# Multi-wavelength spectroscopic study of cold gas in external galaxies

The physical conditions and volume filling factors of various gas phases in the interstellar medium (ISM) depend on the radiation field, metallicity, dust content, cosmic ray density and supernova rate, i.e. they are directly affected by the radiative, chemical and mechanical feedback associated with the in situ star formation. In addition, the ISM mediates between the stellar- and the galactic-scale processes. Therefore, the ISM phases are expected to contain an imprint of the collective outcome of all the processes that shape the star formation history of the Universe. This thesis is focused on understanding the cold neutral medium (CNM) phase, that serves as the reservoir for star formation in galaxies. We have used quasar absorption line spectroscopy to probe gas in and around galaxies. This is one of the most powerful tools to probe the temperature, density, ionization state and chemical enrichment of the diffuse gas in a wide variety of astrophysical environments. In particular, H I 21-cm absorption towards background radio-loud quasars is an excellent tracer of the CNM phase in intervening galaxies in a dust- and luminosity-unbiased way. The main results from our multi-wavelength studies of cold gas in external galaxies are summarized below.

**(I) Distribution of cold H I gas around $z < 0.4$ galaxies:**

With a view to map the distribution of high neutral hydrogen column density ($N(\mathrm{H\,I}) \geq 10^{19}\,\mathrm{cm}^{-2}$) cold ($T \sim$ few 100 K) gas around galaxies, we have carried out a systematic search of H I 21-cm absorption in a sample of 55 $z < 0.4$ galaxies towards radio sources at impact parameters, $b \sim 0-35$ kpc. The H I 21-cm absorption searches were carried out using ∼250 hrs of Giant Metrewave Radio Telescope (GMRT) and Karl G. Jansky Very Large Array (VLA) observations. The optical properties of the galaxies were obtained using long-slit spectroscopic observations with the South African Large Telescope (SALT), and images and fibre spectra from the Sloan Digital Sky Survey (SDSS). In our statistical sample of 40 quasar-galaxy-pairs or QGPs, probed by 45 sightlines, we have found seven H I 21-cm absorption detections. The measurements from our survey have increased the existing number of sensitive H I 21-cm optical depth measurements at low-$z$ by more than a factor of three and the number of H I 21-cm detections from QGPs by a factor of two.

Combining our H I 21-cm measurements with those present in the literature with similar sensitivity, as well as with optical properties of the galaxies, we have studied the radial and azimuthal profiles of H I 21-cm absorption around low-$z$ galaxies, and quantified the covering factor of H I 21-cm absorbers as a function of various physical parameters (Dutta et al. 2017a, MNRAS, 465, 588). The main results from this study are: (i) *The strength ($\int \tau dv$) and covering factor ($C_{21}$) of H I 21-cm absorbers decreases, albeit slowly, with increasing impact parameter (see Fig. 1).* There is a weak anti-correlation (rank correlation coefficient = −0.20 at 2.42$\sigma$ level) between $\int \tau dv$ and $b$. $C_{21}$ decreases from $0.24^{+0.12}_{-0.08}$ at $b \leq 15$ kpc to $0.06^{+0.09}_{-0.04}$ at $b = 15-35$ kpc. $\int \tau dv$ and $C_{21}$ show similar declining trend with radial distance along the galaxy's major axis and distances scaled with the effective H I radius. (ii) *There is a tentative indication that most of the H I 21-cm absorbers could be co-planar with the extended H I discs.* $\int \tau dv$ and $C_{21}$ are higher when the radio sightline passes near the galaxy's major axis. (iii) $\int \tau dv$ and $C_{21}$ do not depend significantly on the host galaxy properties, i.e. luminosity, stellar mass, colour, and surface star formation rate density. *Hence, the distribution of H I 21-cm absorbers seems to be more sensitive to geometrical parameters rather than physical parameters related to the star formation in galaxies.* (iv) The relative strength of Ca II and Na I absorption in the SDSS spectra of the quasars suggest that the most of the H I 21-cm absorbers are not likely to arise in the dusty star-forming disks. (v) The detection rate of H I 21-cm absorption in our galaxy-selected QGP sample is four times less than that in damped Lyman-$\alpha$ systems (DLAs; $N(\mathrm{H\,I}) \geq 2 \times 10^{20}\,\mathrm{cm}^{-2}$) at $z < 1$. This indicates *small sizes (parsec to sub-parsec scale) and patchy distribution of cold gas clouds around low-$z$ galaxies.* Our results suggest that about ∼30% of the H I gas within ∼30 kpc around galaxies contributes to the DLA population, and ∼60% of the DLAs have cold gas that can produce detectable H I 21-cm absorption.

