PROCEEDINGS OF SCIENCE

Mapping H I absorption at z=0.026 against a resolved background CSO

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Observing atomic hydrogen in absorption is an extremely powerful probe of galaxies at all redshifts: the detection sensitivity is not dependent on many of the properties of the system under study, but rather depends on the unrelated characteristics of the background source. The H I hyperfine 21-cm line enables a determination of the kinematics and gas distribution in the intervening absorbers and presents several advantages over Ly-α as it does not saturate and is unaffected by dust. One application is the study of small-scale structure in the ISM of external galaxies as, if the background radio source is resolved into several components, different independent sight lines through the absorbing gas layer can be studied. Here we present Global VLBI observations of J0855+5751, a Jy-strength Compact Symmetric Object against which H I absorption at a redshift of 0.026 was previously discovered using observations with the Green Bank Telescope. The combination of high angular resolution and sensitivity has allowed us to map the H I absorption across the lobes and to probe the spatial distribution of cold gas in the foreground galaxy on scales ranging from 3 to 30 pc.

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1. Introduction

Observing atomic hydrogen in absorption is an extremely powerful probe of galaxies at all redshifts as the detection sensitivity is independent of the properties of the system under study, depending instead on the unrelated characteristics of the background source. Whilst detection of the Lyman-α line has proved very successful at probing the physical state of a wide range of media at $z > 0$, the H I hyperfine 21-cm line presents several advantages as it does not saturate and is unaffected by dust [6].

One application of 21-cm absorption line studies that has not been exploited much is the study of small-scale structure in the ISM of external galaxies. If a background radio source is resolved into several components, different independent sight lines through the absorbing gas layer can be studied. Observations of background structures on the order of tens of mas will typically probe the ISM of foreground galaxies on scales of tens of pc. This scale nicely bridges the gap between the few pc that can be studied in the Milky Way galaxy ISM in absorption against background radio sources [9], and the more than 100-pc scales that are probed by high resolution 21-cm emission line maps of nearby galaxies [2, 12].

Neutral hydrogen opacity fluctuations on parsec scales provide information on the processes that regulate star formation. The structure and turbulence of the neutral medium determine the size distribution of molecular clouds and affect the shape of the stellar initial mass function [8]. Therefore, measuring the small scale structure of the ISM in both our and external galaxies is essential to understand how cold gas is converted into stars over cosmic time. Correlating the integrated 21-cm absorption profile shapes with the VLBI radio continuum extent of the background sources, suggests that the neutral gas is patchy with a typical correlation length of 30 to 100 pc [3]. An analysis of Galactic 21-cm absorption lines [4] concluded that the ISM can be modelled by "blobby sheets": the cold neutral medium (CNM) consists of sheet-like structures and blobs or cloudlets embedded in the warm neutral medium (WNM).

With VLBI it is possible to produce resolved spectra against the different components of the background source. Very Long Baseline Array (VLBA) observations of a radio-loud quasar [10] resulted in 21-cm absorption line spectra at $z = 0.08$ toward three components separated by $\sim$10 and 90 pc at the distance of the galaxy. The measured optical depths toward the two components differ by up to a factor of 10 for the narrowest components and much less for the broader component. This observation is interpreted as seeing dense small clouds of $<$10 pc embedded in a diffuse neutral medium on scales of several tens of pc, in support of the "blobby sheets" model.

Here we report Global VLBI observations of a substantially resolved radio source, J0855+5751, the radio emission from which is being absorbed in the ISM of a foreground dwarf galaxy at $z = 0.026$. We asssume a standard standard ΛCDM cosmology throughout.

