Probing Galaxy evolution with HI 21cm Absorption Spectroscopy

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1. Central Questions: Neutral Gas in Galaxies Over Cosmic Time

Understanding the process by which gas in galaxies is converted into stars is one of the important open issues in galaxy evolution. Over the last decade, deep optical and near-infrared studies have yielded many insights into the evolution of star formation in galaxies showing, for example, that the star formation activity at $z \gtrsim 1$ both was far higher than in the present Universe (e.g. Hopkins 2004, ApJ, 615, 209) and occurred in very different galaxies from those that dominate star formation today (e.g. Le Floc'h et al. 2005, ApJ, 632, 169). While such studies have so far been restricted to bright galaxies or a few deep fields, the upcoming James Webb Space Telescope will allow them to be extended to normal star-forming galaxies at high redshifts. Cm- and mm-wave interferometers like the Expanded Very Large Array (EVLA) and the Atacama Large Millimeter Array will also soon yield information on the molecular gas content of these galaxies through studies of redshifted CO and HCN lines. Thus, within the next few years, a plethora of information will be available on the distribution of *stars, ionized gas, and molecular gas* in a large number of galaxies at $z \gtrsim 1$, allowing detailed tests of models of galaxy formation.

One of the crucial pieces of the puzzle of understanding star formation in galaxies is the behavior of the *neutral atomic gas.* It is known in the local Universe that star formation is closely linked to the neutral gas content, with the SFRs of galaxies showing a tight correlation with their total HI masses (e.g. Doyle & Drinkwater 2006, MNRAS, 372, 977). However, very little is known about physical conditions in neutral gas in high-redshift galaxies and active galactic nuclei (AGNs). In the local Universe, such gas is best studied in the HI 21cm *emission* line, which can provide detailed information on the gas distribution and its relation to star formation, gas kinematics, gas and dark matter masses, etc. Unfortunately, the weakness of the HI 21cm transition implies that extremely large telescopes would be needed to carry out such studies in high-z galaxies. For example, merely detecting HI 21cm emission from a $z \sim 2.5$ galaxy at the knee of the local HI mass function, i.e. with $\mathrm{M}^{\star}_{\mathrm{HI}} \sim 6.5 \times 10^9 \, M_\odot$, would require ~ 360 hours with even the Square Kilometer Array (SKA).

Redshifted HI 21cm absorption provides an alternative route to trace physical conditions in the neutral gas in high-z galaxies. This enables us to both study the cold gas (in which star formation takes place) in "normal" galaxies lying towards background radio-loud sources, and probe physical conditions in the environment of active galactic nuclei (AGNs). In this White Paper, we address the contributions that redshifted HI 21cm absorption studies might make towards answering the following two questions:

- **What are the physical conditions in the neutral gas in galaxies from which stars form?**
- **What are the physical conditions in AGNs, and how are AGNs fuelled ?**

2. Scientific Context (A): Neutral Gas in High Redshift Galaxies

2.1 Damped Lyman-α systems

Gas-rich galaxies at high redshifts are most easily detected through their absorption signatures in the optical spectra of background quasars. Such absorption-selected galaxy samples provide a powerful probe of galaxy evolution as they are likely to be more representative of the "typical" gas-rich galaxy at a given redshift. The highest HI column density systems (with $N_{\rm HI} \geq 2 \times 10^{20}$ cm^{-2}), the damped Lyman-α absorbers (DLAs), are the largest repository of neutral gas at high redshifts, with a total HI content that is a significant fraction of the stellar mass in today's galaxies (e.g. Wolfe et al. 2005, ARA&A, 43, 861). DLAs are thus an important gas reservoir for high-z star formation; understanding the redshift evolution of DLAs is critical to understanding normal galaxy evolution.

More than a thousand DLAs are known today, largely from searches through spectra from the Sloan Digital Sky Survey (e.g. Prochaska et al. 2005, ApJ, 635, 123). However, while optical/UV absorption studies have provided interesting information on abundances and metallicities in high-z DLAs and their evolution (e.g. Prochaska et al. 2003, ApJ, 595, L9; Kulkarni et al. 2005, ApJ, 618, 68), very little is known about physical conditions in the neutral gas, the typical size or mass of the absorbers, or even their SFRs. Optical imaging studies are hindered by the fact that the absorbing galaxy lies below the point-spread function of the background quasar, and one cannot determine the transverse size of the DLA through optical/UV spectroscopy as the background quasars are point sources at these wavelengths. Further, few DLAs (~ 50) are known at $z < 1.7$ (where space-based telescopes are needed to observe the Lyman-α line), which comprises 70% of the age of the Universe and where galaxies are known to undergo strong evolution. Even high-z DLA samples are almost entirely drawn from surveys of optically-selected quasars and could hence be biased against evolved absorbers, where a high dust extinction could remove the background quasar from such a sample; e.g. Fall & Pei 1993, ApJ, 402, 479). Finally, most optical resonance transitions (including Lyman-α) are insensitive to physical conditions like density and temperature. As a result, despite nearly three decades of study, physical conditions in high-z DLAs, and their redshift evolution, remain matters of controversy (e.g. Wolfe et al. 2005).