**(II) Parsec- to kiloparsec-scale structures in the H I gas around low-$z$ galaxies:**
The patchy nature of cold H I gas around low-$z$ galaxies is further supported by our observations of parsec- and kiloparsec-scale structures in the H I gas around two low-$z$ galaxies. The results from our multi-wavelength studies of these two systems are summarized below.

Using Lyman $-\ \alpha$ and molecular $H_2$ absorption detected in the Hubble Space Telescope − Cosmic Origins Spectrograph (HST−COS) spectrum, and metal absorption detected in the Very Large Telescope − Ultraviolet Echelle Spectrograph (VLT−UVES) spectrum towards PKS 0439−433, we have carried out a detailed analysis of cold parsec-scale gas at $b \sim 8$ kpc from a $z = 0.1$ star-forming galaxy (Dutta et al. 2015, MNRAS, 448, 3718). Using Very Long Baseline Array (VLBA) 1.4 GHz continuum emission from the radio source and H I 21-cm absorption we have constrained the size of the molecular gas to be $\lesssim$100 pc. The inferred physical and chemical conditions from our photoionization modelling suggest that the gas may be tracing a recent metal-rich outflow from the host galaxy.

Next, our GMRT H I 21-cm absorption and emission observations and Keck High Resolution Echelle Spectrometer (HIRES) spectrum have revealed kpc- to sub-kpc-scale structures in the H I gas associated with the $z = 0.02$ spiral galaxy, UGC 00439 (Dutta et al. 2016, MNRAS, 456, 4209). Using H I 21-cm absorption towards different components of the extended background radio source, and Ca II and Na I absorption towards the optical quasar, we find a factor of $\sim$7 variation in the H I 21-cm optical depth over a $\sim$7 kpc region at $b \sim 25$ kpc from UGC 00439 (see Fig. 2). The absorption is most likely tracing clumpy cold gas corotating with the galaxy. The absorption could also be tracing gas that is stripped out of the H I disc of the galaxy due to tidal interactions with two neighbouring galaxies at $\sim$150 kpc.

**(III) Search for cold H I gas in strong Mg II systems at $0.3 < z < 1.5$:**
Due to the lack of a large sample of spectroscopic galaxies at high redshifts, it is difficult to extend our H I 21-cm absorption survey of QGPs to redshifts beyond $\sim$0.4. Strong Mg II absorbers (rest equivalent width of Mg II $\lambda$2796, $W_{\rm Mg\,II} > 1$ Å) are believed to trace gas with high $N$(H I) like DLAs (Rao et al. 2006, ApJ, 636, 610). However, strong Mg II absorbers can arise from a wide variety of environments such as stellar discs, outflowing gas, accreting gas and intra-group gas. Using systems at $z < 1.65$ and at $z \sim 2$, where simultaneous measurements of $N$(H I) and $W_{\rm Mg\,II}$ are possible (Rao et al. 2006; Noterdaeme et al. 2012, A&A, 547, L1; Zhu & Menard 2013, ApJ, 770, 130), we have found that the probability of selecting DLAs can be increased by a factor of $\sim$2, by selecting strong Mg II absorbers with $W$(Fe II $\lambda$2600) ($W_{\rm Fe\,II}$) $> 1$ Å (referred as strong Fe II systems). Hence, we have carried out a survey of H I 21-cm absorption in 16 strong Fe II systems at $0.5 < z < 1.5$ selected from SDSS, using 110 hrs of GMRT and Green Bank Telescope (GBT). Our survey has resulted in six new H I 21-cm absorption detections, increasing the known number of detections in strong Mg II systems at this redshift range by $\sim$50%. All these absorbers would be DLAs considering a spin temperature of 500 K, demonstrating that a *selection technique based on Fe II absorption strength can increase the probability of detecting high $N$(H I) cold gas by a factor of $\sim 4$.*

