Broad, weak 21 cm absorption in an early type galaxy: spectral line finding and parametrization for future surveys

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ABSTRACT

We report conclusive verification of the detection of associated H I 21 cm absorption in the early-type host galaxy of the compact radio source PMN J2054–4242. We estimate an effective spectral line velocity width of 418 ± 20 km s⁻¹ and observed peak optical depth of 2.5 ± 0.2 per cent, making this one of the broadest and weakest 21 cm absorption lines yet detected. For \( T_{\text{spin}}/f > 100 \) K the atomic neutral hydrogen column density is \( N_{\text{HI}} \gtrsim 2 \times 10^{21} \) cm⁻². The observed spectral line profile is redshifted by 187 ± 46 km s⁻¹, with respect to the optical spectroscopic measurement, perhaps indicating that the H I gas is infalling towards the central active galactic nucleus. Our initial tentative detection would likely have been dismissed by visual inspection, and hence its verification here is an excellent test of our spectral line detection technique, currently under development in anticipation of future next-generation 21 cm absorption-line surveys.

Key words: methods: data analysis – galaxies: active – galaxies: ISM – radio lines: galaxies

1 INTRODUCTION

The cold atomic neutral hydrogen content of galaxies (HI) plays a vital role in the evolution of galaxies, through formation of stars and efficient accretion of matter on to active galactic nuclei (AGNs). By using the 21 cm hyperfine transition of HI, observed as absorption against a background radio source of known brightness, we can measure the distribution and kinematics of line-of-sight cold gas \( (T \sim 100 \) K). Previous observations of the 21 cm line in associated absorption often exhibit spectral line profiles with both a deep, narrow component \( (\sim 10 \text{ km s}^{-1}) \) and broad wings from a shallow component \( (\sim 100 \text{ km s}^{-1}) \) (e.g. Mirabel 1989; Morganti et al. 2001, 2005a; Salter et al. 2010; Allison et al. 2012a). From observations at high spatial resolution there, is evidence that in some cases these broad, shallow components might be associated with a circumnuclear torus (e.g. Struve & Conway 2010; Morganti et al. 2011). Additionally, Morganti et al. (2005b) have successfully detected extremely broad absorption within gas-rich hosts, each of which has an existing deep, narrow absorption-line component. These systems are associated with high-velocity gas outflows, providing a probe of the feedback between the central radio source and the star-forming interstellar medium of its host galaxy. Other examples of extreme broadening include the detection of H I absorption towards the candidate binary black-hole 4C 37.11 (Maness et al. 2009; Morganti et al. 2009), with a full width at zero-intensity of 1600 km s⁻¹ and dominated by two narrow, deep peaks. However, there are currently very few detections that are dominated by broad absorption, with no (or very little) accompanying narrow component (see e.g. Jaffe 1990).

In previous work, Allison et al. (2012a) reported the tentative detection of broad \( (\Delta V_{\text{FWHM}} \sim 500 \text{ km s}^{-1}) \) H I 21 cm absorption towards the compact flat-spectrum radio source, PMN J2054–4242 (Griffith & Wright 1993; Healey et al. 2007), using a spectral line detection method based on a Monte Carlo Bayesian technique. From observations using the Australia Telescope Compact Array Broadband Backend (CABB; Wilson et al. 2011), and by considering the ratio of the marginal likelihoods, the data were found to warrant the inclusion of the spectral line hypothesis over the continuum-only hypothesis. Here we report further observations to conclusively verify the presence of this broad and shallow absorption line. This is one of the broadest and weakest 21 cm absorption lines yet detected in isolation, with no previous indication of absorption from an existing deep, narrow component. Conclusive verification of this detection provides an excellent test of our spectral line finding method, a technique that can be used for detecting and parametrizing such spectral lines in future large-scale absorption surveys.

Throughout this Paper we adopt a flat \( \Lambda \)CDM cosmology with \( \Omega_M = 0.27, \Omega_{\Lambda} = 0.73 \) and \( H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1} \). Quantities estimated from the data are given by their mean and 1 \( \sigma \) uncertainty unless otherwise stated.

2 OBSERVATIONS AND DATA REDUCTION

In addition to the observations in 2011 April reported by Allison et al. (2012a), a further 12 h observation of PMN J2054–4242, at \( RA(J2000) = 20^h54^m01^s79 \) and Dec. \( (J2000) = \sim –42°42′38″7 \), was carried out in 2012 June 17–18. The CABB system provides a zoom band of 64 MHz across 2048 channels, which at the centre frequency of 1.342 GHz has a ve-
The synthesized-beam weighted spectrum, combining ATCA 21 cm data from observations in 2011 April and 2012 June. The data were binned to a resolution of 21 km s$^{-1}$, which is approximately three times that of the individual spectra. The optical spectroscopic redshift is indicated by the vertical arrow ($z_{\text{opt}} = 0.042893 \pm 0.000150$; Jones et al. 2009).

