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The strange case of a sub-DLA with very little HI

N. Kanekar[1] and J. N. Chengalur[2]

[1] Kapteyn Astronomical Institute, University of Groningen, Post Bag 800, 9700 AV Groningen, The Netherlands
e-mail: `nissim@astro.rug.nl`
[2] National Centre for Radio Astrophysics, Post Bag 3, Ganeshkhind Pune – 411 007, India
e-mail: `chengalu@ncra.tifr.res.in`

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Abstract. We report a deep search for HI 21cm emission from the $z = 0.00632$ sub-DLA toward PG1216+069 with the Giant Metrewave Radio Telescope. No emission was detected and our 5σ upper limit on the mass of any associated galaxy is $M_{\rm HI} \lesssim 10^7\ M_\odot$, nearly 3 orders of magnitude less than $M^\star_{\rm HI}$. The $z \sim 0.006$ absorber is thus the most extreme known deviation from the standard paradigm in which high column density quasar absorption lines arise in the disks of gas-rich galaxies.

Key words. galaxies: evolution – galaxies: formation – galaxies: ISM – cosmology: observations – radio lines: galaxies

1. Introduction

Neutral atomic gas clouds at high redshift can currently be detected only via the absorption lines they produce if they happen to lie along the line of sight to an even more distant quasar. Although present technology allows one to detect Lyman-α absorption lines from clouds with as low an HI column density as $N_{\rm HI} \sim 10^{13}$ cm^{-2}, the bulk of the neutral gas at $z \sim 3$ turns out to be in extremely rare systems, with column densities higher by several orders of magnitude, viz. $N_{\rm HI} \gtrsim 10^{20}$ cm^{-2}. At such large $N_{\rm HI}$, the optical depth is substantial even in the Lorentzian wings of the Lyman-α profile; these systems are called damped Lyman-α absorbers or DLAs.

In the local universe, the disks of spiral galaxies have characteristic HI column densities $\gtrsim 10^{20}$ cm^{-2} over a large spatial scale. High z DLAs are thus natural candidates for the precursors of today's large galaxies (e.g. Wolfe 1988). The nature of high redshift DLAs and their evolution with redshift have hence been of much interest to astronomers studying galaxy formation and evolution. Unfortunately, cosmological dimming makes it impossible to directly image high redshift DLAs; the information obtainable is hence limited to the gas that lies along the narrow pencil beam that is illuminated by the background quasar. It is primarily for this reason that, despite decades of study, the nature of high redshift damped absorbers remains an unsettled issue, with models ranging from large, rotating disks (e.g. Prochaska & Wolfe 1997) to small, merging proto-galaxies (e.g. Haehnelt et al. 1998). Detailed absorption studies with 10-m class optical telescopes have established that current samples of high redshift DLAs typically have low metal abundances ($\lesssim$0.1 solar; Pettini et al. 1997) and that these abundances evolve slowly, if at all, with redshift (e.g. Prochaska et al. 2003; Kulkarni et al. 2004). This is somewhat surprising if the absorbers are indeed typically the precursors of large galaxies like the Milky Way.

Low redshift ($z \lesssim 0.5$) DLAs offer the possibility of direct identification of the absorbing galaxy by optical imaging, (e.g. le Brun et al. 1997; Rao et al. 2003; Chen & Lanzetta 2003). Since the HI mass function is dominated by bright galaxies (e.g. Zwaan et al. 1997), one might a priori expect that low z DLAs should primarily be associated with large spirals. Interestingly enough, however, it has been found that a wide variety of galaxy types are responsible for damped absorption at low redshifts (e.g. Rao et al. 2003; Bowen et al. 2001), with no particular type dominating the current (admittedly rather small) low z sample. One possible explanation is that, although the total HI mass is dominated by large spiral galaxies, the HI cross-section at the $\sim 10^{20}$ cm^{-2} threshold varies across galaxy type in such a way as to yield an even distribution of absorbers across a range of galaxy luminosities (Zwaan et al. 2002). On the other hand, it is also possible that, although the optical counterparts to these low redshift DLAs are faint, they have unusually large HI envelopes and thus, a large *total* mass. Such a preferential selection might well occur since absorption surveys are biased toward objects with a large HI cross-section. Unfortunately, it is very difficult to observationally test the latter scenario as this requires detection of the HI 21-cm line and current radio instrumentation limits searches for 21-cm emission from galaxy-sized objects to the very nearby universe, $z \lesssim 0.1$. Almost no DLAs are known at these low redshifts and hence, searches for 21-cm emission have been carried out in only three absorbers; in all cases, the HI mass has been found to be lower than $M^\star_{\rm HI}$, the typical mass of local bright spirals (Lane 2000; Kanekar et al. 2001; Bowen et al. 2001; Chengalur & Kanekar 2002). Identifying such $z \lesssim 0.1$ DLAs is of much importance as it is only these systems that can be followed up in detail in all wavebands, to estimate the total mass (as opposed to the luminous mass). We note, in passing, that such DLAs *cannot* be identified (except by accident) using the MgII selection criterion of Rao & Turnshek (2000), as the MgII lines are redshifted into optical wavebands only for redshifts $z > 0.1$.