The main results from this survey (Dutta et al. 2017b, MNRAS, 465, 4249) are: (i) The H I 21-cm detection rate increases with $W_{\rm Fe\,II}$, being four times higher in systems with $W_{\rm Fe\,II} \geq 1$ Å compared to in systems with $W_{\rm Fe\,II} < 1$ Å. (ii) The incidence of H I 21-cm absorption in strong Fe II systems remains constant over $0.5 < z < 1.5$ within the uncertainties. However, the incidence of H I 21-cm absorption in DLAs is found to increase from $z \sim 3$ to $z < 1.5$, which may indicate towards an increasing filling factor of cold gas in DLAs with time. (iii) *The systems which give rise to H I 21-cm absorption tend to cause more reddening due to dust in the spectrum of the background quasar, as well as produce stronger metal absorption on an average (see Fig. 3).* (iv) The velocity widths of intervening H I 21-cm absorption lines show an increasing trend (significant at 3.8$\sigma$) with redshift at $z < 3.5$, which may be due to the H I 21-cm absorbers probing more massive galaxy halos at high-$z$.

Next, thanks to the SDSS-Baryon Oscillation Spectroscopic Survey (BOSS), a large number of quasar spectra are available which can be searched for Mg II absorption at $z < 0.5$, where identification of host galaxies is relatively easier. We have carried out a survey of H I 21-cm absorption in eleven strong Mg II systems at $0.3 < z < 0.5$ selected from SDSS DR-12, using 108 hrs of GMRT (Dutta et al. 2017c, MNRAS, 468, 1029). This survey has resulted in two H I 21-cm absorption detections. The lack of H I 21-cm absorption in the other nine Mg II systems could be because they are arising from sub-DLAs, from which we do not have sufficient optical depth sensitivity to detect cold $\sim$100 K gas. By comparing with H I 21-cm searches in strong Mg II systems at $0.5 < z < 1.5$ from the literature, we do not find any significant evolution in the incidence and number density per unit redshift of H I 21-cm absorbers in strong Mg II systems at $0.3 < z < 1.5$.

*The results from our low- and high-z H I 21-cm absorption surveys along with the detailed studies of individual absorption line systems will be crucial to interpret the data from upcoming blind H I 21-cm absorption line surveys using the Square Kilometer Array pathfinders.* To gain further insight into the metal, dust, molecular content and host galaxy properties of cold gas, our surveys will be followed up with optical, ultraviolet and sub-millimetre spectroscopy and imaging.