Velocity resolution $\sim 7 \text{ km s}^{-1}$. The six-element ATCA was arranged in the 6D East-West configuration, with baseline distances in the range 0.08 – 5.88 km. With this configuration we obtained an angular scale sensitivity range of approximately 8 – 600 arcsec, and a primary beam full width at half-maximum (FWHM) of 35 arcmin. We observed the target source in 20 min scans, which were interleaved with 1.5 min observations of the nearby secondary calibrator, PKS B2211–388 ($S_{1.384 \text{ GHz}} = 1.86 \pm 0.01 \text{ Jy}$) for gain and band-pass calibration. For the calibration of the absolute flux scale, we observed PKS B1934–638 ($S_{1.384 \text{ GHz}} = 14.94 \pm 0.01 \text{ Jy}$) at regular intervals separated by 2 h. For the 2012 June epoch, we achieved a total integration time of 8.6 h on the target source.

We implemented the same data reduction procedure as reported by Allison et al. (2012a), again subtracting the baseline ripple signal from other continuum sources within the field of view. The data were flagged, calibrated and imaged using tasks from the MIRIAD package (Sault et al. 1995), and implemented using a purpose-built CABB H$\alpha$ data reduction pipeline. We updated our original procedure to include some minor improvements to the calibration and baseline ripple subtraction, and have applied these here to the data obtained both in 2011 April and 2012 June. Assuming that the flux density of PMN J2054–4242 has not varied significantly between the two epochs (which was not evident from our observations), we constructed a single, natural weighted data cube from the combined visibility data. Since the ATCA does not observe at constant radial velocity (known as Doppler tracking), the observed frequency channels for each epoch correspond to slightly different velocities. To obtain approximately uniform variance in flux across the velocity spectrum, we binned the data to a resolution of 21 km s$^{-1}$, which is approximately three times that of the individual spectra. Fig. 1 shows the resulting synthesized-beam weighted spectrum centred on PMN J2054–4242. Based on the median absolute deviation from the mean (e.g. Whiting 2012), the estimated per spectral-channel uncertainty is 1.05 mJy, which is consistent with the uncertainties in the spectra for each epoch and the subsequent velocity binning (see Table 1). The 21 cm H$\alpha$ absorption can clearly be seen upon visual inspection, slightly redshifted with respect to the systemic velocity, given by optical spectroscopy from the 6dF Galaxy Survey (6dFGS; Jones et al. 2009). This feature is seen throughout observations in both epochs, and in both polarizations, strongly indicating that it is not generated by a transient artefact such as radio frequency interference. We also do not see this feature in spectra that are randomly selected at positions away from the source. At a third epoch, during another observing program in 2012 April, we obtained further low spectral resolution (230 km s$^{-1}$) CABB data. While not useful for parametrizing the absorption, the 21 cm spectral line profile is wide enough to be seen across three channels in the data and so provided additional verification of our detection.

3 ANALYSIS

Here we provide a brief summary of the method used for 21 cm spectral line detection and parametrization. For a more detailed description please refer to work by Allison et al. (2012a,b) and references therein. In order to verify whether 21 cm H$\alpha$ absorption has been detected with significance, we estimated the conditional probability of a spectral line model (parametrized by a sum of spectral line components and a first-order polynomial) and compared it to that of a continuum-only model (also parametrized by a first-order polynomial). We also included a nuisance parameter, which represents systematic error due to imperfect data reduction. The model spectrum is multiplied by this parameter, with a non-uniform prior probability given by a normal distribution of $\mu = 1.0$ and $\sigma = 0.1$, which represents a 10 per cent systematic error. Note that we have revised our estimate of the systematic error in the ATCA data with respect to that given by Allison et al. (2012a).

We have assumed no prior information about the probability of detection of a spectral-line, since it is difficult to draw strong statistical conclusions from the existing small sample of detected associated H$\alpha$ absorption systems (e.g. Curran & Whiting 2010; Curran et al. 2011a; Allison et al. 2012a). Therefore, the ratio of probabilities for each model hypothesis, given the data, is equal to the ratio of probabilities for the data given the model hypotheses (also known as the ratio of marginal likelihoods or Bayesian evidence). We define the statistic $R$ by

$$R \equiv \ln \left( \frac{E_{\text{H}\alpha}}{E_{\text{cont}}} \right),$$

(1)

where $E_{\text{H}\alpha}$ and $E_{\text{cont}}$ are the Bayesian evidence for the spectral line and continuum-only models respectively. If the value of $R$ is greater than zero, then this gives the level of significance for the spectral line hypothesis. However, if the value of $R$ is less than zero, then the data do not warrant the inclusion of a spectral line component in the model and so we reject this hypothesis.

