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Parsec-scale structures and diffuse bands in a translucent interstellar medium at $z \simeq 0.079^\star$

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ABSTRACT

We present a detailed study of the QSO–galaxy pair [SDSS J163956.35+112758.7 ($z_q = 0.993$) and SDSS J163956.38+112802.1 ($z_g = 0.079$)] based on observations carried out using the Giant Metrewave Radio Telescope (GMRT), the Very Large Baseline Array (VLBA), the Sloan Digital Sky Survey and the ESO New Technology Telescope. We show that the interstellar medium of the galaxy probed by the QSO line of sight has near-solar metallicity $[12 + \log(O/H) = 8.47 \pm 0.25]$ and dust extinction $[E(B-V) \sim 0.83 \pm 0.11]$ typical of what is usually seen in translucent clouds. We report the detection of absorption in the $\lambda 6284$ diffuse interstellar band (DIB) with a rest equivalent width of $1.45 \pm 0.20$ Å. Our GMRT spectrum shows a strong 21-cm absorption at the redshift of the galaxy with an integrated optical depth of $15.70 \pm 0.13$ km s$^{-1}$. Follow-up VLBA observations show that the background radio source is resolved into three components with a maximum projected separation of 89 pc at the redshift of the galaxy. One of these components is too weak to provide useful 21-cm H I information. The integrated H I optical depth towards the other two components are higher than that measured in our GMRT spectrum and differ by a factor 2. By comparing the GMRT and VLBA spectra we show the presence of structures in the 21-cm optical depth on parsec scales. We discuss the implications of such structures for the spin-temperature measurements in high-$z$ damped Lyman $\alpha$ systems. The analysis presented here suggests that this QSO–galaxy pair is an ideal target for studying the DIBs and molecular species using future observations in optical and radio wavebands.

Key words: ISM: lines and bands – ISM: molecules – quasars: absorption lines – quasars: individual: SDSS J163956.35+112758.7.

1 INTRODUCTION

Understanding parsec-scale H I opacity fluctuations in the interstellar medium (ISM) of galaxies and how they depend on the feedback from in situ star formation is very important. In the Galaxy, the radio observations of H I 21-cm absorption towards high-velocity pulsars and extended radio sources, the optical observations of Na I absorption lines towards globular clusters and binary stars have shown that the diffuse ISM is structured on parsec to sub-parsec ($\sim 10$ au) scales (Frail et al. 1994; Bates et al. 1995; Heiles 1997; Deshpande 2000; Rollinde et al. 2003; Boissé et al. 2005; Brogan et al. 2005; Roy et al. 2012). These small-scale structures, due to large overpressures, cannot survive rapid evaporation in the standard pressure-equilibrium-based models (see for example McKee & Ostriker 1977) and therefore raises many important questions regarding the nature of the ISM. It is possible that these are transient phases controlled by turbulence (Mac Low & Klessen 2004).

Physical conditions in H I gas associated with high-redshift galaxies can be probed by 21-cm absorption. In particular, the H I 21-cm optical depth combined with a determination of $N(\text{H I})$ from Lyman $\alpha$ absorption yields an estimate of the spin temperature, $T_S$ (Kanekar & Chengalur 2003) which is a good indicator of the kinetic temperature (Roy, Chengalur & Srianand 2006). However, to fully interpret high-redshift 21-cm spin-temperature measurements one needs to know the parsec-scale structure of the H I gas. In turn, if radio emission of the background QSO has structures at different scales

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then Very Large Baseline Interferometry (VLBI) spectroscopy can be used to probe the spatial variations of the \( \text{H} \) gas opacity.

Due to limitations of existing facilities, VLBI spectroscopic observations of QSO absorbers are limited to low redshifts only. In the case of the \( z_{\text{abs}} = 0.0912 \) damped Lyman \( \alpha \) (DLA) towards B0738+313, Lane, Briggs & Smette (2000) found the background source to be partially resolved at milliarcsec (mas) scales. Within the measurement uncertainties they do not find any strong variations in the \( \text{H} \) optical depth across 20 pc. The associated galaxy could be a low surface brightness dwarf at an impact parameter of \( \leq 3.5 \) kpc without any signature of ongoing star formation (see Turnshek et al. 2001). In the case of the \( z = 0.033 \) 21 galaxy towards J104257.58+074850.5, the background radio source is unresolved in the Very Large Baseline Array (VLBA) image and the 21-cm absorption is found to be similar over 27.1 pc \( \times \) 13.9 pc (see Borthakur et al. 2011 for details). Note that the impact parameter in this case is 1.7 kpc and the foreground galaxy is a low-luminosity spiral with low gas phase metallicity and dust extinction along the QSO sight line.

Alternatively, time variability of 21-cm absorption is seen in two cases [the absorbers towards B0235+164 (Wolfe, Briggs & Davis 1982) and B1127–145 (Kanekar & Chengalur 2001), suggesting that the \( \text{H} \) gas is patchy on parsec scales. Interestingly, the \( z_{\text{abs}} = 0.524 \) absorption system towards B0235+164 is one of the extragalactic systems that shows diffuse interstellar bands (DIBs; Junkkarinen et al. 2004). Using a large sample of \( z \leq 1.5 \) Mg II absorbers searched for 21-cm absorption together with mas scale radio images, Gupta et al. (2012) have concluded that the \( \text{H} \) gas is patchy with a typical correlation length of 30–100 pc based on different correlation analyses.