2.2. "Blind" HI 21cm Absorption Surveys

Studies of galaxy evolution critically require an unbiased sample of DLAs with a uniform sampling in redshift; this can be achieved through "blind" (i.e. with no optical selection) absorption surveys in the HI 21cm line (e.g. Kanekar & Briggs 2004, New Astr. Rev, 48, 1259). HI 21cm absorption is readily detectable in high HI column density sightlines, with $N_{\rm HI} \gtrsim 10^{20}$ cm^{-2}, precisely those that would give rise to damping wings in the Lyman-α line. HI 21cm absorption surveys are thus well-matched toward the construction of DLA samples. Such surveys also contain no intrinsic redshift bias, such as that arising from the ultraviolet cut-off in the atmosphere. Flux-limited radio samples are also unaffected by foreground dust extinction. Blind HI 21cm absorption surveys can thus be used to obtain samples of damped Lyman-α systems unbiased by dust extinction and redshift coverage. Follow-up spectroscopy in the Lyman-α line would also then yield unbiased estimates of the cosmological mass density of the neutral gas in galaxies (e.g. Wolfe et al. 2005).

2.3 HI in High-z DLAs: The Spin Temperature

HI 21cm absorption studies of DLAs towards radio-loud quasars can be used to determine the harmonic-mean spin temperature T_s of the neutral gas, using the expression $N_{\rm HI} =$

1.823×10^{18} $\mathrm{T_s} \int \tau_{21}\, \mathrm{d}V$, where τ_{21} is the HI 21cm optical depth, $N_{\rm HI}$ is in cm^{-2}, $\mathrm{T_s}$ in K, and dV in km s^{-1}. The spin temperature contains information on the distribution of neutral gas in different temperature phases along the sightline, specifically on the fraction of HI in the cold phase (the CNM) that can serve as fuel for star formation. It is also one of the few direct tracers of physical conditions in the neutral gas in high-z galaxies.

The paucity of known DLAs towards radio-loud quasars and the poor frequency coverage of radio telescopes below ~ 1 GHz has meant that there are today only ~ 30 DLAs with spin temperature estimates at all redshifts (e.g. Kanekar & Chengalur 2003, A&A, 399, 857). Fig. 1[A] shows $\mathrm{T_s}$ plotted versus redshift for all known DLAs with $\mathrm{T_s}$ estimates (Kanekar et al. 2009a, in prep.); the majority of high-z DLAs have high spin temperatures, $\mathrm{T_s} > 700$ K, with only one of 22 systems at $z \gtrsim 2$ having $\mathrm{T_s} \lesssim 300$ K, in the range of Galactic values (e.g. Braun & Walterbos 1992, ApJ, 386, 120). High-z DLAs thus appear to have only small fractions ($\lesssim 10\%$) of cold HI, with most of the HI in the warm phase. The detection rate of HI 21cm absorption in DLAs has also been found to increase with decreasing redshift, from $\sim 33\%$ at $z \gtrsim 1.7$ to $\sim 85\%$ at $z < 0.9$ [Kanekar et al. 2009b, MNRAS (submitted)], probably due to a larger fraction of cold HI and a lower spin temperature in low-z DLAs. The redshift dependence of the spin temperature suggests an evolution in the temperature distribution of DLAs, due to either evolving physical conditions in the gas or changes in the nature of galaxies that give rise to DLAs at a given redshift.

