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HI 21cm absorption studies of high-z galaxies

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Abstract. I describe results from HI 21cm absorption studies of neutral hydrogen in the Galaxy and damped Lyman-α systems, and the implications for physical conditions in the interstellar medium of the Milky Way and high-z galaxies.

Keywords : quasars: absorption lines - galaxies: evolution - galaxies: ISM

1. Introduction

HI 21cm absorption studies towards radio-loud active galactic nuclei (AGNs) provide an interesting probe of physical conditions in the neutral atomic gas phase in galaxies and AGN environments (e.g. Vermeulen et al. 2003; Kanekar & Briggs 2004). They can also be used in conjunction with absorption studies in other spectral lines to probe putative redshift evolution in the fundamental constants (e.g. Kanekar 2012). In this review, I will discuss the implications of our HI 21cm absorption studies for gas conditions in "normal" galaxies, ranging from the Milky Way to high-z damped Lyman-α systems.

The HI 21cm optical depth along a sightline depends on both the HI column density and the gas temperature. For compact background quasars, if the HI column density can be independently determined (from either HI 21cm emission studies or the Lyman-α absorption profile), HI 21cm absorption spectroscopy yields the gas "spin temperature" $\mathrm{T_s}$, the column-density-weighted harmonic mean of the temperatures of different HI phases along the sightline. Such spin temperature measurements may be used to study the distribution of gas in different temperature phases in the Galaxy, as well as the redshift evolution of this gas temperature distribution in cosmologically-distant objects. This article first describes results from a large HI 21cm absorption

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study of gas in the Milky Way, before moving on to consider physical conditions in high-z absorption-selected galaxies, the damped Lyman-α systems.

2. A column density threshold for cold gas formation in the Galaxy

We have used the Westerbork Synthesis Radio Telescope (WSRT), the Giant Metrewave Radio Telescope (GMRT) and the Australia Telescope Compact Array to obtain deep, high-velocity-resolution ($\approx 0.26 - 0.52$ km s^{-1}) Galactic HI 21cm absorption spectra towards 35 compact radio-loud quasars (Kanekar et al. 2003; Braun & Kanekar 2005; Roy et al. 2013). Galactic HI 21cm absorption was detected against every source but one, B0438−436. The final HI 21cm optical-depth spectra have root mean square (RMS) noise values of $\approx 0.0002 - 0.0013$ per 1 km/s channel, with a median RMS noise of $\approx 5 \times 10^{-4}$ per 1 km/s channel, amongst the deepest HI 21cm absorption spectra ever obtained. HI column densities for each sightline were obtained from the Leiden-Argentine-Bonn survey (e.g. Kalberla et al. 2005).

Low spin temperatures ($T_s < 600$ K) were obtained for 24 of the 25 sightlines with $N_{HI} \geq 2 \times 10^{20}$ cm^{-2}, while all ten sightlines with $N_{HI} < 2 \times 10^{20}$ cm^{-2} were found to have high spin temperatures, $\gtrsim 600$ K (see Fig. 1(B) of Kanekar, Braun & Roy 2011). The median spin temperature for sightlines with $N_{HI} \geq 2 \times 10^{20}$ cm^{-2} is ~ 340 K, while that for sightlines with $N_{HI} < 2 \times 10^{20}$ K is ~ 2500 K. Thus, there appears to be a physical difference between sightlines with HI column densities lower and higher than $\approx 2 \times 10^{20}$ cm^{-2} (Kanekar et al. 2011).

