PRAMANA — journal of physics
© Indian Academy of Sciences
Vol. 53, No. 6
December 1999
pp. 1013–1019

The nature of low redshift damped Ly-α systems

NISSIM KANEKAR and JAYARAM N CHENGALUR
National Centre for Radio Astrophysics, Tata Institute of Fundamental Research, University of Pune Campus, P.O. Bag 3, Ganeshkhind, Pune 411 007, India
Email: nissim@ncra.tifr.res.in; chengalur@ncra.tifr.res.in

Abstract. Damped Ly-α systems are the major repository of the observed neutral HI at high redshift. These systems are most efficiently detected via absorption spectra taken against distant QSOs. In this paper, we review some of the observational constraints on the nature of these objects, and also discuss the implications of recent observations of two low redshift damped absorbers, made with the Giant Metrewave Radio Telescope. We find that, for the lowest redshift ($z = 0.0912$) damped Ly-α system, if the system is a rotating gas disk, then the total associated HI mass has to be less than 2×10^9 M$_\odot$, if the disk is at low inclination angles, and less than 10^{10} M$_\odot$ if the system is edge on. All limits are 3σ.

Keywords. Quasars; absorption lines; galaxies; evolution; ISM; general; cosmology; observations.

PACS No. 2.0

1. Introduction

Neutral gas, being the building material out of which the luminous material of galaxies is formed, is an important tracer of the history of galaxy formation in the Universe. The most efficient way to detect neutral gas at high redshift is via spectra taken against bright quasars at a higher redshift. At the highest HI column densities, $N_{HI} > 2 \times 10^{20}$ atoms cm^{-2}, the width of the Ly-α absorption profile becomes dominated by the broad damped wings, making these systems particularly easy to identify. As a consequence of a number of large systematic surveys (eg. [1] and references therein) it is now well established that the total neutral hydrogen mass in damped Ly-α absorbers at $z \sim 3$ is at least comparable to the mass in luminous galaxies at $z \sim 0$. This is consistent with the idea that damped Ly-α systems are galactic precursors, and that, in the interval between $z = 3$ and $z = 0$, the gas in damped Ly-α systems became depleted via conversion into stars. The HI gas density in damped Ly-α systems is indeed observed to fall rapidly with decreasing redshift, consistent with this idea.

The fundamental quantity that is constrained by surveys for damped Ly-α absorbers is the probability (per unit redshift) of finding a damped system. This is proportional to $n\sigma$, where n is the volume number density of such systems and σ is their average cross section. Neither n nor σ is separately constrained by the detection rates in blind surveys. If one assumes that damped Ly-α systems are the progenitors of $z = 0$ L_* galaxies, and that each absorber gives rise to exactly one L_* galaxy (i.e. that number is conserved) then one can estimate the average cross-section, σ. These estimates yield a σ that is a factor of 3 times larger than that of low redshift spiral galaxies. It has therefore been suggested [2] that damped systems are giant gaseous disks, whose extent gets truncated as the system evolves and gas is progressively converted into stars. Another possible scenario is that number is not conserved, and one has a very large number of small absorbers at high redshift, with these systems merging over a period of time to produce the galaxies that are seen today. This would be broadly in keeping with the current theoretical models of hierarchical galaxy formation.

The most direct way of differentiating between the above two scenarios is to determine the typical transverse size of damped systems. This is not possible via absorption spectra, because the background UV continuum source has negligible transverse extent. Since some fraction of quasars also have associated radio continuum emission, one can, for these quasars, attempt to observe absorption in the 21cm spectral line of HI. If the background radio continuum source is extended, spatially resolved imaging of the 21cm absorption can be used to measure the transverse size of the absorber. This technique has been tried only for one absorber so far, the object at $z = 2.04$ towards the quasar PKS 0458-02. The single dish spectrum of this absorber was found to be identical to that obtained on a two element VLBI interferometer [3], implying that the absorbing system has no internal structure on scales ~ 8 kpc.

Another possible approach to constraining the transverse size of damped Ly-α systems is to determine the extent of the optical emission (if any) associated with the absorber. This would, of course, at best place a lower limit on the absorber size, since the optical emission could be spatially much less extended than the gas. A handful of systems have been detected at high redshifts, and their sizes and impact parameters are all ~ 10 kpc [4]. Many of these systems are however atypical in that they have an absorption redshift $z_{\rm abs}$ greater than the emission redshift $z_{\rm em}$ of the quasar, indicating that they are physcially associated with the quasar.