An anti-correlation has been detected between spin temperature and metallicity in a sample of 26 DLAs at all redshifts (Kanekar et al. 2009a), suggesting that the high $\mathrm{T_s}$ values found in most high-z DLAs arise due to a lack of cooling routes owing to a low metal abundance. This is probably because the global fractions of cold and warm neutral gas in a galaxy are primarily governed by its central pressure and average metallicity (Wolfire et al. 1995, ApJ, 443, 152). Determining the relations between the cold gas fraction, star formation rate, gas metallicity, and gas pressures in an unbiased sample of DLAs, and the evolution of these relations with redshift, would significantly improve our understanding of the evolution of star formation in normal galaxies. HI 21cm absorption studies provide an important ingredient of the puzzle, the spin temperature. However, Fig 1[A] shows that the number of detections of HI 21cm absorption in high-z DLAs is still very small (7 at $z \gtrsim 1.7$). Similarly, there are almost no $\mathrm{T_s}$ estimates in the "redshift desert" $0.7 < z < 1.7$, as few DLAs are known here towards radio-loud quasars.

2.2 HI Kinematics: Spatial Mapping of HI 21cm Absorption

The broad aims of mapping gas in high redshift galaxies are to determine the spatial extent of the galaxies, measure their kinematics, relate the gas distribution to star formation, distinguish between regular rotation (i.e. disk-like kinematics) and turbulent motions, and, if the motions are disk-like, compute the dynamical mass to test theories of galaxy assembly. Much of this information can be obtained from high spatial resolution HI 21cm absorption studies, if the background radio continuum is extended on angular scales larger than the telescope resolution. Such studies can determine whether the velocity field is quiescent (i.e. well-ordered) or whether disruptive events (e.g. mergers) have recently occurred. The absorption velocity field can be modeled to determine the dynamical mass, if sufficient spatial resolution and sensitivity are available. Absorption mapping also provides a lower limit to

