Tracing the neutral gas environments of young radio AGN with ASKAP

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At present neutral atomic hydrogen (H\(_i\)) gas in galaxies at redshifts above \(z \sim 0.3\) (the extent of 21 cm emission surveys in individual galaxies) and below \(z \sim 1.7\) (where the Lyman-\(\alpha\) line is not observable with ground-based telescopes) has remained largely unexplored. The advent of precursor telescopes to the Square Kilometre Array will allow us to conduct the first systematic radio-selected 21 cm absorption surveys for H\(_i\) over these redshifts. While H\(_i\) absorption is a tracer of the reservoir of cold neutral gas in galaxies available for star formation, it can also be used to reveal the extreme kinematics associated with jet-driven neutral outflows in radio-loud active galactic nuclei. Using the six-antenna Boolardy Engineering Test Array of the Australian Square Kilometre Array Pathfinder, we have demonstrated that in a single frequency tuning we can detect H\(_i\) absorption over a broad range of redshifts between \(z = 0.4\) and 1.0. As part of our early science and commissioning program, we are now carrying out a search for absorption towards a sample of the brightest GPS and CSS sources in the southern sky. These intrinsically compact sources present us with an opportunity to study the circumnuclear region of recently re-started radio galaxies, in some cases showing direct evidence of mechanical feedback through jet-driven outflows. With the sensitivity of the full ASKAP array we will be able to study the kinematics of atomic gas in a few thousand radio galaxies, testing models of radio jet feedback well beyond the nearby Universe.

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1 Introduction

Compact steep spectrum (CSS) and gigahertz-peaked spectrum (GPS) radio sources have typical sizes much less than the gas distribution in their host galaxies and so provide us with a means to directly observe the interaction between radio-jets and the inner region of the interstellar medium (ISM). By studying the kinematics of the neutral gas around luminous young radio sources we can test models of early jet-ISM interaction (e.g. Wagner et al. [2012]) that contributes significantly to AGN feedback in powerful radio galaxies (e.g. Holt et al. [2008] Nesvadba et al. [2008]).

Direct evidence for fast (> 1000 km s\(^{-1}\)) and massive (up to 50 M\(_{\odot}\) yr\(^{-1}\)) outflows of atomic, molecular and ionised gas associated with radio jet-ISM interaction have now been found in several systems (e.g. Mahony et al. [2013] Morganti et al. [2013] Tadhunter et al. [2014]). Absorption from neutral atomic hydrogen (H\(_i\)) gas located in front of the radio source is an excellent tracer of the kinematics of circumneutral neutral gas and is thus an important tool in revealing the presence of neutral gas outflows (e.g. Morganti et al. 2005; Teng et al. 2013). Previous 21 cm spectroscopic surveys of radio-loud AGN have found that detection rates of H\(_i\) absorption are highest in the most compact radio galaxies (e.g. Chandola et al. 2011; Gupta et al. 2006; Morganti et al. [2001]; Vermeulen et al. [2003]) suggesting that these young sources are cloaked behind high column density gas (Emonts et al. [2010]; Pihlström et al. [2003]), but that orientation and geometric effects (including the size and distribution of the gas clouds) may also play a significant role (Curran et al. [2013]; Orienti et al. [2006]). Comparisons of the absorption line profiles in larger samples of extended and compact radio sources show a prevalence of asymmetries and larger widths (\(\Delta v \gtrsim 200\) km s\(^{-1}\)) associated with the latter, implying that the inner circumnuclear medium is significantly disturbed by younger radio jets clearing their way through the ISM (e.g. Ger"eb et al. [2015])