In order to calculate the Bayesian evidence, we used an efficient Monte Carlo algorithm provided by Feroz & Hobson (2008) and Feroz et al. (2009), called MULTINEST, which implements the nested sampling algorithm by Skilling (2004). We optimized the significance statistic $R$ by increasing the number of spectral line components, thus giving the best-fitting spectral line model.
4 RESULTS AND DISCUSSION

4.1 Parametrization of the 21 cm absorption

We implemented the analysis method outlined in Section 3, initially representing the 21 cm spectral line by multiple Gaussian components. The data in both epochs warrant the inclusion of the spectral line model over the continuum-only model and, by comparing the Bayesian evidence for different numbers of spectral line components, the single-component model is favoured. However, while a single Gaussian does provide a good fit to the combined data (at maximum likelihood $\chi^2_{\text{red}}/d.o.f = 0.94 \pm 0.06$), upon visual inspection the spectral line profile appears more steep sided than predicted by this model. To test this hypothesis, we tried an empirically motivated spectral line model, which provides for a simultaneously broad and steep-sided trough-like profile, and is given by the product of two Gauss error functions (R. Jurek and T. Westmeier, private communication). This is a simplified version of the 21 cm spectral line model developed by Westmeier, Jurek & Obreschkow (in preparation). Since this model contains one more parameter than a single Gaussian profile, which determines the steepness of the profile sides, it must provide a significantly better representation of the data in order to be preferred.

Again using Bayesian inference, we found that the 2011 April data favour the single Gaussian model, while the 2012 June and combined data favour the trough-like model. This result is perhaps unsurprising given the relatively low signal-to-noise ratio (S/N) of the 2011 April data. In the case of the combined data (at maximum likelihood $R = 109.5 \pm 0.1$), when we replaced the uniform prior for the redshift of the 21 cm spectral-line with a normal prior of $\Delta v_{\text{obs}} = 1823 \pm 500 \text{ km s}^{-1}$, given by the 6dFGS optical redshift (Jones et al. 2009) and typical infall/outflow gas velocities, the spectral line significance increases to $R = 111.8 \pm 0.1$. Figure 2 shows the best-fitting spectral line model for each of the individual spectra and the velocity-binned combined data.

For a sufficiently bright background source, the actual optical depth is related to the continuum flux density ($S_{\text{cont}}$), the fraction of flux that is covered by the foreground HI gas ($f$) and the observed spectral-line depth ($\Delta S_{\text{line}}$). This relationship is given by

$$\tau(v) = -\ln \left(1 - \frac{\Delta S_{\text{line}}}{S_{\text{cont}}}\right),$$

where $\tau(v)$ is the optical depth of the absorbing gas as a function of the rest-frame radial velocity. If we assume that the 21 cm absorption is optically thin ($\Delta S_{\text{line}}/S_{\text{cont}} \lesssim 0.3$), the above expression reduces to

$$\tau(v) \approx \frac{\Delta S_{\text{line}}}{S_{\text{cont}}} \approx \frac{\tau_{\text{obs}}(v)}{f},$$

where $\tau_{\text{obs}}(v)$ is the observed optical depth. Since many 21 cm absorption lines in the literature are far from being well modelled by a single Gaussian component, for the purpose of comparison, we define an effective width by

$$\Delta v_{\text{eff}} = \frac{\int \tau_{\text{obs}}(v) \, dv}{\tau_{\text{obs, peak}}},$$

where $\tau_{\text{obs, peak}}$ is the peak observed optical depth. This definition of the spectral line width avoids missing the contribution of broad, shallow components (as when using the FWHM), or the width parameter being strongly dependent on the spectral uncertainty (as when using the full width at zero-intensity). For the special case of a single Gaussian component, the effective width is just a factor of 1.06 times the FWHM. In Table 1 we summarize the derived spectral line parameters from the best-fitting models. Parameter values estimated from the 2011 April and 2012 June data are mostly consistent with each other and any significant differences are the result of the choice of model parametrization (the single Gaussian is intrinsically more peaked than the trough-like model). The small difference between the value of $R$ for our re-analysis of the 2011 April data, with that from the previous analysis by Allison et al. (2012a), is the result of improvements to our data reduction method.