It has been shown that, like 21-cm absorption, one can use \( \text{H}_2 \) absorption to probe the cold neutral medium in \( z \geq 1.8 \) DLAs (Ledoux, Petitjean & Srianand 2003; Srianand et al. 2005; Noterdaeme et al. 2008). Recently Balashev et al. (2011), using partial coverage arguments, derived the linear size of the \( \text{H}_2 \)-bearing core and the \( \text{H} \) envelope to be \( 0.15_{-0.05}^{+0.05} \) and \( 8.2_{-4.1}^{+5.5} \) pc, respectively, for the \( z_{\text{abs}} = 2.3377 \) DLA towards Q1232+082. Srianand et al. (2012), combining 21-cm and \( \text{H}_2 \) information for a sample of high-\( z \) DLAs, concluded that the typical size of \( \text{H}_2 \) bearing clouds is \( \leq 15 \) pc.

All this indicates that the ISM of high-\( z \) galaxies is structured on parsec scales. However, most of the evidences are based on indirect arguments. In addition, one would like to connect the structures seen in \( \text{H} \) to other observable properties of the galaxy such as metallicity, dust content, local star formation, etc. We are performing a systematic search for 21-cm and OH absorption in a well-selected sample of quasar–galaxy pairs (QGPs, a fortuitous alignment of a background visible galaxy with a distant background quasar) with impact parameter \( b \leq 20 \) kpc. In case of detection we also perform optical long-slit and VLBA spectroscopic follow-up observations. Initial results from the Giant Metrewave Radio Telescope (GMRT) observations of five QGPs, with the redshift of the galaxies in the range \( 0.03 \leq z_{\text{q}} \leq 0.18 \) are presented in Gupta et al. (2010).

Here, we present a detailed analysis of a very special QGP with the background QSO (J163956.35+112758.7, \( z_{\text{q}} = 0.993 \)) sight line piercing through the optical disc (Fig. 1) of the foreground galaxy (J163956.38+112802.1, \( z_{\text{g}} = 0.079 \) or corresponding heliocentric velocity of \( v_{\text{hel}} \sim 23710 \) km s\(^{-1}\)). We report the detection of 21-cm, Na I absorption and DIBs in this galaxy. We use a long-slit spectrum to study the star formation rate (SFR), metallicity and rotation curve of the galaxy. The background radio source is well resolved at mas scales. We perform the VLBA spectroscopy and discuss the parsec-scale structures in the \( \text{H} \) gas. We will use a flat cosmological model with \( \Omega_m = 0.27, \Omega_{\Lambda} = 0.70 \) (Komatsu et al. 2009).
Table 1. Emission line parameters of the galaxy SDSS J163956.38+112802.1.

| Line (l) | $F_{\lambda}(10^{-17}$ erg s$^{-1}$ cm$^{-2}$) | $F_\lambda(H_\alpha)/F_\lambda$ |
|----------|---------------------------------|--------------------------------|
| H$\alpha$ | 147.0 ± 2.9                     | 1.00                           |
| H$\beta$  | 33.3 ± 1.8                      | 4.41 ± 0.26                    |
| [O ii]λ3728 | 75.3 ± 4.1                    | 1.95 ± 0.11                    |
| [O ii]λ3760 | 15.9 ± 1.4                   | 9.25 ± 0.82                    |
| [O ii]λ5008 | 42.9 ± 1.8                    | 3.42 ± 0.16                    |
| [N ii]λ6549 | 6.3 ± 1.2                     | 23.17 ± 4.54                   |
| [N ii]λ6585 | 28.7 ± 1.8                    | 5.11 ± 0.34                    |
| [S ii]λ6718 | 28.5 ± 1.7                    | 5.16 ± 0.33                    |
| [S ii]λ6732 | 20.3 ± 1.5                    | 7.24 ± 0.55                    |

2 PHYSICAL CONDITIONS IN THE GALAXY

2.1 Metallicity and dust in the emission line regions

Strong emission lines from the foreground galaxy are seen in the Sloan Digital Sky Survey (SDSS) spectrum (see Fig. 1). They suggest the presence of a star-forming region within a projected separation of 2.2 kpc to the QSO sight line.\(^1\) We fit the emission lines using Gaussians and the integrated line fluxes are summarized in Table 1. A luminosity distance of 354.1 Mpc is used to convert these fluxes into luminosities. The last column in this table gives the ratio of the H$\alpha$ flux with respect to that of other emission lines. Following Argence & Lamareille (2009), we derive the optical depth in the systemic V band of the galaxy, $\tau_V^{[\text{Balmer}]} = 1.39 \pm 0.18$, using the observed H$\alpha$/H$\beta$ ratio, the intrinsic Balmer ratio of 2.85 (Osterbrock & Ferland 2006) and the wavelength dependence of the dust optical depth (i.e. $\tau_V$) as given by equation (3) of Wild et al. (2007). We estimate a dust-uncorrected surface density of the SFR of 0.006 $M_\odot$ yr$^{-1}$ kpc$^{-2}$. Applying the dust correction will increase this estimate by a factor of 3 for $\tau_V^{[\text{Balmer}]}$ quoted above. If we assume that this disc galaxy obeys the Kennicutt–Schmidt law, then we get $N(H\,\text{ii}) \sim 2.6 \times 10^{21}$ cm$^{-2}$ using the best-fitting parameters of Kennicutt (1998a,b). Using the measured O3N2 ratio (i.e. $\log \left( F_\lambda(O\,\text{III} \,\lambda 5007)/F_\lambda(H_\beta) / [F_\lambda(N\,\text{ii} \,\lambda 6585)/F_\lambda(H_\alpha)] \right)$ and the best-fitting relationship given in Pettini & Pagel (2004) we get 12+log(O/H) = 8.47 ± 0.25. Thus, the QSO sight line is passing close to (i.e. within 2.2 kpc) a star-forming region having near-solar metallicity and high N(H$\,\text{ii}$).