Recently, Tripp et al. (2004) reported the discovery of an extremely low redshift ($z = 0.00632$) absorption system toward the quasar PG 1216+069, with a high HI column density, $N_{\rm HI} \sim 2 \times 10^{19}$ cm^{-2}. While the absorption profile shows clear damping wings, its column density is somewhat smaller than the cut-off of 2×10^{20} cm^{-2} that has traditionally been used to define DLAs (e.g. Wolfe et al. 1986). This system is hence classified as a sub-DLA. However, it should be emphasized that the column density threshold used to define DLAs is entirely arbitrary and that the absorber properties do not show any sharp qualitative differences here.

Interestingly enough, although the new absorber is at a very low redshift, it has an extremely low metallicity, $\sim 1/40$ Solar (Tripp et al. 2004), one of the lowest measured in the gas phase in the nearby universe and, in fact, similar to that of high z DLAs (e.g. Prochaska et al. 2003). No optical counterpart can be seen in the Hubble Space Telescope (HST) image of the field (Tripp et al. 2004); the nearest L_* galaxy has a projected separation of ~ 252 h_{71}^{-1} kpc[1]. We report here the results of a search for HI 21-cm emission from the $z \sim 0.006$ sub-DLA, using the Giant Metrewave Radio Telescope (GMRT; Swarup et al. 1991).

2. Observations, data reduction and results

The GMRT observations were conducted on the 28th and 30th of August 2004. The total on-source time was ~8 h, with 29 antennas. The observing bandwidth of 2 MHz, centred at 1411.5 MHz, was divided into 128 spectral channels, yielding a spectral resolution of ~15.6 kHz. The total velocity coverage was thus ~425 km s^{-1}, with a resolution of ~3.3 km s^{-1}. Flux and bandpass calibration were done using short scans on 3C 147 and 3C 286 at the start and end of each observing run, while the compact source 1150−003 was used for phase calibration. The flux density of 1150−003 was measured to be 2.7 ± 0.1 Jy.

Data reduction was carried out using standard tasks in "classic" AIPS. Visibilities from the different days were calibrated separately and then combined together using the AIPS task DBCON; the combined data were used to make the final images, with the task IMAGR. We note that the GMRT has a hybrid configuration, with fourteen antennas in a central array (the "central square") and the remaining sixteen distributed in the three arms of a "Y" (Swarup et al. 1991). The central square antennas yield baselines of $\lesssim$1 km (i.e. $U - V$ coverage out to $\sim 5k\lambda$ at 1411.5 MHz), while longer baselines (up to a maximum length of ~25 km, or a $U - V$ coverage to $\sim 120k\lambda$ at 1411.5 MHz) are obtained with the arm antennas. Continuum images and spectral cubes were hence made with a variety of $U - V$ ranges and tapers, allowing a search for HI and continuum emission at various spatial resolutions ranging from $\sim 3''$ to $\sim 40''$. The continuum emission was subtracted using two independent approaches: (1) in the $U - V$ plane, using the task UVSUB and (2) in the image plane, using the task IMLIN. The two strategies gave very similar results; the numbers quoted below are for the $U - V$ plane approach.

Table 1. rms noise levels and 5σ HI mass limits.