Since the inferred spin temperatures are the column-density-weighted harmonic means of the spin temperatures of different phases along each sightline, a high T_s value indicates the presence of a smaller fraction of the cold neutral medium (CNM), while a low T_s indicates a high CNM fraction. Thus, the fact that the average T_s values are significantly higher on sightlines with low HI column densities, $N_{HI} < 2 \times 10^{20}$ cm^{-2}, indicates that such low-N_{HI} sightlines contain low CNM fractions, far smaller than those on sightlines with $N_{HI} \geq 2 \times 10^{20}$ cm^{-2}. This is likely to arise naturally due to inefficient self-shielding against ionizing ultraviolet (UV) photons (Schaye 2004; Kanekar et al. 2011). Our results suggest that a total HI column density of $\approx 2 \times 10^{20}$ cm^{-2} is needed for self-shielding to become entirely efficient at excluding UV photons from the interior of HI clouds. Below this threshold, sufficient UV photons penetrate into the cloud interior, heating and ionizing the gas, and hindering the survival of the cold phase.

While semi-analytical or numerical estimates of self-shielding have suggested that HI clouds are mostly neutral for $N_{HI} \gtrsim 10^{20}$ cm^{-2} (e.g. Viegas 1995), this is the first direct evidence for a change in physical conditions at this column density. Thus, there appear to be three HI column densities at which phase transitions occur in the neutral interstellar medium (ISM), at $N_{HI} \approx 2 \times 10^{20}$ cm^{-2} resulting in the formation

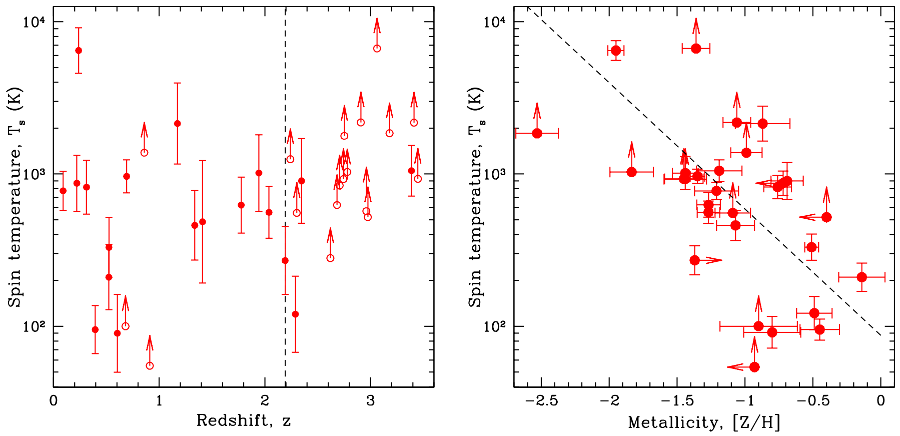

Figure 1. Left: The spin temperature T_s plotted against redshift for the 37 DLAs of the sample; non-detections of Hɪ 21cm absorption are shown by lower limits to T_s. The median DLA redshift, z_{med} = 2.192, is indicated by the vertical dashed line. **Right:** The spin temperature plotted against metallicity [Z/H] for the 29 DLAs with estimates of both quantities; the dashed line shows the fit to the T_s-[Z/H] relation.

of cold Hɪ (Kanekar et al. 2011), at $N_{HI} \sim 5 \times 10^{20}$ cm^{-2} resulting in the formation of molecular hydrogen (Savage et al. 1977), and finally, at $N_{HI} \sim 10^{22}$ cm^{-2}, when most of the atomic gas is converted into the molecular phase (Schaye 2001).

3. The spin temperature of high-z damped Lyman-α systems

Damped Lyman-α systems (DLAs) are the highest Hɪ column density absorbers detected in quasar absorption spectra (e.g. Wolfe et al. 2005). With Hɪ column densities $\geq 2 \times 10^{20}$ cm^{-2}, similar to values seen in the Milky Way and nearby galaxies, DLAs are the high-z counterparts of local gas-rich galaxies. DLA samples are especially interesting because they are absorption-selected, and hence do not contain a bias towards the most luminous galaxies at a given redshift.