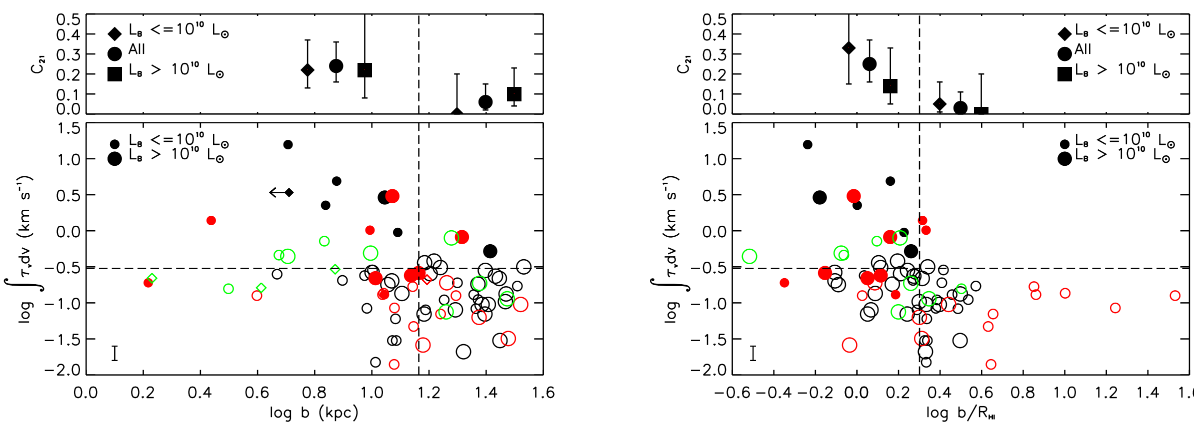


Figure 1: *Left:* Integrated H I 21-cm optical depth around $z < 0.4$ galaxies as a function of impact parameter ($b$). The black, green and red circles are for QGPs in the statistical, non-statistical and literature sample, respectively. The solid and open circles represent measurements and $3\sigma$ upper limits, respectively. The small (large) circles are for galaxies with $L_B$ less (greater) than $10^{10}\ L_\odot$. Galaxies without luminosity measurements available are plotted as diamonds. The typical error in the optical depth measurements is shown at the bottom left of the plot. To the top of the plot, the covering factor ($C_{21}$) of H I 21-cm absorbers is shown as a function of $b$ in two different bins demarcated at the median $b$. The circles, diamonds and squares in the top panels show $C_{21}$ for all the galaxies, galaxies with $L_B$ less and greater than $10^{10}\ L_\odot$, respectively. *Right:* The same as in the figure to the left for $b$ scaled with effective H I radius, $R_{\rm H\,I}$. In both panels, the horizontal dotted lines mark $\int \tau dv = 0.3$ km s$^{-1}$ and the vertical dotted lines mark the median $b$ and $b/R_{\rm H\,I}$. **Both the absorption strength and covering factor are found to decline with increasing $b$ and $b/R_{\rm H\,I}$.**