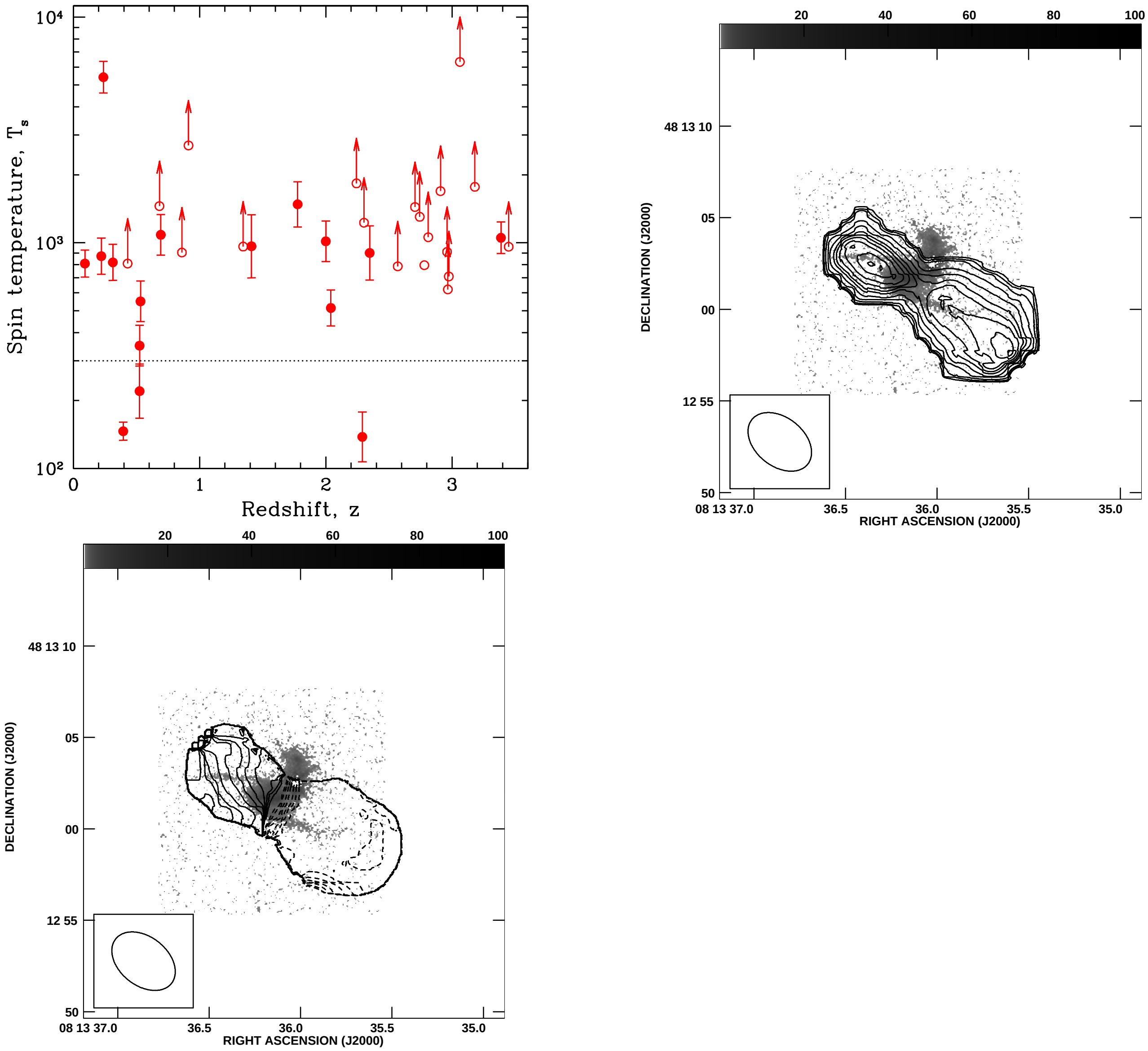

Figure 1: [A] Left panel: The spin temperature T_s plotted against DLA redshift for the 32 DLAs with T_s estimates (Kanekar et al. 2009a). The dashed horizontal line is at $T_s =$ 300 K; 90% of Galactic sightlines show $T_s <$ 300 K (Braun & Walterbos 1992). [B] Right panel: The contours show the integrated HI 21cm optical depth from the $z \sim 0.437$ DLA towards 3C196, overlaid on a Hubble Space Telescope (HST) image (in greyscale; Ridgway & Stockton 1997, AJ, 114, 511)
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the physical extent of the galaxy; for example, Fig. 1[B] shows a map of the integrated HI 21cm absorption from the $z \sim 0.437$ DLA towards the radio galaxy 3C196 obtained with the Giant Metrewave Radio Telescope (GMRT), showing that the HI extends to a radius of at least ~ 70 kpc, far beyond the optical galaxy. HI 21cm absorption is also sensitive to the presence of *cold* HI, which is likely to trace regions of star formation. Finally, while absorption studies only determine the H I 21cm optical depth, assuming a spin temperature of ~ 100 K yields a good lower limit to the neutral gas mass of the galaxy.

The lack of known DLAs toward extended sources like radio galaxies has meant that H I 21cm mapping studies sensitive to galactic scales of $\gtrsim 10$ kpc have only been possible in two DLAs at $z \sim 0.4$ (e.g. Fig. 1[B]). Surveys for H I 21cm absorption towards radio galaxies are needed to obtain DLA samples suitable for follow-up mapping studies.

2.3 Magnetic Fields in Galaxies: The Zeeman Effect

Although magnetic fields are widely believed to play an important role in a host of astrophysical processes ranging from star formation to the formation of large-scale structure (e.g. Brandenburg & Subramanian 2005, Phys. Rep, 417, 1), the origin and evolution of galactic magnetic fields remains poorly understood. The primary reason for this is the lack of observational input: although the importance of magnetic fields in determining the state and evolution of the ISM has long been appreciated, there have been almost no reliable estimates of the field strength at cosmological distances. Zeeman-splitting measurements in the H I 21cm line provide one of the few methods by which one might measure the local magnetic field in neutral gas in high-z galaxies. Recently, Wolfe et al. (2008; Nature, 455, 638) used H I 21cm absorption studies with the Green Bank Telescope (GBT) to derive an extremely high magnetic field strength ($\sim 84\,\mu$G) in the $z \sim 0.692$ DLA towards 3C286; this is an order of magnitude higher than the typical field strengths of $\sim 6\,\mu$G measured in diffuse gas in the Milky Way (e.g. Heiles & Troland 2004, ApJS, 151, 271). High average field strengths (similar to values in today's galaxies) have also been obtained in the host galaxies of $z \sim 1.3$ Mg II absorbers, by comparing the net rotation measures of samples of quasars with and without strong foreground Mg II absorption (Bernet et al. 2008, Nature, 454, 302). The high field strengths derived from both the Zeeman-split measurements and the Faraday rotation studies suggest that high magnetic field strengths may be a generic feature of high-z galaxies; such fields could play a critical role in high redshift galaxy evolution. This would also require dynamo models to be significantly more efficient than hitherto estimated (e.g. Brandenburg & Subramanian 2005). Measuring the typical magnetic field strength in a significant number of high-z galaxies is thus of much importance. This requires a sample of strong H I 21cm absorbers at high redshifts, and radio telescopes with good low frequency coverage and high sensitivity.

