio jet of TXS 1954+513. However, since the jet direction is likely to lie close to our line of sight to the core, in both cases the gas cloud appears to be moving in the direction of the VLBI radio jet and away from the core. It is possible that the neutral gas in the vicinity of the AGN is being driven outward by the ram pressure of the radio jet, as has been suggested by recent numerical simulations (e.g. Wagner & Bicknell 2011; Wagner et al. 2012).

In summary, we have used the GMRT 610 MHz receivers to obtain only the fifth detection of associated redshifted HI 21 cm absorption at high redshifts, \( z > 1 \), in the blazar TXS 1954+513. The AGN has a core-dominated triple structure in the GMRT image, with the two radio lobes oriented nearly perpendicular to the VLBI-scale radio jet; this misalignment may arise due to either a twisted radio jet or restarted AGN activity with a spin-flip of the central black hole. The HI 21 cm absorption is detected towards the radio core of the GMRT 640 MHz image, i.e. towards either the VLBI core or the VLBI-scale radio jet, and is blueshifted by \( \approx 328 \text{ km s}^{-1} \) from the AGN redshift, suggesting that the HI cloud causing the absorption is being driven outward by the ram pressure of the jet. We have also used Nickel Telescope R- and B-band photometry of TXS 1954+513 to infer a high rest-frame 1216 \( \pi \text{Jy} \) luminosity of \( (4.1 \pm 1.2) \times 10^{23} \text{ W Hz}^{-1} \) for the blazar. This is the first case of associated HI 21 cm absorption detected from an AGN with a rest-frame UV luminosity \( < 10^{23} \text{ W Hz}^{-1} \), showing that neutral gas can survive in the vicinity of active galactic nuclei with high ultraviolet luminosities.

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Associated HI 21 cm absorption at z = 1.223

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