$\theta_{\rm HPBW}$ bmaj $''\times$ bmin$''$	rms mJy/Bm	$r_{\rm HPBW}$ h_{71}^{-1} kpc	$M_{\rm HI}$ 10^6 $M_\odot$
39.4×37.7	0.62	5.0	11
26.1×23.1	0.52	3.3	8.8
12.3×9.9	0.45	1.6	7.7
2.9×2.5	0.30	0.4	5.0

Finally, the GMRT does not do on-line Doppler tracking, implying that any required Doppler shifts must be applied to the data off-line. In the present case, however, it was not necessary to apply a differential Doppler shift to the data of the two observing runs since this shift was found to be small, relative to the channel separation. No off-line Doppler corrections were hence applied while making the image cubes.

The central ninety channels of the band were averaged together to map the continuum, at various spatial resolutions. The low resolution ($\sim 39.4'' \times 37.7''$) image shows good agreement with the NRAO VLA Sky Survey map of the same region (Condon et al. 1998). Our somewhat higher sensitivity allows us to detect faint emission from the quasar itself; we measure a flux density of ~2.8 ± 0.3 mJy. The peak flux density in the image is ~14.6 ± 0.3 mJy.

The data cubes were examined for line emission at a variety of spectral resolutions; in all cases, no significant line emission was found in the vicinity of the quasar line-of-sight. Besides a visual inspection, the AIPS task SERCH was used to search for line emission in the different cubes. No statistically significant emission features were detected in the cube, except from the galaxy VCC 297; this system is discussed later. The highest resolution ($2.9'' \times 2.5''$) cube did show a weak (3.3σ) emission feature at the quasar location (albeit ~70 km s^{-1} away from the optical redshift); if real, it corresponds to an HI mass of 4×10^6 $M_\odot$. However, this is not very believable as the feature is spatially unresolved and seen only in a single velocity channel, after smoothing the data to a resolution of 13 km s^{-1}. Further, if real, this concentration of gas would imply an HI column density $\gtrsim 10^{21}$ cm^{-2}, (i.e. considerably larger than the column density of the sub-DLA) and it would be surprising that no associated metal lines were found at this velocity.

Table 1 summarizes our results, for a representative selection of spatial resolutions; the data have been smoothed to a velocity resolution of 20 km s^{-1} in all cases, a fairly typical velocity width for a small galaxy. The different columns in the table are: (1) the half-power beam width (HPBW) of the synthesized beam (i.e. the spatial resolution, in arcsec), (2) the

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[1] We assume $\Omega_{\rm m} = 0.27$, $\Omega_\Lambda = 0.73$ and $H_0 = 71$ km s^{-1} Mpc^{-1} throughout this paper.

rms noise (in mJy/Bm) at this spatial resolution, (3) the physical distance at $z = 0.00632$ (in kpc), corresponding to the synthesized HPBW, and (4) the 5σ upper limit on the HI mass of the $z \sim 0.006$ sub-DLA at this spatial resolution (in units of 10^6 $M_\odot$), assuming that the HI profile has a top-hat shape, with a velocity width of 20 km s^{-1}. Note that lower spatial resolutions are obtained by weighting down data from the more distant antennas; this implies that the mass limit *improves* at higher spatial resolution.

3. Discussion

The 5σ upper limits on the HI mass of the galaxy listed in the last column of Table 1 are extremely small, nearly 3 orders of magnitude lower than $M^\star_{\rm HI}$. This is quite remarkable, given the high HI column density estimated from the Lyman-α line. Of course, it should be pointed out that the mass limits quoted in the table are based on the assumption that the absorber is entirely contained within the synthesized beam. It is, in principle, possible that the HI emission is actually spread over a larger angular scale and is not detected in our interferometric observations either because the flux per synthesized beam falls below our detection threshold or because the flux is resolved out or due to a combination of both effects. We initially consider this possibility, before discussing the implications of our results for the nature of the $z = 0.00632$ sub-DLA.