2.2 Modelling the QSO spectral energy distribution

The background QSO spectrum is highly reddened (see Fig. 1). We found an independent estimate of $\tau_V$ and $E(B - V)$ by fitting the QSO spectral energy distribution (SED) using

$$f_\lambda = A f_\lambda^{[1]} e^{-\tau_\lambda} + B f_\lambda^{[2]}.$$  

(1)

Here $f_\lambda^{[1]}$ and $f_\lambda^{[2]}$ are, respectively, the observed flux at $\lambda$, the flux in the QSO composite spectrum at $\lambda_\lambda = \lambda(1 + z_Q)$ and the flux in the galaxy continuum that also enters the SDSS fibre. We approximate the latter with a spiral galaxy template at $\lambda_\zeta = \lambda(1 + z_g)$. A and B are normalization factors, and $z_Q$ and $z_g$ are the redshifts of the QSO and the foreground galaxy, respectively. The form of $\tau_\lambda$ is taken from the Milky Way extinction curve (Fitpatrick & Massa 1988). The fitting method used is very similar to the one used in Srianand et al. (2008) and Noterdaeme et al. (2009). As can be seen from the right-hand panel of Fig. 1, the best fit (with $\chi^2 = 1.23$) to the observed spectrum is obtained for $A_V = 2.56 \pm 0.02$ [with $E(B - V) = 0.82 \pm 0.01$ and $R_V = 3.1$]\(^2\) where $A_V = 1.086 \tau_\lambda$. The quoted errors are mainly statistical ones. In Fig. 1, we also show the distribution of $A_V$ obtained for a control sample of SDSS QSOs with $z \sim z_Q$. For this exercise we do not consider the foreground galaxy contribution to the SED (i.e. the second term in equation 1). The r.m.s. of the $A_V$ distribution of 0.11 reflects a typical systematic error in the SED-fitting method due to the dispersion of the unreddened QSO SED. Therefore, the reddening noted in the present case is significant at more than the 20σ level. The measured value of $A_V$ is consistent with the line of sight passing through a translucent region (defined as a region with $1 \leq A_V \leq 10$ (van Dishoeck & Black 1989; Snow & McCall 2006)). If we use the relationship between $N(H\,\text{ii})$ and $A_V$ derived in the Galactic ISM (Bohlin, Savage & Drake 1978), then the above inferred $A_V$ is consistent with $N(H\,\text{ii}) = 4 \times 10^{21}$ cm$^{-2}$. The difference between the two $A_V$ estimates obtained using the Balmer decrement (i.e. $A_V^{[\text{Balmer}]} = 1.51 \pm 0.10$) and the fit of the QSO SED can be attributed to differences in the dust opacity (or differences in $N(H\,\text{ii})$), if we assume uniform dust-to-gas ratio) towards the QSO and the H$\alpha$ emitting regions. In passing, we wish to point out that the line of sight discussed here has more dust opacity than any of the high-$z$ dusty Mg II and CO systems that also produce 2175 Å absorption (Srianand et al. 2008; Noterdaeme et al. 2009; Jiang et al. 2011).

The SED-fitting procedure used above predicts the relative contributions of the QSO and the galaxy as a function of wavelength (top-right panel in Fig. 1). We independently estimate this ratio at different wavelengths using different SDSS broad-band images within an aperture of 1.5 arcsec centred at the position of the quasar. We use the following steps: (1) cut an image stamp of 80 pixels on a side around the QGP, (2) subtract a constant background obtained by averaging the counts in more than 10 neighbouring regions close to the pair, (3) obtain the radial surface brightness profile of the galaxy (after masking the quasar) by fitting isophotal ellipses using STSDAS package in IRAF and (4) derive the total counts due to the galaxy within an aperture of 1.5 arcsec radius at the location of the quasar using the fitted isophots. The estimated ratios together with the errors (mainly from Poisson statistics) are also shown in the top-right panel of Fig. 1. They are very much consistent with the curve obtained from the SED fitting. This confirms the robustness of our fitting procedure. In addition, based on the ellipticity of the outer isophots in the $r$ and $i$ bands, we measure a disc inclination angle of $\sim 63^\circ$.

2.3 Na I absorption

Using the European Southern Observatory (ESO) New Technology Telescope (NTT), we performed long-slit spectroscopic observations of the QSO–galaxy pair aligning the slit (of width 1.2 arcsec and length 4.1 arcmin) along the semimajor axis of the galaxy. The spectra ($4 \times 2700$ s exposures) were obtained in good seeing conditions ($\sim 0.8$ arcsec) using the ESO Faint Object Spectrograph and Camera (EFOSC2) covering the wavelength range 6040–7135 Å at a spectral resolution of 200–250 km s$^{-1}$. The data were processed

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1 The SDSS fibre has a diameter of 3 arcsec and was centred on the QSO. An angular scale of 1 arcsec corresponds to a projected size of 1.474 kpc at the redshift of the galaxy. Therefore, the SDSS spectrum is the juxtaposition of the QSO spectrum with that of the galaxy within a radius of 2.2 kpc.