Since the width of the Ly-α profile in damped Ly-α systems is determined solely by the column density, it contains no information on the kinematics of the absorber. On the other hand, the absorption due to low ionization metals, such as SiII 1808 is typically not saturated; these profiles hence do contain information on the kinematics of the absorbing gas. Further, since such ions are associated with neutral hydrogen, these profiles also trace the kinematics of the neutral gas. Of course, one only has information along the narrow line of sight towards the unresolved background UV continuum from the QSO. High resolution spectroscopic observations of a large sample of damped systems [5] have shown that their metal profiles are typically asymmetric; i.e. the largest optical depth occurs preferentially at the edge of the profile. Prochaska and Wolfe [5] used Monte Carlo simulations of such profiles and found that their observations are best fit by models in which damped Ly-α systems are thick, rapidly rotating ($V_{\rm rot} \sim 225$ km/s) disks; this appears reasonable since edge asymmetries arise naturally in such rotating gaseous disks. These models, if confirmed, would be difficult to reconcile with theoretical models of hierarchical galaxy formation, where dark halos with masses corresponding to a rotation velocity of ~ 225 km/s are extremely rare at high redshift [6,7]. It turns out, however, that asymmetric metal line absorption profiles are also obtained in hierarchical merging scenarios. Hydrodynamic simulations of galaxy formation through the merger of smaller sub-units show that lines of sight passing through such merging clumps also lead to characteristically asymmetric absorption profiles [8]. Further, McDonald and Miralda–Escude [9] show that such profiles can also arise from gas moving randomly in a spherical halo.

The recent identification of a number of low redshift damped Ly-α systems, has led to a number of detailed studies of these absorbers. At these low redshifts, follow-up ground- or HST-based imaging allows the luminosity of the associated galaxy to be measured, and often, even its morphological type to be determined. A study of 7 intermediate redshift damped absorbers by Le Brun *et al* [10] shows that these systems are associated with galaxies of a variety of morphological types and luminosities, and not with L_* spirals, as would be expected in the thick rotating disk models. Similarly, one of the lowest redshift systems, the $z = 0.16$ absorber towards QSO 0850+440 [11] is associated with an S0 galaxy. Further, the velocity of the absorber is the opposite of that expected from the sense of rotation of the disk of the associated galaxy. In fact, for QSO-galaxy pairs at the very lowest redshifts, a large fraction of the 21 cm absorption appears to arise from extended tidal features.

At low redshifts, $z \tilde{<} 0.22$, existing radio telescopes have sufficient sensitivity to be able to observe HI emission from L_* spirals. The required integration time is large, $\sim 30 - 50$ hours, but not impractically so; one can hence attempt to observe the neutral gas at these redshifts in emission. This has an advantage over optical emission in that the observations are sensitive to the total gas extent of the absorber (and not just to the region where star formation has taken place, which is typically much smaller in size than the gaseous disk), and also because the emission spectrum will directly give the rotational velocity of the galaxy.

For damped Ly-α systems that lie in front of radio loud quasars it is possible to augment the optical/UV spectra with HI 21 cm absorption spectra. Such a comparison, yields, among other things (and under suitable assumptions), the spin temperature, T_s, of the HI gas. Derived spin temperatures of damped Ly-α systems have, in general, been much larger than those observed in the disk of the Galaxy or in nearby galaxies [12,13], implying that either damped Ly-α systems are not disks, or that the ISM in the damped Ly-α proto-disks is considerably different from that in the local $z = 0$ disks, presumably due to evolutionary effects.

We report, in this paper, spin temperature measurements for two low redshift damped Ly-α systems and also limits on the HI gas associated with the lowest redshift damped Ly-α towards OI 363, based on observations made with the Giant Metrewave Radio Telescope.

2. Observations and data reduction

The line of sight towards the quasar OI 363 intersects two damped Ly-α systems, one at $z = 0.0912$, and the other at $z = 0.2212$. Both these systems were observed using the GMRT [14,15]. The backend used was the proto-type eight station FX correlator, which gives a fixed number (128) of spectral channels over a total bandwidth that can be varied from 64 kHz to 16 MHz. Due to various ongoing maintenance and installation activities, the actual number of antennas that were available during our observing runs varied between six and eight.