If the absorbing galaxy were far larger than the GMRT synthesized beam, the mass limits of Table 1 would refer only to the HI mass within the beam and not to that of the entire galaxy. For example, if the galaxy were a face-on disk of diameter 10 kpc, twice our coarsest resolution, the upper limit to its *total* HI mass would be a factor of ~4 larger than that listed in the first line of Table 1, i.e. $M_{\rm HI} \lesssim 4 \times 10^7$ $M_\odot$. However, dwarf irregular galaxies with low HI masses ($\lesssim 10^8$ $M_\odot$) have fairly small HI diameters (e.g. Stil & Israel 2002a,b; Begum et al. 2003). For example, all ten dwarf irregulars with $M_{\rm HI} \lesssim 10^8$ $M_\odot$ in the sample of Stil & Israel (2002a,b) have size $\lesssim$5 kpc, our coarsest resolution. In fact, of the 27 dwarfs in the Stil & Israel sample with estimates of HI extent, the only galaxies that have physical sizes larger than 11 kpc are the five systems with $M_{\rm HI} \gtrsim 6.5 \times 10^8$ $M_\odot$ (i.e. considerably larger than the upper limit in Table 1). Further, if we assume that $N_{\rm HI} \sim 2 \times 10^{19}$ cm^{-2} throughout the absorber, the total HI mass in an area 5 kpc in diameter is $\sim 3 \times 10^6$ $M_\odot$, comparable to our detection threshold. The latter is a severe under-estimate of the true HI mass, if the absorption arises in a normal galaxy, since large fractions of even dwarf galaxy disks have $N_{\rm HI} \gtrsim 10^{20}$ cm^{-2}. It is thus highly unlikely that the absorption arises in a dwarf galaxy whose HI disk is so extended that the flux per synthesized beam falls below our detection threshold. Similarly, the second scenario, that the flux is resolved out because it arises from a highly uniform HI distribution, is also rather improbable as this would require a very small velocity gradient over the entire spatial extent of the gas, for emission to not be detected even at the highest velocity resolutions.

The nearest known HI-rich galaxy to the sub-DLA is VCC 297, which has $L = 0.25$ $L_\star$ (Impey et al. 1999), $M_{\rm HI} = 2.7 \times 10^8$ $M_\odot$ and a velocity width W_{50} of 145 km s^{-1} (Giovanelli et al. 1997); this is ~87 h_{71}^{-1} kpc away from the QSO sightline. VCC 297 lies at the edge of our field of view, where imaging is particularly difficult because of the asymmetry of the edges of the GMRT primary beam. The emission velocity of VCC 297 also lies at the edge of the observing band where the sensitivity is lower; further, there appears to be some low level interference at these edge channels (note that none of these problems are present at the centre of our field of view and observing band, where the emission from the sub-DLA would arise). Next, the optical extent of VCC 297 is a factor of ~3 larger than our synthesized beam; its HI extent is likely to be at least this large, reducing the flux per synthesized beam. Despite these problems, HI emission from VCC 297 is reliably detected in the spectral cubes (see Fig. 1). The emission was readily apparent to the eye and was also detected by the automatic search algorithm SERCH, at a signal-to-noise ratio of ~12. Finally, as a concrete counter-example, a dwarf galaxy at $z = 0.0051$ with $M_{\rm HI} \sim 2 \times 10^7$ $M_\odot$ was serendipitously discovered in a different GMRT observation, with essentially identical observational setup and rms noise (Chengalur et al. 2004). From all of the above, we conclude that it is highly unlikely that the sub-DLA arises in a galaxy with HI mass substantially larger than the limits quoted in Table 1. Further, if one assumes a uniform HI column density of 2×10^{19} cm^{-2} throughout the absorber (and a disk geometry), our HI mass limit of $\sim 10^7$ $M_\odot$ implies an upper limit of ~9 kpc to the size of any associated galaxy. It is still not impossible, of course, that the sub-DLA arises in a more massive, highly extended, smooth HI cloud, but this would require it to be completely unlike any known low redshift galaxy.

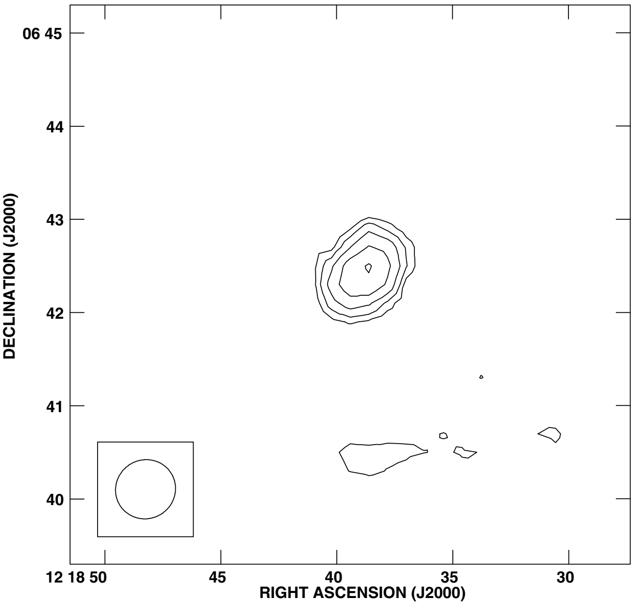

Fig. 1. Integrated HI 21-cm emission profile toward VCC 297, made from the 39″ × 34″ resolution image cube. The contours are at 0.08, 0.12, 0.17, 0.25 and 0.36 Jy/Bm km s^{-1}.