2 The derived value of $E(B - V)$ depends on our choice of $R_V$. In the absence of $R_V$ measurement we adopt $R_V = 3.1$ as seen in the Milky Way.
using standard IRAF3 long-slit routines. 1D spectra were extracted with sub-apertures having a width of 5 pixels (i.e. projected size of \(\sim 2\) kpc). The results are summarized in Fig. 2.

In the spectra of the QSO (shown in the bottom panel in Fig. 2) we detect Na i \(\lambda\lambda 5891,5897\) lines with rest equivalent widths, \(W_r = 0.65 \pm 0.10\) and 0.58 \(\pm 0.10\) Å, respectively, at \(z_R\). Using the empirical relationship between \(E(B - V)\) and \(W(\text{Na i})\) reported recently by Poznanski, Prochaska & Bloom (2012) we estimate \(E(B - V) = 0.31^{+0.04}_{-0.02}\) and 0.47 \(\pm 0.09\) from the measured equivalent widths. The \(E(B - V)\) we measure from the SED fitting is higher than these values but consistent within uncertainties.

As the doublet ratio is close to 1 and the resolution of our spectrum is low it is most likely that the lines are saturated. A very conservative lower limit of log \(N(\text{Na i})\geq 12.78\) is obtained assuming the optically thin case. Consequently, we derive \(N(\text{H} I) \geq 10^{21}\) cm\(^{-2}\) from the known correlation between \(N(\text{Na i})\) and \(N(\text{H} I)\) found in our Galaxy (Ferlet, Vidal-Madjar & Gry 1985; Wakker & Mathis 2000).

2.4 Diffuse interstellar bands

All the optical observations presented above suggest that the gas along the line of sight has \(N(\text{H} I) \geq 10^{21}\) cm\(^{-2}\), with near-solar metallicity and high dust content. In such cases one can expect to detect absorption from different molecular species and DIBs (Sarre 2006). In Fig. 2, we have marked the expected positions of DIBs using vertical dashed lines. A clear absorption is detected at the expected position of the \(\lambda = 6284\) Å DIB. Using a Gaussian fit we measure a rest equivalent width of 1.46 \(\pm 0.21\) Å and full width at half-maximum (FWHM) = 14 \(\pm 2\) Å. The measured FWHM is 1.4 times larger than what is seen in nearby starburst galaxies (Heckman & Lehnert 2000) and roughly a factor of 2.2 higher than what is seen in the Galactic ISM towards HD 204827 (Hobbs et al. 2008). No other DIB absorption is detected at more than the 3\(\sigma\) significance level. We place a 3\(\sigma\) upper limit of 0.66 Å for the rest equivalent width of the \(\lambda 5780\) DIB feature.

In the local universe DIB observations are available for the ISM of Magellanic clouds (Cox et al. 2006, 2007; Welty et al. 2006), M33 (Cordiner et al. 2008), M31 (Cordiner et al. 2011), NGC 1448 (Sollerman et al. 2005) and some nearby starburst galaxies (Heckman & Lehnert 2000). In Fig. 3, we plot \(W(\lambda 6284)\) against \(E(B - V)\) found in these cases. The strength of \(\lambda 6284\) is affected by the strength of the radiation field and metallicity. Low equivalent width is explained by stronger radiation field and/or lower metallicity (Cox et al. 2006, 2007; Welty et al. 2006). It is interesting to note that the metallicity measured in the present case is close to that measured in M31 and starburst galaxies studied by Heckman & Lehnert (2000). However, the equivalent width of the \(\lambda 6284\) DIB is found to be higher than that predicted by the correlation found by Friedman et al. (2011). This may imply slightly low ambient radiation field found in the QSO sight line. Alternatively, if we assume that the physical conditions in the galaxy studied here are similar to that of the Galactic ISM, then we get log \(N(\text{H} I) = 21.76 \pm 0.25\) and \(E(B - V) = 1.30 \pm 0.20\) from the observed \(W(\lambda 6284)\) and the correlations found by Friedman et al. (2011). Interestingly, the \(N(\text{H} I)\) value inferred here matches well, albeit with large uncertainties, with that we infer from the \(A_V - N(\text{H} I)\) relationship of Bohlin et al. (1978). In addition, the inferred \(E(B - V)\) may mean \(R_V = 1.9^{+0.3}_{-0.2}\) and not 3.1 as we have assumed before. This is similar to what has been inferred for the host galaxies of high-z supernovae (Wang et al. 2006). Therefore, it is important to have independent measurements of \(N(\text{H} I)\) and \(R_V\) for the present case.

In all the local measurements discussed above \(W(\lambda 5780)\) is found to be smaller than \(W(\lambda 6284)\). If we use the correlations found by Friedman et al. (2011), we obtain \(W(\lambda 5780) = 0.61 \pm 0.08\) Å. We
show the expected profile in the bottom panel of Fig. 2. From the residual plot shown in the top panel of Fig. 2 we can say that the observed spectrum is consistent with $\lambda 5780$ DIB feature having the predicted equivalent width. From table 3 of Welty et al. (2006), we find the average value of the $W_r(\lambda 6284)/W_r(\lambda 5780)$ ratio to be 2.9 ± 0.2 in the case of the Magellanic clouds. Based on this we obtain $W_r(\lambda 5780) = 0.5 \pm 0.1$ Å. Detecting this feature and other DIB features in a high signal-to-noise ratio (SNR) spectrum will allow us to probe the physical state of the gas in more detail.