For the observations of the $z = 0.0912$ system, the bandwidth was set to 1.0 MHz. No spectral taper was applied, giving a channel spacing of ~ 1.8 km s^{-1}. Two observing runs were made, one on 27 June 1998 and the other on 5 July 1998. The on source time for each run was about six hours. Two observing runs were also taken for the $z = 0.2212$

system (on 26 June 1998 and 4 July 1998), the first with a total bandwidth of 1.0 MHz (i.e. a channel spacing of ~ 2.0 km s^{-1}) and the other with a total bandwidth of 0.5 MHz (i.e. a channel spacing of ~ 1.0 km s^{-1}). Each of these observing runs had an on source time of $\sim$ 4 hours. Bandpass calibration at both redshifts was done using 3C 295, which was observed at least once during each observing run.

The data was converted from the raw telescope format to FITS and then reduced in AIPS in the standard way. Maps were produced after subtracting out the continuum emission of the background quasar using UVLIN, and spectra extracted from the resulting three dimensional cube. The GMRT does not do online doppler tracking; this is, however, unimportant since the doppler shift within any one of our observing runs was a small fraction of a channel. For the lower redshift system, data from the observations on different days were corrected to the heliocentric frame and then combined.

The final spectrum for the $z = 0.0912$ system is shown in figure 1. The peak optical depth is ~ 0.18 (i.e. a depth of 390 mJy with the continuum flux of OI363 being 2.0 Jy), and occurs at a redshift of $z = 0.09123 \pm 0.00001$. The FWHM of the line is small, $\sim$ 5 km s^{-1}. Finally, the detected absorption lines were deleted from this spectrum and the latter smoothed to a velocity resolution of $\sim$ 30 km s^{-1}, to search for 21 cm emission. RMS noise values reached were 0.57 mJy (per 30.6 km s^{-1} channel) No evidence for 21 cm emission was seen. In the case of the higher redshift system, the peak optical depth is ~ 0.07 and the redshift measured from the 2.0 km s^{-1} spectrum is 0.2212 ± 0.00001. See Chengalur and Kanekar [16] for the 21 cm spectrum of the $z = 0.2212$ system.

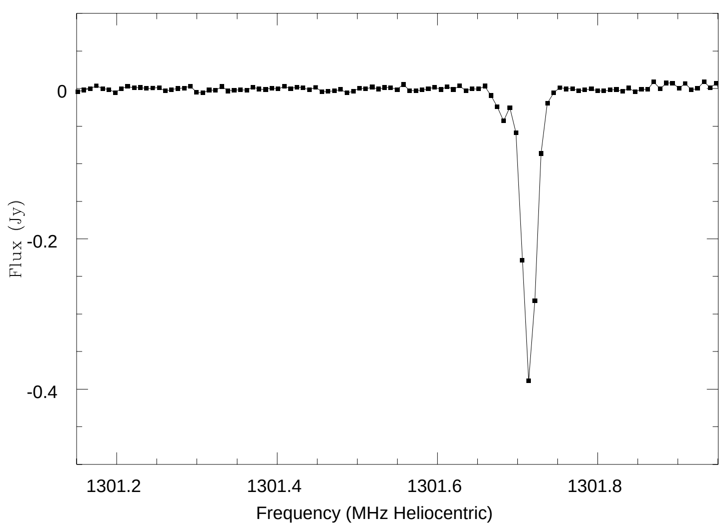

Figure 1. GMRT redshifted 21cm absorption spectrum of the lower redshift system towards OI363. The channel spacing is $\sim$ 1.8 km s^{-1}. The deepest optical depth ($\sim$ 0.18) is at a heliocentric redshift of 0.09123. The width (FWHM) of the line is $\sim$ 5 km s^{-1}.

3. Discussion

3.1 *HI mass estimates*

For emission from optically thin HI gas, the emission spectrum is directly related to the total HI mass, viz.,

$$M_{\rm HI} = 2.35 \times 10^5 \frac{D_L^2}{1+z} \int S(v){\rm d}v \quad {\rm M}_\odot, \tag{1}$$

where D_L is the luminosity distance of the emitting gas (in Mpc), $S(v)$ is the flux in the line in Jy, and v is the velocity in km/s. This expression is true as long as the gas has a spin temperature larger than that of the background continuum, i.e. in the absence of any background source, one is sensitive to gas in both the cold and the warm phase. In nearby $z \sim 0$ galaxies, the cold phase of the ISM appears to be marginally optically thick, however, even in this case the error introduced by using eq. (1) is not substantial. In case there is a background source, one is sensitive only to the gas that is not coincident (spatially and in velocity) with the background source.