2. J0855+5751

H I absorption was initially discovered in J0855+5751 as part of a survey conducted with the Green Bank Telescope (GBT) looking for absorption in small-impact parameter pairs of optical galaxies and background radio-loud quasars (Zwaan et al., in preparation). The foreground object (SDSS J085519.05+575140.7, a dwarf galaxy) lies at a redshift of $z = 0.026$ and is separated from

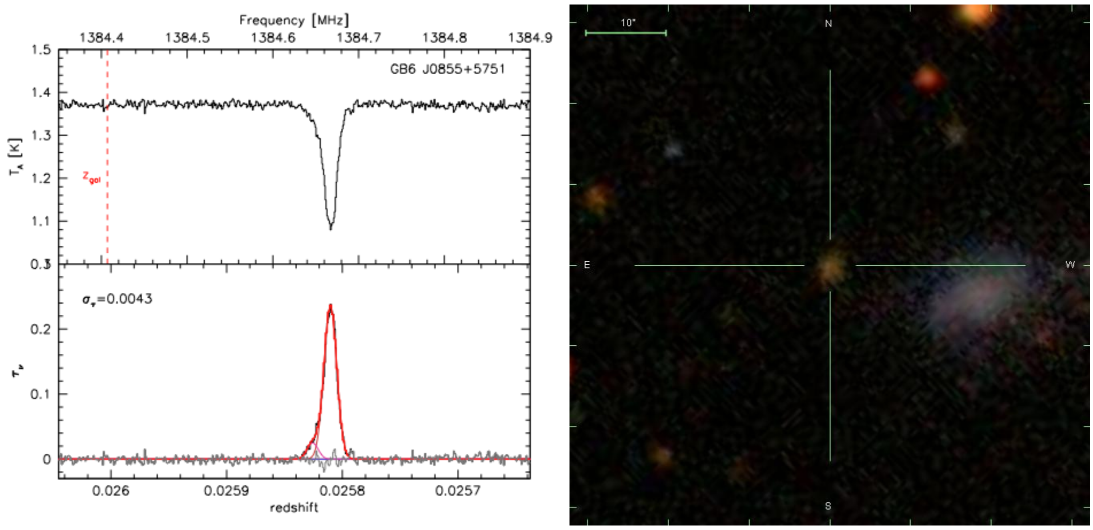

Figure 1: Left: GBT H I spectrum of J0855+5751. Right: SDSS image centred on J0855+5751. The foreground absorber is the extended blue galaxy to the West.

J0855+5751 by a projected distance of 6.8 kpc at this redshift. The absorption has a peak optical depth of 24 per cent and can be modelled satisfactorily with two Gaussian components (Fig. 1).

Whilst unresolved on arcsec scales, VLBA observations at 2.3 [1] and 5 GHz [5] have demonstrated that this source consists of two components separated by about 60 mas, both of which are extended on scales of $\sim$10 mas (Fig. 2). On the basis of the observed VLBI structure, this source has been classified as a Compact Symmetric Object (CSO) [11].

The redshift of J0855+5751 is not known, but the radio source is likely powerful ($S_{125\ \mathrm{MHz}} > 2.5 \times 10^{25}$ W m^{-2} Hz^{-1} for $z = 0.1$) and compact (projected size < 0.5 kpc for $z = 1$). Taken together with an observed radio spectrum that peaks at 300 MHz and the lack of detectable polarization, the source fulfils many criteria of CSS/GPS sources [7].

3. Global VLBI observations of J0855+5751

Global VLBI observations took place over a period of 13 h during June 2013 using a 17-station array. This comprised the 10 antennas of the VLBA, plus the EVN antennas at Effelsberg, Jodrell Bank (Lovell), Westerbork (operating as a phased array), Torun, Medicina, Zelenchukskaya and Badary. Data were recorded in 4 dual circularly-polarized subbands, each with a width of 2 MHz. Three of these measured the continuum, whilst the remaining one was centred on the absorption line (1384.6 MHz). We did not phase reference, partly because J0855+5751 is bright enough to self-calibrate, but also because a bright ($\sim$1 Jy) calibrator source (J0854+5757) is located only 7 arcmin away.