This is only the third detection of DIBs due to intervening absorbers in QSO spectra (see Jukkarianen et al. 2004; Ellison et al. 2008). In previous cases the $\lambda 5780$ DIB was detected without clear detection of the $\lambda 6284$ DIB. This is very much contrary to what has been seen in the local universe (apart from the rare sight line towards Sk 143, as seen in Welty et al. 2006) and in the present case. York et al. (2006), by analogy with Sk143, attributed these unusual line ratios to the ISM being more protected from the ambient ultraviolet radiation field.

The present NTT spectrum does not allow us to search for molecular absorption. However, based on known correlations in the Galactic ISM we expect $\log N(\text{CH}) \geq 13.8$, $\log N(\text{CH}^+) \geq 13.5$ and $\log N(\text{CN}) \geq 12.4$ (Welty et al. 2006). Therefore, high-resolution follow-up spectroscopy of this source could yield very good insights into the ISM of this external galaxy.

### 2.5 Hz rotation curve

In this section, we study the large-scale kinematics of the emission line gas using the NTT long-slit spectrum. In the left-hand panel of Fig. 4, we show the $H\alpha$ emission observed in different sub-apertures together with the best-fitting Gaussian profiles. The measured FWHM is close to our spectral resolution suggesting low-velocity dispersion along the line of sight. The 2D spectrum around the $H\alpha$ range after subtracting the QSO trace is shown in the right-hand panel. While the rotation is apparent we also notice that the blue side is brighter suggesting additional star formation activity.

![Figure 4](https://example.com/fig4.png)

**Figure 4.** Left-hand panel: velocity plot showing the $H\alpha$ emission extracted at different locations in the galaxy. Top-right: 2D spectra in the region of $H\alpha$ and [N ii] emission lines after subtracting the QSO light. The horizontal lines show the location of the QSO trace. Bottom-right: the rotation curve obtained from the $H\alpha$ line. The star is the velocity of the $H\alpha$ gas seen in 21-cm absorption towards the QSO (see Section 3.1). The zero of the velocity scale is set at $Z_{\text{abs}} = 0.0791$ and zero of the spatial scale is set at the position of the QSO.

Coincidentally, the QSO sight line is very close to this star-forming region. The angular separation between the centre of the QSO trace and the centre of the nearest star-forming region (based on the peak of the Hz emission) is 0.48 arc sec. This corresponds to a physical separation of 0.7 kpc. The different values of $A_V$ measured towards the Hz emitting region and the QSO reflect roughly a factor of 2 change in $A_V$ within a projected separation of 0.7 kpc. Therefore, the projected distance (and associated dust extinction) is large enough so that the gas along the QSO sight line may not be influenced by the star-forming region. The QSO sight line is at an impact parameter of 4 kpc from the galactic centre. The rotation curve plotted in Fig. 4 suggests an asymptotic circular velocity of $\sim 125$ km s$^{-1}$. This circular velocity for a typical radius of 10 kpc corresponds to a dynamical mass of $\sim 4 \times 10^{10} M_\odot$ after correction for the inclination angle of 63°. This suggests that the host galaxy is a low-mass disc galaxy.

### 3 21-CM ABSORPTION AND PARSEC-SCALE STRUCTURES

#### 3.1 GMRT 21-cm spectrum

As the background QSO is radio loud (with 1.4 MHz flux density of $\sim 164$ mJy) we get an opportunity to study the property of the cold $H\i$ gas along this dusty sight line. The source is unresolved in the Faint Images of Radio Sky at Twenty-centimetre (FIRST) image with a deconvolved size of 1.32 arcsec × 0.82 arcsec. As expected, a very strong 21-cm absorption was detected by GMRT observations on 2010 July 02 (2 MHz bandwidth split into 128 channels having a velocity resolution of $\sim 3.5$ km s$^{-1}$per channel). We obtained a higher resolution (2.08 MHz bandwidth split into 512 channels having a velocity resolution of 0.93 km s$^{-1}$per channel) GMRT spectrum on 2011 July 14 and 16. All these data were reduced using the National Radio Astronomy Observatory (NRAO) Astronomical Image Processing System (AIPS) following the standard procedures.

The radio source is unresolved in our GMRT image (with a spatial resolution of 2.5 arcsec × 2.1 arcsec) with a peak flux density of 155 mJy beam$^{-1}$. The 21-cm optical depth profile from the high-resolution spectrum is shown in Fig. 5. The integrated 21-cm optical depth is found to be $T = 15.7 \pm 0.13$ km s$^{-1}$, with 90 per cent of it is within a velocity range of 28 km s$^{-1}$ (see the top panel in Fig. 5). The observed $T$ translates to $N(\text{H} \i) = 2.9 \times 10^{19} (T_\i/f_\i)\text{cm}^{-2}$ with $f_\i$ being the covering factor, the fraction of the background radio emission covered by the absorbing gas. The probable values of $N(\text{H} \i)$ discussed above based on known correlations suggest that the harmonic mean spin temperature of the $H\i$ gas is less than or equal to 100 K as seen in the Galactic ISM.

Another interesting observation is that the $H\i$ gas that produces the 21-cm absorption is redshifted with respect to the peak rotational velocity of the Hz emitting gas at the same location by up to 25 km s$^{-1}$ (see Fig. 4). This once again confirms that the absorbing gas and Hz emitting gas are not co-spatial.