3. Scientific Context (B): AGN Environments

The immediate surroundings of active galactic nuclei are complex regions characterized by extreme physical conditions where the interplay between the enormous amounts of energy released from the nucleus and the ISM is critical in determining the evolution of the system. The role of gas (whether atomic, molecular and ionized) in the nuclear regions is known to be important both in triggering the radio activity and in the subsequent evolution. For example, infalling gas, whether from an accretion disk or an advective flow, is an essential ingredient of AGN activity, as it can feed the central engine, turning a dormant super-massive black hole into an active one. The details of gas accretion (e.g. Bondi accretion from hot gas haloes vs. optically-thick cold accretion disks) can have important implications for the characteristics of the radio emission, producing low-luminosity, edge-darkened FR-I radio galaxies in the first case, and powerful, edge-brightened FR-II systems in the second (e.g. Allen et al. 2006, MNRAS, 372, 21). Conversely, feedback from radio-loud AGN outflows is expected to play a crucial role in regulating star formation in the most massive galaxies (e.g. Croton et al. 2006, MNRAS, 365, 11).

HI 21cm absorption studies offer the unique possibility of tracing the kinematics and morphology of neutral gas in radio-loud AGN environments, and determining the nature of the accretion or the energetics of the outflow. For example, Morganti et al. (2009, arXiv/0902.0863) have recently used Westerbork Synthesis Radio Telescope (WSRT) and very long baseline interferometric (VLBI) observations to detect extremely broad HI 21cm absorption in the nearby radio source 4C37.11, which appears to be the kinematical signature of supermassive binary black holes (separated by only ~ 7 pc) in the centre of the galaxy. Similarly, VLBI HI 21cm absorption observations have detected regularly-rotating structures (circumnuclear torii or accretion disks) around a number of nearby AGNs (e.g. Peck et al. 1999, ApJ, 521, 103). Such high spatial resolution mapping studies are only possible in the HI 21cm line, due to the presence of background radio emission from relativistic jets on 100 pc scales.

Even more intriguing has been the recent WSRT discovery of broad, blue-shifted HI 21cm absorption in a number of nearby radio galaxies (e.g. Morganti et al. 2003, ApJ, 593, L69). This indicates the existence of fast ($\gtrsim 1000$ km s^{-1}), massive ($\sim 50\ M_\odot$ yr^{-1}) HI outflows (Morganti et al. 2005, A&A, 444, L9). The mass outflow rates are comparable to those obtained for starburst-driven superwinds in ultra-luminous infrared galaxies (e.g. Veilleux et al. 2005, ARA&A, 43, 769), indicating that AGN outflows could play a similar role to superwinds in enriching the intergalactic medium with metals and inhibiting star formation in the AGN host galaxy. However, the HI 21cm absorption is extremely weak (peak optical depth typically $\sim 10^{-3}$) and wide ($\gtrsim 1000$ km s^{-1}), and thus difficult to detect, requiring both high spectral dynamic range and wide bandwidths. Such absorption searches have hence only been possible against a few nearby, bright radio galaxies. It is important to determine whether such jet-driven HI outflows are a common phenomena in radio-loud AGNs; if so, they could play an important role in recycling galactic material at all redshifts. Equally important is whether such outflows are detected at all phases of AGN evolution, or whether they are confined to the "radio mode", causing the suppression of cooling flows and the quenching of star formation in the host galaxy (e.g. Croton et al. 2006).

4. HI 21cm Absorption Studies over the Next Decade

Significant progress is likely to be made in HI 21cm absorption studies over the next decade with current and upcoming instrumentation. Optical DLA surveys have recently begun to target samples of radio-loud quasars that are suitable for follow-up HI 21cm absorption studies (e.g. Ellison et al. 2008, MNRAS, 388, 1349). These should allow the number of T_s measurements at $z > 1.7$ to be significantly increased years, with the sensitive receivers of the GBT and the GMRT. Both these telescopes have also been used to target strong MgII absorbers at $z < 1.7$, and have already yielded ~ 15 new detections of HI 21cm absorption in the redshift desert of Fig. 1[A] (e.g. Gupta et al. 2007, ApJ, 654, L111). Follow-up HST spectroscopy in the Lyman-α line will provide estimates of the spin temperature in these absorbers. Searches for "associated" H I 21cm absorption from AGN environments are also now being extended to $z \gtrsim 3$, using the GMRT and the GBT.