The column density of atomic neutral hydrogen (in cm$^{-2}$) as a function of the integrated optical depth (in km s$^{-1}$) is given by (Wolfe & Burbidge 1975)

$$N_{\text{HI}} = 1.823 \times 10^{18} \frac{T_{\text{spin}}}{100 \text{ K}} \int \tau(v) \, dv \approx 1.823 \times 10^{18} \frac{T_{\text{spin}}}{T} \int \tau_{\text{obs}}(v) \, dv,$$

where $T_{\text{spin}}$ is the mean harmonic spin temperature of the gas (in K). Based on this relation, we estimate the HI column density towards PMN J2054–4242 to be

$$N_{\text{HI}} \approx 1.91 \pm 0.14 \times 10^{21} \left(\frac{T_{\text{spin}}}{100 \text{ K}}\right) \left(\frac{1}{T}\right) \text{ cm}^{-2},$$
Table 1. A summary of the derived properties of H\textsc{i} absorption from model fitting to the ATCA 21 cm data, where $\sigma_{\text{chan}}$ is the estimated uncertainty per channel; $c_{\text{peak}}$ is the redshift at peak spectral-line depth; $\Delta S_{\text{line,peak}}$ is the peak spectral line depth; $S_{\text{cont,peak}}$ is the continuum flux at peak spectral line depth; $f_{\tau_{\text{obs}}(v)dv}$ is the velocity integrated observed optical depth; $\Delta v_{\text{eff}}$ is the effective velocity width (as defined by equation[4]). $R$ is the natural logarithm of the ratio of probabilities for the single-component spectral line model versus the continuum-only model; $\chi^2_{\text{red}}/d.o.f$ is the reduced chi-squared statistic for the best-fitting (maximum likelihood) model parameters (under the assumption of model linearity). Note that the uncertainties include the systematic error in the data represented by a nuisance parameter with a normal prior.

| Epoch       | Resolution (km s\(^{-1}\)) | $\sigma_{\text{chan}}$ (mJy) | $c_{\text{peak}}$ (km s\(^{-1}\)) | $\Delta S_{\text{line,peak}}$ (mJy) | $S_{\text{cont,peak}}$ (mJy) | $f_{\tau_{\text{obs}}(v)dv}$ (km s\(^{-1}\)) | $\Delta v_{\text{eff}}$ (km s\(^{-1}\)) | $R$ | $\chi^2_{\text{red}}/d.o.f$ |
|-------------|-----------------------------|-----------------------------|-------------------------------|-----------------------------------|-------------------------------|-----------------------------------------------|----------------------------------------|-----|--------------------------|
| 2011 April  | 7                           | 3.83                        | 13073 ± 38                    | 4.8 ± 0.8                         | 160 ± 11                      | 15.8 ± 2.8                                    | 540 ± 120                              | 24.2 ± 0.1 | 0.98 ± 0.03    |
| 2012 June   | 7                           | 1.21                        | 13048 ± 10                    | 3.9 ± 0.4                         | 163 ± 10                      | 10.1 ± 0.7                                    | 418 ± 20                               | 95.0 ± 0.1 | 1.02 ± 0.03    |
| Combined    | 21                          | 1.05                        | 13046 ± 10                    | 4.1 ± 0.4                         | 163 ± 10                      | 10.5 ± 0.7                                    | 418 ± 20                               | 109.5 ± 0.1 | 0.91 ± 0.06    |

which for values of $T_{\text{spin}}/f > 10$ K is equivalent to that of a damped Lyman-$\alpha$ absorber ($N_{\text{H}} > 2 \times 10^{20}$ cm\(^{-2}\)).