#### 3.2 Spatially resolved VLBA spectroscopy

The VLBA observations of J1639+1127 were carried out on 2011 July 27 and October 1. The total and on-source observing times were 10 and 6.3 h, respectively. One 8 MHz baseband channel pair was used in these observations, with right- and left-hand circular polarization sampled at 2 bits, and centred at the frequency of the redshifted $H\i$ 21-cm line. The data were correlated with 4096 channels (channel width of 0.45 km s$^{-1}$) and 2 s correlator integration.
time. We followed the standard data-reduction procedures for reducing the VLBA data (see for example Momjian, Romney & Troland 2002; Srianand et al. 2012). The radio continuum emission is resolved into multiple components at mas scales (Fig. 6). We use the multiple Gaussian fits to the VLBA images and found three distinct components. The results are summarized in Table 2. Only 78 per cent of the flux density measured with the GMRT is recovered with the VLBA. Components A and C, which are separated by 55.8 mas (implying a linear line-of-sight separation of 89 pc at the redshift of the galaxy), have nearly equal flux densities and contribute to 98 per cent of the total flux density seen in the VLBA image. The peak flux densities of these components are 47 and 65 per cent of their respective total flux densities, suggesting structures at few mas scales in the radio emission.

The 21-cm absorption towards the peak emission of A and C extracted from our VLBA observations (smoothed to a channel width of 0.9 km s\(^{-1}\)) to match the GMRT spectrum are shown in Fig. 6. The integrated 21-cm optical depths, given in the last column of the Table 2, are more than that measured in our GMRT spectrum and differ by a factor of 2 within the 89 pc probed by the two sight lines. Unlike the GMRT spectrum, which is very smooth, the 21-cm spectrum towards component C shows the presence of narrow absorption components superposed on a smooth absorption profile. This confirms the patchy distribution of the absorbing gas at parsec scales.

To probe this further, we compare in Fig. 7 the optical depth profiles seen in the GMRT and the VLBA observations. Fig. 7 also shows the difference in optical depth (i.e. \(\Delta \tau\)) between the lines of sight towards A and C as a function of velocity. While broad smooth absorption profiles with nearly identical optical depths are seen, narrow absorption components (identified with vertical dotted lines in Fig. 7) are clearly seen only towards C. The top panel of Fig. 7 shows the fractional difference in \(\tau\) between the two sight lines compared to \(\tau_A\). It is clear that on average \(\tau_C \approx 5 \times \tau_A\) in the velocity range \(-5\) to \(10\) km \(s^{-1}\), where the optical depth towards C is dominated by several narrow components. This basically confirms the large variations in H\(_i\) optical depth over a length-scale of 89 pc for narrow H\(_i\) components.

### 3.3 Tiny clouds and parsec-scale structure

As the deconvolved sizes of the VLBA components correspond to a projected size of \(\sim 8\) pc, the next question we wish to address is whether there is any optical depth variation over this length-scale. We do this by comparing the optical depth profiles seen towards A and C with the total optical depth profile seen in the GMRT spectrum. In general we can write

\[
\tau_{\text{GMRT}}(v) = f_A \tau_A(v) + f_C \tau_C(v) + \tau_D(v).
\]

Here, \(f_A\) and \(f_C\) are the covering factors of the gas component having optical depth \(\tau_A(v)\) and \(\tau_C(v)\), respectively. \(\tau_D(v)\) is the optical depth towards components not seen in the VLBA image. \(f_C\) will be 0.37 if the absorbing gas covers all the radio emission.

### Table 2. Results of VLBA observations.

| Source | Flux density (mJy beam\(^{-1}\)) | Total flux density (mJy) | Deconvolved angular size (mas\(^2\)) | PA (deg) | \(dv\) (kms\(^{-1}\)) |
|--------|----------------------------------|-------------------------|--------------------------------------|--------|----------------------|
| A      | 26.8                             | 57.4                    | 9.9 \times 6.7                       | +31.6  | 17.6 ± 1.6           |
| B      | 1.7                              | 2.1                     | 8.8 \times 0.0^a                     | +107.2 | –                    |
| C      | 36.8                             | 56.8                    | 5.9 \times 4.1                       | +62.0  | 37.6 ± 2.9           |

\(^a\)An angular extent of 0 indicates a source size much smaller than the synthesized beam.
seen in the VLBA image from the component C (i.e. $f_C$ is ratio of flux density of component C to the total flux density measured in the GMRT image). Therefore, if we assume a plane parallel gas slab covering only the emission from component C, then we expect $\tau_{GMRT}(v) = 0.37 \tau_C(v)$. If we assume $\tau_A(v) = \tau_C(v)$, then we expect $\tau_{GMRT}(v) = 0.74 \tau_C(v)$. If $\tau_A(v) \leq \tau_C(v)$, then we expect $0.37 \leq \left( \frac{\tau_{GMRT}(v)}{\tau_C(v)} \right) \leq 0.74$. In contrast, if $\tau_A(v) \geq \tau_C(v)$, then $\tau_{GMRT}(v)/\tau_C(v) \geq 0.74$. Note that this condition is also obtained when additional components are present towards the broad diffuse emission resolved out in the VLBA image (i.e. $\tau_D \geq 0$). This discussion clearly suggests that by looking at the ratio of the optical depth observed by GMRT and VLBA in one of the components, we will be able to draw broad conclusions about the optical depth variability at small scales.