Next, the wide frequency coverage of the L-band receivers of the EVLA (940−2000 MHz) and the new EVLA correlator will soon allow blind H I 21cm absorption surveys out to $z \sim 0.5$. A 12-hour EVLA run per field would yield 5σ detections of H I 21cm absorption from all DLAs with $T_s < 1000$ K and $z \lesssim 0.5$, towards background sources with 1 GHz flux densities $\gtrsim 80$ mJy. Every EVLA L-band continuum observation will also *automatically yield such absorption survey data towards all radio sources in the field-of-view.* Finally, the 35 km baselines of the EVLA A-array will provide a resolution of $\sim 1.8''$ (i.e. ~ 10 kpc) at $z \sim 0.5$, allowing estimates of the spatial extent of the H I for all detections of H I 21cm absorption at $z < 0.5$ against extended radio sources. The high EVLA sensitivity, wide bandwidth and high spectral dynamic range will also allow searches for fast AGN outflows from a large number of AGNs out to $z \sim 0.5$.

Similarly, the Australian SKA Pathfinder (ASKAP) will have a wide field-of-view (~ 30 deg^2), receivers covering $700 - 1500$ MHz, and a bandwidth of 300 MHz (Johnston et al. 2007, PASA, 24, 174), allowing simultaneous searches for redshifted H I 21cm absorption over $0.1 < z < 0.5$ or $0.5 < z < 1$ towards all background radio sources in the field. 50 hour ASKAP integrations on ~ 100 fields should yield ~ 250 new H I 21cm absorbers at $0.5 < z < 1$ in a total time of ~ 5000 hours. A similar survey speed will be obtained with the new APERTIF $700 - 1700$ MHz receivers on the WSRT.

Finally, the high sensitivity and uniform frequency coverage of the GBT imply that it is an excellent instrument for deep studies of detected H I 21cm absorbers, e.g. for Zeeman-split measurements. Such studies will also soon be possible on the GMRT, which is being upgraded with a wide-band correlator and new receivers covering $300 - 1420$ MHz.

5. Advancing the Science: Technical Developments

Clearly, the next decade is likely to be an extremely interesting period for redshifted H I 21cm absorption studies. However, there are areas where technical developments or extensions of current facilities could significantly aid progress in this field; these include (1) RFI-mitigation algorithms, (2) focal-plane phased arrays, (3) EVLA and VLBA upgrades.

- **RFI-mitigation algorithms:** The biggest hindrance to redshifted H I 21cm absorption studies is RFI from a host of terrestrial communication signals at the low redshifted line frequencies. Most such signals are highly time-variable, often on very short time scales (< 1 second). Progress in low-frequency spectroscopy would be much aided by the development and implementation of modern RFI mitigation algorithms [e.g. Boonstra 2005 (Ph.D. thesis, Delft)], to edit out the RFI at high time and frequency resolution before the data are averaged in the correlator.

- **Focal-plane phased arrays:** Blind surveys for H I 21cm absorption require a wide field-of-view, which is currently not available on high-sensitivity telescopes like the GBT or the EVLA. Over the next decade, it should be possible to increase the field-of-view of the GBT (and perhaps the EVLA) by more than an order of magnitude through the use of phased-array feeds at the focal plane. Development work is needed to obtain wide frequency coverage and low system temperatures for such focal-plane feed arrays.

- **EVLA and VLBA upgrades:** The EVLA L-band receivers will allow HI 21cm absorption mapping studies, with a spatial resolution of $\sim$ 10 kpc, out to $z \sim 0.5$. Equipping the EVLA and the Pie Town antenna [of the Very Long Baseline Array (VLBA)] with a sensitive low-frequency receiver covering $0.7-1$ GHz would allow such HI 21cm absorption mapping (with 10 kpc spatial resolution) to be carried out for all $z < 1$ DLAs towards extended radio sources. If the remaining VLBA antennas are also equipped with such receivers, it would enable mapping of accretion disks around AGNs out to $z \sim 1$, with a spatial resolution of $<$ 70 pc. Both upgrades would yield very interesting science as galaxies are known to undergo significant evolution at $z < 1$.

Finally, looking beyond the next decade, the SKA will provide substantial improvements over current facilities for redshifted HI 21cm absorption studies, in sensitivity, mapping capabilities and wide fields-of-view (Kanekar & Briggs 2004). However, technical developments in RFI-mitigation algorithms and focal-plane phased arrays are critical to achieve both the sensitivity and the field-of-view specifications of the SKA.