The data were correlated using the SFXC software correlator at the Joint Institute for VLBI in Europe (JIVE) with three separate passes. Two of these were used to produce “continuum” data sets with 16 channels per subband. For one of these, each source was correlated as usual at its observed position, but for the second, all the scans apart from the bandpass calibrator were correlated at

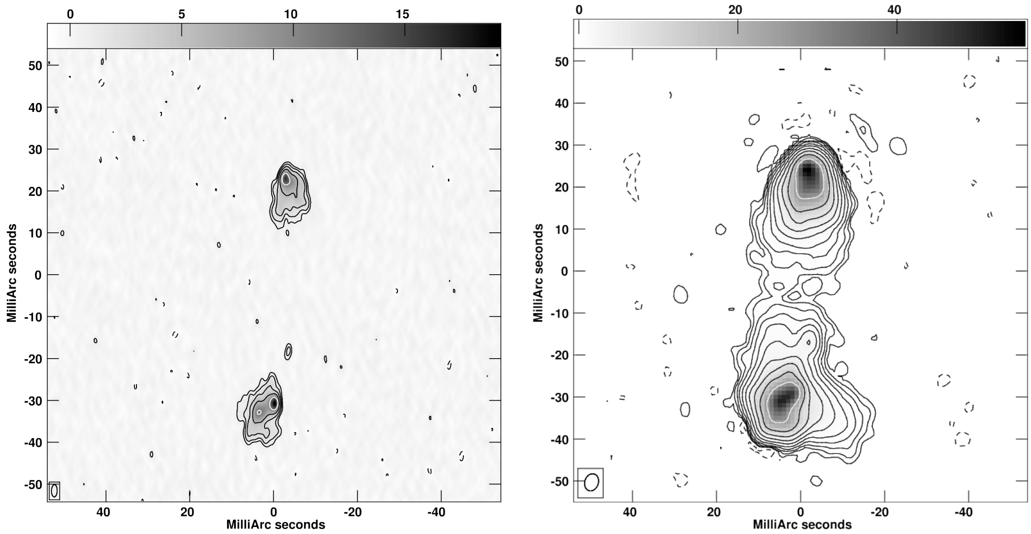

Figure 2: Left: VLBA image of J0855+5751 at 5 GHz. These data were observed as part of VIPS, the VLBA Imaging and Polarimetry Survey [11, 5] but were re-reduced by us. Right: Global VLBI continuum map of J0855+5751 at an average frequency of 1386 MHz. The 1-σ rms noise in the map is 15 μJy beam^{-1} and the restoring beam has a size of 4.2×3.2 mas^2 at a position angle of $-18\overset{\circ}{.}3$. Both maps are centred at 08:55:21.357, +57:51:44:10 (J2000) and are shown to the same scale.

the position of the in-beam phase calibrator. For the third pass, only the subband containing the absorption was correlated, but at much higher spectral resolution. We used 2048 channels with Hanning smoothing to produce a velocity resolution of $\simeq$420 m s^{-1}. The correlator averaging time was 4 s.

Data reduction was performed using AIPS, initially calibrating the in-beam calibrator data following standard procedures. Fringe-fitting was performed on all antennas apart from WSRT and the calibration then transfered to the low-resolution J0855+5751 data. As expected, the in-beam phase referencing produced an excellent initial map of the source, which was then improved upon using iterative mapping and self-calibration of all antennas. Finally, the total calibration was applied to the full-resolution target data, the bandpasses calibrated and residual Earth motion removed using CVEL.

4. Results

The final continuum map is shown in Fig. 2 and, with a 1-σ rms noise of 15 μJy beam^{-1}, is the highest sensitivity VLBI map of this source and, combined with the lower observing frequency, detects much more of the lobe emission than was previously the case. Of particular interest is the spur of emission extending from the southern lobe in a south-westerly direction. This suggests that the jet has encountered some obstacle in the ISM of the AGN host galaxy and consequently been deflected from its original trajectory. This might be related to the fact that the southern lobe in general has a more complex morphology than its northern counterpart in both the 1.4 and 5-GHz maps.