4.2 High velocity cold gas towards PMN J2054–4242

By applying Bayesian inference to our 21 cm ATCA data we have detected cold, high column density H\textsc{i} gas towards the compact flat-spectrum radio source PMN J2054–4242. The observed total integrated optical depth for the absorption is relatively large (see Table[1]), however, this is distributed over a broad spectral line width, producing a modest peak optical depth of $\tau_{\text{peak}} = 2.5 \pm 0.2$ per cent. The 21 cm spectral line is redshifted with respect to the optical spectroscopic redshift ($z_{\text{opt}} = 0.042893 \pm 0.000150$; Jones et al. 2009) by 187 ± 46 km s\(^{-1}\), possibly indicating that the gas is infalling towards the central radio source. The strong broadening of the line perhaps suggests that the cold gas has very high velocity, or that the infall is accelerated along the line of sight. A high spatial resolution 21 cm study of the similarly compact radio source PKS B1814–637, by Morgan et al. (2011), showed that the broadened absorption component in that system was likely located within a circumnuclear disc, while the deeper narrower component arises from absorption in an extended disc of gas on the kpc scale. The absence of a narrow component in the spectrum of PMN J2054–4242 is perhaps indicative of either low column density (or missing) large-scale cold gas, or that any extended structure is orientated away from the line of sight to the radio source. These hypotheses are consistent with the optical classifications of the host galaxies for each of these sources: PKS B1814–637 is hosted by a gas-rich regular edge-on disc, while for PMN J2054–4242 the host is an early type (Loveday 1996). However, without further information, we can only speculate here as to the physical nature of the spectral line broadening. We are therefore pursuing follow-up multiwavelength and high spatial resolution observations to test these interpretations of the 21 cm ATCA data.

4.3 The scarcity of broad, weak 21 cm absorption lines

The left-hand panel of Fig[2] shows the initial detection of broad 21 cm absorption towards PMN J2054–4242 (2011 April). From visual inspection of this spectrum, one might reject the feature as being an artefact, due to its wide profile and low peak S/N. Indeed by using the automated source-finding tool DUCHAMP (Whiting 2012), this original feature was only detected with significance once we had smoothed the spectral data (using a Hann window function with a width of 5) and applied a threshold cutoff of three times the S/N. However, by using a Bayesian approach to spectral line finding and fitting, Allison et al. (2012a) found that the feature was significant above the noise and that it occupied a parameter space that was different to that of the false detections from continuum artefacts. The redshift is close to that of the optical spectroscopic measurement, which strongly suggests that it arises from associated H\textsc{i} absorption. All of these indicators prompted further observations in 2012 June, with a longer integration time, leading to confirmation that the feature is indeed a 21 cm absorption line.

Such broad, shallow 21 cm absorption lines physically correspond to a large spread in the velocity of H\textsc{i} gas along the line of sight. Existing detections of broad absorption are often associated with an accompanying narrow, deeper component. For example, Morganti et al. (2005b) conducted a targeted survey of 11 bright radio-loud AGNs, with evidence of past star formation and a rich inter-stellar medium, and most with existing detections of deep, narrow H\textsc{i} absorption. The broad bandwidth available ($\pm 2000$ km s\(^{-1}\)) and the high sensitivity achieved ($\sim 0.4 – 0.8$ mJy beam\(^{-1}\)), using the Westerbork Synthesis Radio Telescope, allowed detection of broad and shallower absorption with $\tau_{\text{peak}} < 0.01$. Morganti et al. detected broad, shallow absorption towards 6 radio galaxies, all of which were associated with existing deep, narrow components, and had bulk blueshifted motion interpreted as line-of-sight cold gas outflows. However, our detection of a single broad absorption line towards PMN J2054–4242 raises the question as to whether there exist a population of very shallow and broad H\textsc{i} absorption lines, which have no associated narrow, deep component, and as yet remain largely undetected.

To address this question, we show in the top panel of Fig[3] the peak observed optical depth, versus the effective spectral line width, for a representative sample of detections of 21 cm associated H\textsc{i} absorption in the literature (Curran et al. 2013 also present a similar plot of the FWHM for a literature sample of redshifted absorbers). We have treated multiple spectral components as a single detection, so that a profile exhibiting a single broad component will have a larger effective width than that with both broad and strong narrow components. Upon inspection of Fig[3] it is evident that these data exhibit a weak anticorrelation.
The observed 21 cm peak optical depth (top), and in flux units (bottom), versus the spectral line width (as defined by equation 4), for detections of associated H I absorption. The empty stars represent a sample from the literature (see text for details and references therein), and the filled star represents our detection towards PMN J2054–4242. The lines represent H I absorption for the maximum observed column density $\sim 10^{22}$ cm$^{-2}$, and constant $T_{\text{spin}}/f$ of 100 K (solid), 300 K (dashed), and 1000 K (dot-dashed).

Figure 3. The observed 21 cm peak optical depth (top), and in flux units (bottom), versus the spectral line width (as defined by equation 4), for detections of associated H I absorption. The empty stars represent a sample from the literature (see text for details and references therein), and the filled star represents our detection towards PMN J2054–4242. The lines represent H I absorption for the maximum observed column density $\sim 10^{22}$ cm$^{-2}$, and constant $T_{\text{spin}}/f$ of 100 K (solid), 300 K (dashed), and 1000 K (dot-dashed).

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