While more than 7000 DLAs are currently known at $z > 2.2$, it has been very difficult to identify the absorber hosts in optical images or to detect them in radio Hɪ 21cm or CO emission lines. Absorption studies remain our main source of information about the absorbers. For DLAs towards compact radio-loud quasars, the Hɪ column density obtained from the Lyman-α absorption profile can be combined with the integrated Hɪ 21cm optical depth to obtain the spin temperature of the atomic gas, and thence, the fraction of gas in the warm and cold phases. Hɪ 21cm absorption studies of high-z DLAs can thus be used to study the temperature distribution of neutral gas, its redshift evolution, and its relation to local conditions. Early studies of a handful of DLAs found evidence that DLA spin temperatures appeared systematically higher than T_s values seen in the Galaxy (e.g. Wolfe & Davis 1979; Wolfe, Briggs & Jauncey 1981). However, until recently, the lack of DLAs known towards radio-loud quasars, the poor low-frequency coverage of radio telescopes and radio frequency interference (RFI) meant that only a few T_s estimates, and mostly limits, were available in high-z DLAs (e.g. Wolfe et al. 1985; Carilli et al. 1996).

Over the last decade, we have attempted to address the paucity of HI 21cm absorption studies of DLAs via a number of approaches. We have carried out an optical survey for DLAs towards radio-loud quasar samples, with the Very Large Telescope (VLT), the Gemini Telescope and the William Herschel Telescope (Ellison et al. 2008). We have used the Green Bank Telescope (GBT), the GMRT and the WSRT to carry out searches for redshifted HI 21cm absorption in DLAs detected in our survey as well as systems from the literature (Kanekar & Chengalur 2003; Kanekar et al. 2006; York et al. 2007; Kanekar, Chengalur & Lane 2007; Ellison et al. 2012; Kanekar et al. 2013, 2014). We have also used the GBT and the GMRT to search for HI 21cm absorption in a large sample of "strong" MgII λ2796 absorbers, to identify DLAs at low redshifts, $z < 1.6$, where the Lyman-α line cannot be observed with ground-based telescopes (Kanekar et al. 2009b). We have used the Very Long Baseline Array to obtain low-frequency images of the background quasars to estimate the fraction of the radio flux density in the compact core and thus, the DLA covering factor (Kanekar et al. 2009a; Ellison et al. 2012; Kanekar et al. 2013, 2014). And, finally, we have used the Keck and Gemini telescopes, and the VLT, to measure metallicities and abundances of a sample of DLAs with T_s estimates to attempt to relate T_s to physical conditions in the absorbers (Ellison et al. 2012; Kanekar et al. 2014).

Overall, we have searched for redshifted HI 21cm absorption in around 50 DLAs and 120 strong MgII λ2796 absorbers, with around one-third of the targets wiped out by RFI. We have obtained $\sim$ 25 detections of HI 21cm absorption in these systems, and $\sim$ 25 strong lower limits on the DLA spin temperature ($T_s \gtrsim 700$ K). Combining our results with literature studies (e.g. Srianand et al. 2012), there are now 37 DLAs at all redshifts with T_s estimates, all with low-frequency estimates of the DLA covering factor. The left panel of Fig. 1 shows the spin temperature plotted versus redshift for these systems.

The detection rate of HI 21cm absorption in high-z DLAs (with $z > z_{med}$, where $z_{med} = 2.192$) is 17^{+16}_{-9}%, while that in low-z DLAs (with $z < z_{med}$) is 83^{+17}_{-21}%. The difference between the two detection rates has $\approx 2.6\sigma$ significance. This is tentative evidence that the probability of detecting HI 21cm absorption increases with decreasing redshift. Further, the T_s distributions of absorber samples above and below the median redshift are different at $\approx 3.5\sigma$ significance. The statistical significance of the difference in T_s distributions is even higher, 4.0σ, if the redshift $z = 2.4$ is used to demarcate the low-z and high-z sub-samples. We conclude that DLA spin temperatures show clear redshift evolution: the high-z sample contains both a smaller fraction of DLAs with low spin temperatures and a lower detection rate of HI 21cm absorption. Finally, we find that the T_s distributions in the full sample of DLAs and in the

Milky Way are different, at $\approx 6\sigma$ significance. This is clear evidence that the neutral ISM in DLAs is significantly different from that in the Galaxy, with far smaller CNM fractions in DLAs than in the Milky Way (Kanekar et al. 2014).