Within the next decade, the advent of the Square Kilometre Array (SKA) pathfinder telescopes will enable astronomers to carry out radio-selected H\(_i\) absorption surveys towards a few hundred thousand sources over the entire sky out to redshifts greater than \(z \sim 1\) (Morganti et al. 2015). Larger samples of distant sources can be constructed and compared with more well studied nearby systems (e.g. Maccagni et al. [2014]), greatly aiding our understanding of the typical gaseous environments of distant GPS and CSS sources and their evolution with redshift. Further interpretation of the detected systems will be supported by follow-up observations with millimetre (e.g. the Atacama Large Millimetre Array) and optical facilities (e.g. the Very Large Telescope), providing confirmation of association through
Fig. 1  Example of an ASKAP-BETA spectrum towards the flat spectrum quasar PKS B2252$-089$. For visual clarity the data have been binned from the native spectral resolution of 18.5 kHz to 100 kHz. The barycentric corrected observed frequency is shown on the lower-abscissa, and the upper-abscissa denotes the corresponding H\textsc{i} redshift. The data (black line) denote the absorbed fraction of background continuum and the grey region gives the corresponding RMS spectral noise multiplied by a factor of 5. The absorption line, first detected by Curran et al. [2011] using the Green Bank Telescope, is visible in the spectrum at $\nu_{\text{bary}} = 883.6$ MHz, equal to an H\textsc{i} redshift of $z = 0.6076$.  

spectroscopic redshifts. Furthermore, 21 cm spectroscopy at higher spatial resolution using Very Long Baseline Interferometry (VLBI) will allow individual modelling of the distribution and kinematics of the atomic gas. Here we discuss some of the first results from commissioning of the Australian SKA Pathfinder (ASKAP; Deboer et al. 2009; Schinckel et al. 2012), demonstrating the wide fractional bandwidth and exceptionally radio quiet site of this telescope.

2 H I absorption with ASKAP

ASKAP will be a 36-antenna radio interferometer operating at frequencies between 700 and 1800 MHz. Each antenna is equipped with a Phased Array Feed (PAF) “chequerboard” array receiver (Hay & O’Sullivan 2008), containing 188 independent receptors that can be used to form up to 36 primary beams over a 30 degree field-of-view. This will allow astronomers to perform rapid surveying of the cm-wavelength sky. Among several surveys of the entire southern sky, the ASKAP First Large Absorption Survey in H I (FLASH) will search for cool atomic hydrogen towards 150,000 southern ($\delta \lesssim +10^\circ$) radio sources, finding a few thousand intervening and associated systems out to $z = 1.0$.

The telescope is currently in its science demonstration and commissioning phase comprising 6 antennas fitted with the first generation of PAFs, forming the Boolardy Engineering Test Array (BETA; Hotan et al. 2014). In its lowest frequency band between 711.5 and 1015.5 MHz, the BETA telescope enables us to search for H I absorption at redshifts between $z = 0.4$ and 1.0 against the brightest ($S_{1.4} \sim 1$Jy) radio sources in the southern sky. The 16416 spectral channels, separated by 18.5 kHz, give a velocity resolution between 5.5 and 7.8 km s$^{-1}$ over this band. With 6 antennas the array has a 5$\sigma$ sensitivity per 2h on-source (at 1 GHz) of about 0.1 percent absorption against sources brighter than 1 Jy. Assuming a cold-phase 21 cm spin temperature of 100 K and line width of 30 km s$^{-1}$ this equates to an H I column density of approximately $5 \times 10^{20}$ cm$^{-2}$. With the full ASKAP complement of 36 antennas this sensitivity will increase to sources brighter than 150 mJy, greatly increasing the number of available targets. Even with its lower sensitivity, BETA still provides us with a unique opportunity to carry out new science over a largely unexplored epoch.

In Fig. 2 we show an example spectrum towards the flat spectrum quasar PKS B2252-089 from an 8.5h on-source integration with five of the BETA antennas. The source has a continuum flux density of 1 Jy at 800 MHz. This example spectrum demonstrates the power of the telescope for detecting H I gas in absorption, with no strong radio frequency interference evident in this band. The absorption feature originally detected with the Green Bank Telescope (Curran et al. 2011) and associated with the host galaxy of the radio source is clearly evident at a frequency of 883.6 MHz. The striking agreement between the BETA and GBT spectra can be seen in Fig. 2, with the former spectrum confirming the broad wing seen bluewards of the peak absorption.