First, we focus on the most interesting narrow component at $v = 0 \text{ km s}^{-1}$. This component is distinctly visible in C and evident even in the GMRT spectrum, but clearly absent towards A (as suggested by $\Delta \tau \sim \tau_C$). The peak optical depth of this component is $2.5 \pm 0.1$ towards C. Based on the flux densities in the VLBA image, if the absorbing gas covers only C, then we expect the peak optical depth at $v \sim 0 \text{ km s}^{-1}$ in the GMRT spectrum to be $\sim 0.93 \pm 0.05$. However, the measured value in the GMRT spectrum is $0.70 \pm 0.01$, suggesting that if the absorption component is a plane parallel slab with uniform $N(\text{H} I)$, then it would cover only 75 per cent of the continuum emission from component C. The observed parameters, on the contrary simply imply the presence of a strong optical depth gradient within the deconvolved size of component C (i.e. $\leq 6 \text{ mas}$). This angular scale corresponds to a transverse size $<8.8$ pc. As this component is distinctly visible, we fit multiple Gaussian to $\tau_C$. While Gaussian fit to other components may be unphysical, simultaneous fits allow us to get a realistic estimate of FWHM (1.75 km s$^{-1}$) and the peak optical depth (2.5 $\pm$ 0.1) for the narrow component. We get an upper limit of 66 K for the kinetic temperature of the gas from the FWHM. Using this as an indicator of spin temperature ($T_{\text{sp}}$), we get $N(\text{H} I) = 5.4 \times 10^{20}(T_{\text{sp}}/66 \text{ K}) \text{ cm}^{-2}$. If we approximate the absorbing cloud as a sphere, then we get a particle density of $\sim 40 \text{ cm}^{-3}$ using $N(\text{H} I)$ and the transverse size discussed above. Physical conditions in this component are typical of diffuse molecular clouds.

To explore this further, we plot in Fig. 8 the ratio of $\tau_{GMRT}$ to $\tau_C$ in the velocity range that contains 90 per cent of the integrated optical depth. The expected ratios when a parallel slab of gas with constant $\tau$ covers only the component C, all the VLBA components and all the flux seen by GMRT are shown by horizontal lines at 0.37, 0.74 and 1, respectively. We use this plot to discuss the extent of the gas that produces absorption in different velocity ranges.

First, we consider the velocity range $3 \leq v (\text{ km s}^{-1}) \leq 9$ where absorption is seen towards both A and C with $\tau_C \sim 5 \times \tau_A$ (see the top panel in Fig. 7). If the gas towards C and A covers all the radio emission from these components, then we expect $\tau_{GMRT}/\tau_C$ to be 0.44 (i.e. $0.37 \times (1.0 + 0.2)$). From Fig. 8 we see that the observed ratio is consistent with 0.38 in this range. We notice that the optical depth error in each channel in the VLBA spectrum towards C is $\sim 0.1$. For the mean optical depth measured in this velocity range this translates to an error of 0.03 in the ratio. Therefore, in each channel we find the ratio to be lower than 0.44 by 2$\sigma$ level. As this happens over six channels, we see the difference to be significant at the 4.8$\sigma$ level. This difference can be understood if some of the narrow components seen towards C have projected sizes less than 8.8 pc (or the presence of strong opacity gradient within this scale) as seen in the case of the narrow component at $v \sim 0 \text{ km s}^{-1}$.

In the velocity ranges $10 \leq v (\text{ km s}^{-1}) \leq 16$ and $-10 \leq v (\text{ km s}^{-1}) \leq -4$ from Fig. 7, we find $\Delta \tau \sim 0$. Therefore, we expect the ratio of $\tau_{GMRT}$ and $\tau_C$ to be 0.74. In the case of the first velocity range the ratio is above 0.74. In the framework presented above, this could either mean $\tau_A \geq \tau_C$ or contribution to $\tau_{GMRT}$ from the diffuse component resolved in the VLBA image. If we use the average value (1.2) of the measured ratio in this velocity range we get $\tau_A = 2.1 \times \tau_C$. In the second velocity interval the ratio is found to be between 0.36 and 0.74. This is consistent with $\tau_A \leq \tau_C$. Using the mean value of the ratio (0.65) in this velocity range we find $\tau_C \sim 1.4 \times \tau_A$. These are very different from $\tau_C = \tau_A$ we see towards the peak emission in A and C. Therefore, we can conclude
that there are strong opacity gradients at the spatial scale of \(~10\) pc even in the gas that produces absorption in this velocity range.

Finally, in the velocity range \(\sim 18\) to \(\sim 10\) km \(s^{-1}\), the absorption profile is smooth both in the VLBA spectrum towards C and in the GMRT spectrum. Therefore, we smooth the spectra to a 4 km \(s^{-1}\) resolution to increase the SNR. We notice that \(\tau_{\text{GMRT}}/\tau_{\text{C}}\) in this velocity range is \(0.67 \pm 0.03\). This just differs from the expected value of 0.74 by 2.3\(\sigma\) level. Within the observational uncertainty the optical depths seen towards A and C are nearly equal as suggested by the difference in \(\tau\) plotted in Fig. 7. Increasing the SNR of our VLBA spectra will help detecting minor optical depth differences even in this smooth component.

In summary, we find that the 21-cm absorption has both narrow and broad components. The narrow components show optical depth variations by a factor 1.4 to 10 over a 89-pc scale. In one of the narrow components we show that optical depth variations are present over a 8-pc scale. In contrast, the absorption seen in the broad wings are consistent with nearly similar optical depths (i.e. at 2.3\(\sigma\) level) within measurement uncertainty. Thus, a simple picture of the system could be that of several cold, dense and small clouds with characteristic size \(\leq 10\) pc embedded in a smooth diffuse H I medium covering several tens of parsec. This scenario is similar to the ‘blobby sheets’ seen in the Galactic ISM (Heiles & Troland 2003).