The lack of detected 21 cm emission can be used to place upper limits on the HI mass of the damped absorber. The luminosity distance of this system is D_L = 373 Mpc ($z = 0.0912$), using H_0 = 75 km s^{-1} Mpc^{-1} and $q_0 = 0.5$. Thus, the 1σ upper limit on the mass (per 30 km s^{-1} channel) is 6 $\times 10^8$ M$_\odot$. As discussed above, this is only for gas that is not spatially co-incident with the background source. Since the size of the background source (see §3.2) is $\lesssim 30$ pc, orders of magnitude less than a typical galaxy size, spatial coincidence is not a major constraint. Further since the absorption profile is also extremely narrow, it is unlikely that much HI has been missed because it coincides in velocity with the absorbing gas.

Translating this limit on the HI mass per channel into a constraint on the total gaseous mass of the absorbing galaxy is complicated by the fact that the HI emission profile of spiral galaxies are strongly dependent on their inclination to the line of sight. For relatively face on orientations, where the total width is $\lesssim 30$ km/s, we directly have a 3σ HI mass limit of $\sim 2 \times 10^9$ M$_\odot$. For more inclined spirals, the velocity width of the profile increases, and the HI mass per unit velocity decreases. However, even in this case, a sizeable fraction of the mass is concentrated in a narrow velocity range because of velocity crowding. Hence, even for relatively large inclinations, a total HI mass of $\geq 10^{10}$ M$_\odot$ would have resulted in a signal detectable at the 3σ level.

Ground based imaging of the OI 363 field [17] shows that there are no bright spiral galaxies at the right redshift, at small impact parameters to the line of sight. There are however some dwarf galaxies, and also some low surface brightness objects which could be associated with the absorber. Our observations rule out the possibility that the absorber is associated with a gas rich, low surface brightness galaxy, either of intrinsically small total luminosity or whose total luminosity may have been underestimated by ground based observations.

3.2 *Estimates of spin temperature*

The total HI column density of a damped system can be determined from its Ly-α profile; this can be then used, in conjunction with the measured HI 21 cm optical depth, to determine the spin temperature of the absorbing gas (under the assumption that the absorbing gas is homogeneous. For a multi-phase absorber, this derived temperature is the column density weighted harmonic mean of the spin temperatures of the different phases, provided all the phases are optically thin.). We note, further, that OI363 is a highly core-dominated source [18,19], with a core size [20] of $\sim$ 10 milli arcseconds ($\sim$ 16 pc and $\sim$ 31 pc at redshifts of 0.0912 and 0.2212 respectively, for H_0 = 75 km s^{-1} Mpc^{-1} and $q_0 = 0.5$). Given the small size of this central core, the covering factors of the absorbing clouds are likely to be close to unity (for further details, see [16].)

The HI column densities inferred from the present observations, in terms of the spin temperatures of the two damped systems, are $1.82 \pm 0.02 \times 10^{18} T_s$ atoms cm^{-2} and $0.71 \pm 0.04 \times 10^{18} T_s$ atoms cm^{-2}, for the lower and higher redshift systems, respectively. The column densities measured by Rao and Turnshek [17], from the damped Lyman-α lines, are $7.9 \pm 1.4 \times 10^{20}$ atoms cm^{-2} and $1.5 \pm 0.2 \times 10^{21}$ atoms cm^{-2}, again in order of increasing redshift. From this and our HI 21 cm spectra, the spin temperatures that we derive for the absorbers are 825 ± 110 K (for the $z = 0.0912$ absorber) and 1120 ± 200 K (for the $z = 0.2212$ system). For the higher redshift system, our measurement agrees within the errors with that of Lane *et al* (1998). The overwhelming source of the (formal) uncertainty is in the determination of the HI column density from the UV measurements. Thus, even at redshifts where no evolution is expected, the derived spin temperature is significantly higher than that typically seen in the Galaxy. If one assumes that the HI 21 cm spectral width is entirely due to thermal motions, the required kinetic temperatures are ~ 625 K and ~ 750 K for the lower and higher redshifted system respectively, i.e. comparable to the derived spin temperatures. This high spin temperature appears common at both high and intermediate redshifts (see eg. [21–25]).