The striking agreement between the BETA and GBT spectra can be seen in Fig. 2, with the former spectrum confirming the broad wing seen bluewards of the peak absorption. The H I is redshifted by 200 km s$^{-1}$ with respect to the optical [O III] 4959, 5007 emission lines (Drinkwater et al. 1997), which might be indicative of an inflow of cool neutral gas towards the nucleus along the line-of-sight. Alternatively if the peak absorption against the compact radio source is a more accurate indicator of the AGN redshift, then the blue wing would suggest that the radio jets in this source (Liu & Zhang 2002 and references therein) could be driving the atomic gas in an outflow.

3 A pilot 21 cm survey of GPS/CSS sources at cosmological redshifts

The sub-kpc sizes of GPS and CSS sources make them ideal targets for a pilot H I absorption survey with BETA, where the continuum radio emission is well matched to the expected extent of foreground gas clouds. Given the limited sensitivity of the 6-antenna BETA telescope, we are carrying out observations of bright ($S > 1.5$ Jy) southern GPS/CSS sources selected from the unbiased sample of Randall et al. (2011). These sources represent some of the most powerful young or re-started radio galaxies in the Universe. Of the 26 Randall et al. sources we selected 13 with expected H I redshifts in the 711.5 – 1015.5 MHz band, i.e. redshifts between 0.4 and 1.0. Some of these redshifts are only indicative values from optical photometry, but the large fractional bandwidth available with BETA allows us to blindly search for H I and OH absorption over a wide range of redshifts.

At present our observations with the BETA telescope are ongoing, but we have recently achieved our first discovery...
of H I absorption with the ASKAP-BETA telescope (Allison et al. 2015). The background radio source, PKS B1740−517, is in the Randall et al. (2011) sample and has a gigahertz-peaked spectrum with a spectral age of approximately 2500 yrs. The absorption seen at $z = 0.4413$ is characteristically complex, with a deep narrow component that is almost unresolved at 5 km s$^{-1}$ and broader components with more typical widths (see Fig. 3). The complexity of this profile is indicative of gas associated with the host galaxy, where the different velocity components trace either the spatial structure of the radio source, or the gas kinematics caused by the AGN. Association with the host galaxy was confirmed by optical spectroscopy from follow up observations with the Gemini South Telescope, providing the first spectroscopic redshift for this source. This young radio source is likely shrouded within a dense gaseous environment through which we are seeing absorption of the continuum, an interpretation that is supported by the strong absorption of soft X-ray emission seen in archival XMM-Newton data.

4 Summary

Absorption of continuum radio emission by cool H I gas located in the foreground allows us to directly observe the interaction between radio AGN and neutral gas in the surrounding ISM. With H I absorption seen in the spectra of the most compact radio sources we can probe further into the circumnuclear medium and test models of jet-driven feedback in the early stages of radio-jet growth. With our first commissioning observations using the ASKAP BETA telescope we are searching for H I absorption over a continuous redshift range between $z = 0.4$ and 1.0, a range that was previously unobtainable due to smaller available fractional bandwidths and poorer radio frequency environments. We are now carrying out a pilot survey of the brightest and most compact radio sources in the southern hemisphere, including redshifted GPS/CSS sources selected from the sample of Randall et al. (2011). Recently we made our first discovery of H I absorption towards the GPS radio source PKS B1740−517 (Allison et al. 2015), revealing the dense neutral gas surrounding this young radio galaxy. With the full capability of ASKAP we will be able to carry out FLASH (the First Large Absorption Survey in H I) towards 150,000 radio sources across the entire southern sky. This will provide over a thousand detections of associated absorption and allow us to explore the evolution of jet-ISM feedback in young radio AGN as a function of redshift.

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Fig. 3 Recently discovered H I absorption in the host galaxy of the powerful GPS radio source PKS B1740−517. The velocity is given with reference to the optical redshift of $z = 0.44230 \pm 0.00022$ (Allison et al. 2015).
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