Gas cooling in the ISM below temperatures of $\approx$ 8000 K is dominated by collisional excitation of the fine structure lines of metals like Cɪɪ and Oɪ (Wolfire et al. 1995). Kanekar & Chengalur (2001) hence argued that galaxies with low metallicities should have fewer cooling routes than high-metallicity systems like the Milky Way, and should thus have larger amounts of warm gas. The high T_s values in most high-z DLAs can thus be explained if the absorbers are typically low-metallicity systems with low CNM fractions due to a lack of cooling routes. Conversely, DLAs with high metallicities would be expected to have higher CNM fractions and low spin temperatures. Kanekar & Chengalur (2001) used the above arguments to predict the existence of an anti-correlation between T_s and metallicity [Z/H], if metallicity is critical in determining the cold gas content of a galaxy.

The right panel of Fig. 1 shows the spin temperature T_s plotted against metallicity [Z/H] for the 29 DLAs of the sample with estimates of both quantities, along with measurements of the low-frequency covering factor. We have used the non-parametric generalized Kendall-tau rank correlation test to detect the anti-correlation between T_s and [Z/H] at $\approx 3.5\sigma$ significance, taking limits on the two quantities into account appropriately (Kanekar et al. 2009c; Ellison et al. 2012; Kanekar et al. 2014). The dashed line in the figure is a linear fit to the T_s-[Z/H] relation, applied to the 16 DLAs with measurements of both T_s and [Z/H]; this yields $\mathrm{Log}[T_s] = (-0.83 \pm 0.16) \times [Z/H] + (1.94 \pm 0.20)$ (Kanekar et al. 2014). This supports the hypothesis of Kanekar & Chengalur (2001) that low CNM fractions in DLAs arise due to their low metallicities, and thus, a paucity of cooling routes.

Finally, our GBT and GMRT searches for Hɪ 21cm absorption in strong Mgɪɪ λ2796 absorbers at $z \approx 0.5 - 1.5$ have yielded a large number of Hɪ 21cm detections at intermediate redshifts (see also Gupta et al. 2009). We find tentative evidence that the detection rate of Hɪ 21cm absorption increases with decreasing redshift. This indicates that the CNM fraction in normal galaxies increases with time, with significant amounts of cold atomic gas in such galaxies at $z \approx 1.5$ (Kanekar et al. 2009b).

4. Summary

In summary, Hɪ 21cm absorption studies of DLAs are finally coming of age, with spin temperature estimates in nearly 40 systems at all redshifts. We find clear evidence that the spin temperatures of DLAs are typically higher at high redshifts, and also typically higher than values seen in the Galaxy. The high DLA spin temperatures appear to arise due to a higher fraction of warm gas in the absorbers, as the low DLA metallicities imply fewer gas cooling routes. We also find evidence for an Hɪ column density threshold for the formation of cold atomic gas in the Milky Way, implying a third phase transition in the ISM, probably due to inefficient self-shielding against UV radiation at lower column densities. This threshold is very similar to the defining column density of a damped Lyman-α system, indicating a physical difference between damped and sub-damped Lyman-α absorbers.

While the above GMRT and GBT Hɪ 21cm absorption studies have significantly improved our understanding of physical conditions in DLAs, there are still only a handful of detections of Hɪ 21cm absorption in DLAs at $z \gtrsim 2$. The new high-sensitivity 250 − 500 MHz receivers of the upgraded GMRT are poised to make a significant impact on this field.

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