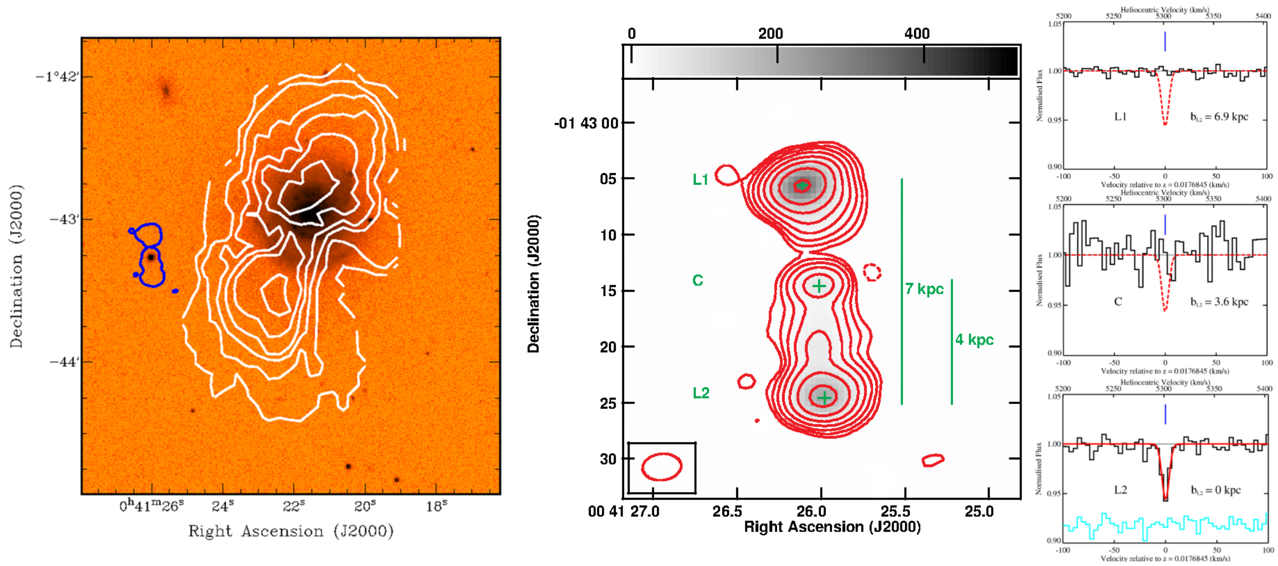


Figure 2: *Left:* SDSS r-band image of the QGP, J0041−0143/UGC 00439. The GMRT H I 21-cm moment-0 map (of spatial resolution $46.4'' \times 33.4''$) is shown in white contours, with the levels corresponding to $N(\text{H I})$ = (0.4, 0.8, 1.2, 1.6, 2.0, 2.4) $\times 10^{20}$ cm$^{-2}$. The outermost contour of the GMRT 1.4 GHz radio continuum of J0041−0143 is shown in blue. *Centre:* GMRT image of J0041−0143 at 1.4 GHz. The contour levels are plotted as 2.5 × (−1,1,2,4,8,...) mJy beam$^{-1}$. Note that solid lines correspond to positive values while dashed lines correspond to negative values. At the bottom left corner of the image the restoring beam is shown as an ellipse. *Right* GMRT H I 21-cm absorption spectra towards the continuum components L1, C and L2, as marked in the centre panel. The best-fitting single Gaussian profile to the H I 21-cm absorption towards L2 is overplotted in solid red line, and the residuals from the fit are plotted below in cyan. This fit is also overplotted in the other two panels in dashed red line for comparison. The vertical tick marks the position of the peak optical depth detected towards L2. **The optical depth declines by a factor > 7 over 7 kpc.**

Fe ii

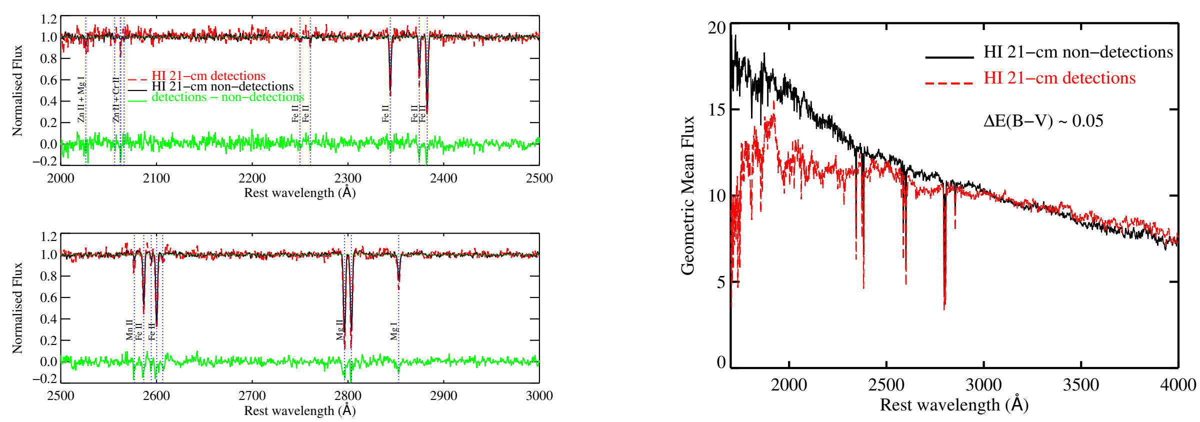


Figure 3: *Left:* The median stacked spectrum of SDSS quasars with strong Fe II systems at $0.5 < z < 1.5$ (in rest frame) which are (not) detected in H I 21-cm absorption is shown as the (black solid) red dashed line. The difference of the stacked spectrum of H I 21-cm non-detections from that of the detections is shown as the green line. The various rest wavelengths of different metal transitions are marked by vertical dotted lines. **The systems which show H I 21-cm absorption, also show systematically stronger absorption (i.e. larger equivalent widths of the metal lines by $\sim 3 - 4\sigma$) than those which do not.** *Right:* The geometric mean stacked spectrum of SDSS quasars with strong Fe II systems at $0.5 < z < 1.5$ (in rest frame) which are (not) detected in H I 21-cm absorption is shown as the (black solid) red dashed line. **H I 21-cm absorption on average causes more reddening in the quasar spectra. The differential reddening, $\Delta E(B - V)$, is 0.05.**