In summary, it appears that even at the lowest redshifts, gas outside the disks of spiral galaxies and with apparent physical parameters considerably different from the ISM of nearby galaxies has a non-trivial contribution to the total absorption cross-section. This is consistent with observations that, even for intermediate redshift damped Ly-α absorbers, the metallicity is considerably lower than typical solar values [21]. The present GMRT observations suggest, further, that evolutionary effects may not play an important role in understanding why the derived spin temperatures for damped Ly-α systems are higher, in general, than those measured in nearby spiral galaxy disks. Finally, the upper limit obtained on the HI mass of the lower redshift absorber indicates that the system is not a high-mass spiral and thus appears to support hierarchical models of galaxy formation.

Acknowledgements

These observations would not have been possible without the many years of dedicated effort put in by the GMRT staff to build the telescope. The GMRT 1400 MHz wide-band feed and receiver system was built by the Raman Research Institute.

References

[1] L J Storrie-Lombardi, R G McMahon and M J Irwin, *Mon. Not. R. Astron. Soc.* **283**, L79 (1996)
[2] A M Wolfe, *QSO Absorption Lines* edited by J C Blades, D Turnshek and C Norman (Cambridge University Press, 1988)
[3] F H Briggs, A M Wolfe, H S Liszt, M M Davis and K M Turner, *Astrophys. J.* **341**, 650 (1989)
[4] S G Djorgovski, M A Pahre, J Bechtold and R Elston, *Nature* **382**, 234 (1996)
[5] J X Prochaska and A M Wolfe, *Astrophys. J.* **487**, 73 (1997)
[6] A Klypin, S Borgani, J Holtzman and J Primack, *Astrophys. J.* **444**, 1 (1995)
[7] G Kauffmann, *Mon. Not. R. Astron. Soc.* **281**, 475 (1996)
[8] M G Haehnelt, M Steinmetz and M Rauch, *Astrophys. J.* **495**, 647 (1998)
[9] P McDonald and J Miralda-Escude, submitted to *Astrophys. J.* (astro-ph:9809237) (1998)
[10] V Le Brun, J Bergeron, P Boissé and J-M Deharveng, *Astron. Astrophys.* **321**, 733 (1997)
[11] K M Lanzetta, A M Wolfe, H Altan, X Barcons, H-W Chen, A Fernández-Soto, D M Meyer, A Ortiz-Gil, S Savaglio, J K Webb and N Yahata, *Astron. J.* **114**, 1337 (1997)
[12] R Braun and R Walterbos, *Astrophys. J.* **386**, 120 (1992)
[13] R Braun, *Astrophys. J.* **484**, 637 (1997)
[14] G Swarup, S Ananthakrishnan, V K Kapahi, A P Rao, C R Subrahmanya and V K Kulkarni, *Current Science* **60**, 95 (1991)
[15] G Swarup, S Ananthakrishnan, C R Subrahmanya, A P Rao, V K Kulkarni and V K Kapahi edited by N Jackson and R J Davis (in High-sensitivity Radio Astronomy, Cambridge, 1997)
[16] J N Chengalur and N Kanekar, *Mon. Not. R. Astron. Soc.* **302**, L29 (1999)
[17] S Rao, and D A Turnshek, *Astrophys. J.* **L500**, L115 (1998)
[18] D W Murphy, I W A Browne and R A Perley, *Mon. Not. R. Astron. Soc.* **264**, 298 (1993)
[19] D J Saikia, G F Holmes, A R Kulkarni, C J Salter and S T Garrington, *Mon. Not. R. Astron. Soc.* **298**, 877 (1998)
[20] C Stanghellini, D Dallacasa, C P O' Dea, S A Baum, R Fanti and C Fanti, *Astron. Astrophys.* **325**, 943 (1997)
[21] P Boissé, V Le Brun, J Bergeron and J-M Deharveng, *Astron. Astrophys.* **383**, 841 (1998)
[22] C L Carilli, W Lane, A G de Bruyn, R Braun and G K Miley, *Astron. J.* **111**, 1830 (1996)
[23] A G de Bruyn, C P O'Dea and S A Baum, *Astron. Astrophys.* **305**, 450 (1996)
[24] N Kanekar and N J Chengalur, *Mon. Not. R. Astron. Soc.*, **292**, 831 (1997)
[25] W Lane, A Smette, F Briggs, S Rao, D Turnshek and G Meylan, *Astron. J.* **116**, 26 (1988)