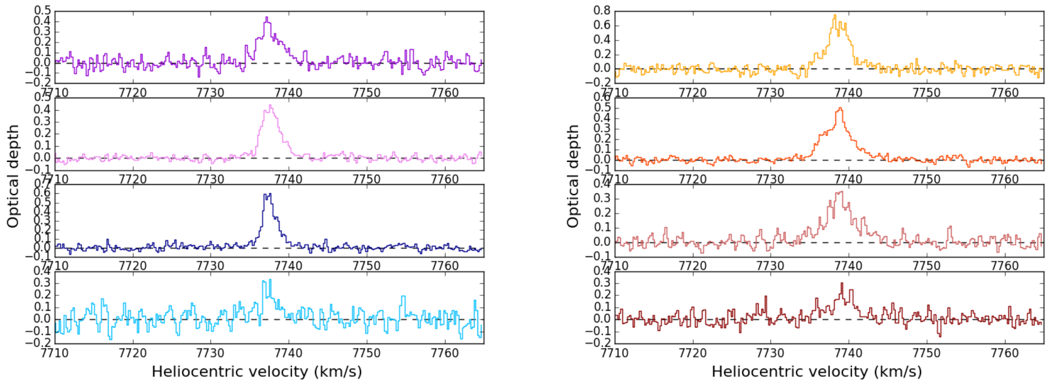

Figure 3: Left: VLBI H I spectra as seen against the north (left) and southern (right) lobes of J0855+5751. The panels are arranged such that each spectrum was measured at a point 4 mas to the North of the spectrum in the panel below. Variations can be seen in the shape, peak velocity and optical depth of each spectrum.

In the original 5-GHz VLBA map [11] a faint feature was visible between the lobes which we presumed was the location of the radio core. It is also present in the superior map made from our re-reduction (the original map was produced using an automated pipeline) and thus its existence seems certain. It is also seen in the new 1.4 GHz map, but deriving a spectral index is difficult due to confusion with the lobe emission. Despite this, the identification of this source as a CSO seems in little doubt.

Spectra of the optical depths observed along a number of different sightlines through the foreground absorber are shown in Fig. 3. The shapes of the spectra are quite complex, especially in the southern lobe, in contrast to the relatively smooth spectrum that was obtained with the GBT. The spatial variation of the absorption line is significant, each independent sightline having a different shape and peak optical depth. Each is separated by only 4 mas which corresponds to a spatial separation of only 2 pc within the foreground galaxy. Although not immediately apparent from Fig. 3, a map of the peak velocity at each pixel demonstrates that there is a systematic shift of approximately 1 km s^{-1} between the velocity of the peak optical depth in each lobe (Fig. 4).

5. Conclusions

We have presented resolved H I absorption spectra from Global VLBI observations of the CSO J0855+5751. These demonstrate that the properties of the cold absorbing gas in the dwarf galaxy SDSS J085519.05+575140.7 vary significantly over scales as small as 2 pc. Although our analysis is not yet complete, these preliminary results demonstrate the power of VLBI to probe the cold neutral medium of external galaxies at very high spatial resolution.

The new data have also yielded the best continuum map of the radio source to date. This is consistent with the previous identification of the radio source as a CSO and identifies a new feature that is indicative of a jet-cloud interaction in the ISM of the radio source's host galaxy. It would be interesting to re-observe this source at 5 GHz with a view to measuring proper motion in the radio components since the last observations at this frequency in 2004.

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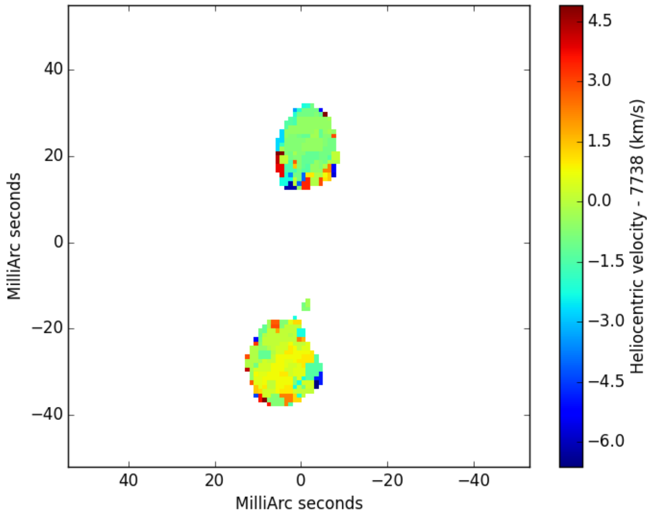

Figure 4: Map showing the variation of the peak velocity in the optical depth spectra as a function of sightline towards J0855+5751. Each pixel has a size of 1 mas. The absorption in the northern lobe is systematically blue-shifted relative to the southern. The edge pixels with more extreme values are probably due to the spectra at these locations being relatively noisy.

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