As discussed in detail by Tripp et al. (2004), the $z \sim 0.006$ sub-DLA is highly unusual in having a very low metallicity ($[{\rm O/H}] = -1.6^{+0.09}_{-0.11}$) despite being at low redshift and lying in a region of high local galaxy density (the outskirts of the Virgo cluster). The sub-DLA also shows an under-abundance of nitrogen and an over-abundance of iron (implying a lack of dust) which also argues in favour of a system that is at an early stage of chemical evolution (Tripp et al. 2004). These abundance patterns are very different from those characteristic of local $L_\star$ spirals, and are consistent with the absence of a luminous optical counterpart to the sub-DLA in the HST image. Of course, the lack of a detected optical counterpart does not entirely exclude a scenario in which the sub-DLA arises in a massive galaxy, since such a system might well be hidden beneath the point spread function of either the QSO itself or a nearby foreground star located near the quasar (Tripp et al. 2004); alternatively, as discussed in the introduction, the absorber might be anomalously gas-rich for its luminosity. However, the stringent upper limit on the HI mass of the absorber provided by our observations indeed rules out this possibility.

The abundance patterns and low metallicity of the $z \sim 0.006$ absorber are consistent with an origin in (i) a low metallicity, gas-rich, blue compact dwarf (BCD) like I Zw 18 or SBS0335−052; (ii) a high velocity cloud (HVC), (iii) a dwarf spheroidal galaxy; or (iv) a dark mini-halo left over from the epoch of reionization (see Tripp et al. 2004 and references therein). However, the mass limits in Table 1 are significantly lower than HI masses typical of low metallicity BCDs ($\gtrsim 10^8$ $M_\odot$; van Zee et al. 1998, Pustilnik et al. 2001). It is also unlikely that the sub-DLA is associated with an HVC, given that the nearest $L_\star$ galaxy (NGC 4260) is ~ 252 h_{71}^{-1} kpc away (in projection) and HVCs have not been detected at such large distances from their parent galaxies, despite deep searches (e.g. Pisano et al. 2004). In fact, for M 31 (the only galaxy that has been sensitively searched for large-scale diffuse HI emission), the typical HI column density falls to values smaller than 10^{15} cm^{-2} by the time one reaches galacto-centric distances of 200 kpc (Braun & Thilker 2004). Similarly, Miller & Bregman (2004) place a limit of ∼25 kpc on the distance of HVCs from their parent galaxy; this implies that the absorption is also unlikely to arise from an HVC associated with the fainter galaxy VCC 297, which is ~ 87 h_{71}^{-1} kpc away. The most likely counterpart is hence an extreme dwarf galaxy (or a dark mini-halo), which is surprising, given the relatively small size of these systems. How likely is it that such a system would show up in an unbiased search for absorption? While there are no existing measurements of the typical size of faint dwarf galaxies at HI column densities of 2×10^{19} cm^{-2}, a linear extrapolation of the results of Zwaan et al. (2002), for systems with higher mass and column density, (and further assuming the faint end slope of the HI mass function to be −1.2) indicates that the HI cross-section offered by $\sim 10^7$ $M_\odot$ galaxies is significantly more than an order of magnitude smaller than that of $M^\star_{\rm HI}$ galaxies. The implied low probability of a sub-DLA arising in the former class of systems may suggest that our understanding of the HI mass function is incomplete at the low mass end.

In summary, contrary to the a priori expectation that systems found via absorption line searches should be biased toward galaxies with large HI mass, our upper limit to the total HI content of the $z \sim 0.006$ sub-DLA is ∼three orders of magnitude lower than $M^\star_{\rm HI}$. This is by far the smallest HI mass limit placed on gas associated with DLAs or sub-DLAs. The $z = 0.00632$ sub-DLA toward PG1216+069 thus appears to be the most extreme known deviation from the standard paradigm for high column density absorbers.

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