4 DISCUSSION

We report the detection of DIBs and 21-cm absorption from the \(z_\text{abs} = 0.079\) galaxy SDSS J163956.38+112802.1 towards the \(z_\text{em} = 0.993\) QSO J163956.35+112758.7. The QSO line of sight in this case is passing through the disc of a relatively low-mass \((\sim 4 \times 10^{10} M_\odot)\), near-solar metalliclicity spiral galaxy at an impact parameter of \(~4\) kpc. The region with highest star formation surface density, inferred from H\(\alpha\) emission, in this galaxy is located within a projected distance of 0.7 kpc from the QSO sight line.

The QSO is highly reddened with \(E(B - V) \sim 0.83 \pm 0.11\) (estimated from the SED fitting) along the line of sight. This suggests that the line of sight is passing through a translucent ISM. The measured \(E(B - V)\), rest equivalent widths of Na D lines and surface density of star formation favour \(N(H\,\text{I}) \geq 10^{21} \text{cm}^{-2}\) along this sight line.

We report the detection of a \(\lambda 6284\) DIB feature in the QSO spectra at the redshift of the galaxy. The strength of this feature per unit reddening is found to be higher than what is seen in the Milky Way. This could be related to differences in the DIB carrier and/or to the ambient radiation field. We also find the FWHM of this feature to be broader than what is typically seen in our Galaxy but close to what is seen in starburst galaxies. Our spectrum is consistent with the presence of the \(\lambda 5780\) DIB with a rest equivalent width predicted from the observed \(\lambda 6284\) DIB feature and the correlation reported by Friedman et al. (2011). Due to poor SNR, no other DIB feature is detected in our spectrum. In order to probe the physical conditions and the nature of the DIB carriers it would be important to obtain high SNR spectrum of the QSO.

Strong 21-cm absorption from the galaxy, spread over 28 km \(s^{-1}\), is detected in our GMRT spectrum. Our follow-up VLBA observations reveal the presence of two strong radio emitting components, separated by 89 pc, that are used to understand the spatial variations of the 21-cm optical depth. First, we notice that the integrated optical depths towards these two components differ by a factor of 2. We show that this difference is mainly dominated by narrow components that are seen only towards one of the VLBA component (i.e. component C). In these narrow components the H I opacity seems to change over \(~10\) pc scales. For one of these narrow components we show the kinetic temperature is \(\leq 66\) K. As we expect dust to be mainly associated with low-temperature gas, if the other narrow components are also cold, then we can speculate that the optical emission from the QSO is associated with the VLBA component C.

In high-z 21-cm absorption line studies of DLAs and Mg II systems, and in the absence of VLBI spectroscopy, one uses the ‘core’ fraction measured from the mas-scale continuum images to correct the optical depths for partial coverage (see for example Kanekar et al. 2009; Gupta et al. 2012; Srianand et al. 2012). In case of DLAs, this allows one to measure the spin temperature of the H I gas. There are three issues that affect this approach. (i) Unambiguous identification of the ‘core’. If the mas morphology of the radio emission is not simple, then multi-frequency VLBI observations are needed to identify the flat-spectrum ‘core’ component. (ii) The fact that the radio sight line towards the ‘core’ may still be tracing a larger gas volume with respect to the optical sight line. (iii) The implicit assumption that a single absorbing cloud covers the ‘core’, i.e. a single covering factor (f\(c\)).

The third issue is mainly related to the patchiness of the absorbing gas on scales of tens of pc, which is typically the resolution provided by VLBI observations, and can only be addressed via VLBI spectroscopy. In the case of J1639+1127 discussed here it is plausible to associate component C with the quasar sight line because it shows clear signatures of the presence of a large amount of cold gas. Under the assumption of a single cloud covering C we would have estimated \(f_\text{c} \sim 0.37\) (57/155). However, if some of the absorption components were to cover only the peak of C, then \(f_\text{c}\) would be off by as much as a factor of 1.5 (56.8/36.8) from the above value. Furthermore, the covering factor estimate could be dramatically off if the core is associated with component B, resulting in \(f_\text{c} \sim 0.01\), or with a component not detected in our VLBA image. This is a possibility considering that the radio continuum morphology of J1639+1127 at high angular resolution (see Fig. 6) resembles that of a compact symmetric object (CSO; Conway 2002). Here, the two dominant radio sources, A and C, would be the two radio lobes of the CSO. Therefore, multifrequency VLBI observations are needed to detect and/or identify the core component to address this issue.

The case of J1639+1127 also demonstrates that associating the entire absorption detected at arcsecond scales through GMRT observations with either A or C component would lead to \(f_\text{c}\) estimates that are at least off by a factor of 2. In general, this means that even when the core component is accurately identified, \(T_\text{S}\) measurements from DLA studies can have large errors especially if the background quasar has significant radio structure at the scales where the absorbing gas has strong optical depth gradients. Therefore, one requires more high-z measurements towards strong core-dominated sources to address the issues related to the measurements of \(T_\text{S}\).

Based on the measured \(E(B - V)\), the equivalent widths of \(\lambda 6284\) DIB and Na D lines and various correlations found in our Galaxy we predict appreciable column densities of molecular species like CH, CH\(^+\) and CN along this line of sight. Detecting these species will allow us to probe the physical and chemical state of this translucent gas in detail. In addition, this is a good target to search for OH lines and molecular lines in radio/mm wavebands.

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