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ON THE PATHWAY TO THE SKA
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Local benchmarks for SKA HI 21-cm surveys

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Abstract. One of the obvious tasks for the Square Kilometer Array is to perform deep neutral hydrogen 21-cm emission line surveys out to large redshifts. For the planning of these surveys, and for the interpretation of the results, it is important to have solid $z = 0$ benchmarks. This paper summarizes some of the results of local extragalactic 21-cm surveys and their implications on the interpretation of the evolution of the Universe's cold gas supply.

1. Introduction

The Square Kilometer Array (SKA) will revolutionize our understanding of the cold gas properties of galaxies. Neutral hydrogen (HI) 21-cm emission line surveys with the SKA will for the first time allow measurements of the gas content of galaxies beyond the current redshift limit of $z \sim 0.2$, set by the sensitivity levels of present-time radio telescopes. These surveys will help understand the role of gas in galaxy evolution through, e.g., accurate measurements of the HI gas mass function and hence of reliable and unbiased measurements of the cosmic HI mass density Ω_{HI} out to redshifts $z \sim 2.5$ (van der Hulst et al. 2004). The interpretation of future SKA HI surveys is very much dependent on well-determined $z = 0$ anchor points, many of which are the outcome of local extragalactic 21-cm surveys. In this short paper I summarize some of the results of these local surveys and discuss how they help in interpreting high z results.

2. Local blind 21-cm surveys

A number of blind extragalactic 21-cm surveys were carried out in the 1970s and 80s, but generally these surveys lacked the sensitivity and sky coverage needed to detect large numbers of galaxies. Larger scale, sensitive surveys were first carried out with the Arecibo Telescope, resulting in samples of 66 (Zwaan et al. 1997), 75 (Spitzak & Schneider 1998), and 265 (Rosenberg & Schneider 2000) extragalactic 21-cm detections. These surveys were followed up by optical observations, which identified all 21-cm detections away from the Galactic Plane where dust extinction is high. One of the most important lessons to be learned from these early surveys is therefore that the galaxy population uncovered by 21-cm surveys is very similar to that seen by optical surveys, i.e., 'dark galaxies' that contain just gas (and dark matter), but somehow have been unable form a stellar component, are extremely rare or nonexistent (see also Doyle et al. 2005).

'Multibeam' systems on large radio telescopes allow much more efficient blind surveys. For example, with the multibeam system on the Parkes Radio Telescope, the sky can be surveyed at 13 independent positions simultaneously. This instrument was used for the large HI Parkes All Sky Survey (HIPASS), which covered two thirds of the sky out to 12.700 km/s, and uncovered 5317 extragalactic HI emission line signals (Meyer et al. 2004; Wong et al. 2006). With such large sample sizes, interesting statistics can be done, such as studies of the effect of environment on the shape of the HI mass function (Zwaan et al. 2005a), spatial clustering properties through the 2-pt correlation function (Meyer et al. 2006), the relation between weak Ly α absorbers and 21-cm emission (Ryan-Weber 2006), etc.

3. The gas mass function is 'flat'

Traditionally, the tool that is used to describe how the Universe's HI gas supply is distributed over galaxies, is the HI mass function. Originally introduced by Briggs (1990) as a diagnostic tool for assessing the completeness of optical galaxy catalogues against 21-cm HI surveys, it is now mainly used as in input in galaxy formation and evolution models (see e.g. Mo et al. 2005 for an example). The slope of the HI mass function gives the relative importance of low mass galaxies compared to L* galaxies, the integration over the mass function defines the cosmological mass density of HI gas, and the dependence of its shape on local densities gives information on environmental effects on gas in-fall and star formation efficiency. Measuring the shape and normalization of the HI mass function at intermediate redshifts will undoubtedly be an important science objective for the SKA.

The HIPASS results allowed the construction of a very accurate gas mass function of galaxies in the local Universe (see Fig. 1). The HIPASS catalogue contains at least one order of magnitude more galaxies than delivered by all other blind HI surveys prior to HIPASS, and the selection function is very well understood (Zwaan et al. 2004). Interestingly, the shape of the HIPASS gas mass function is in good agreement with the earliest estimates from Arecibo surveys, but the accuracy of the galaxy space density measurements has improved enormously. The HI mass function is now well defined over almost four decades of

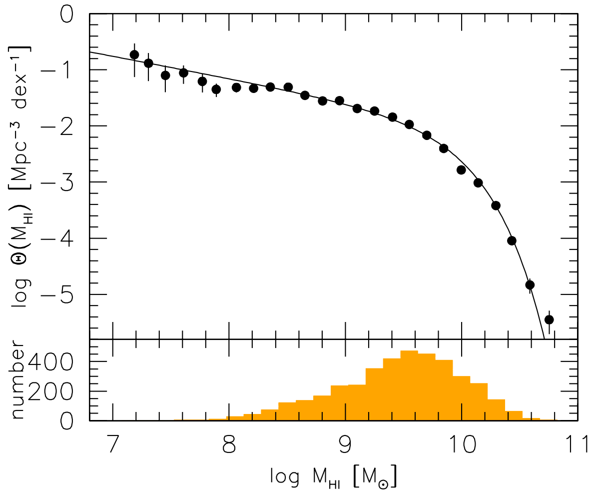

Fig. 1. The HI mass function in the local Universe as measured from HIPASS. The solid line is the best-fit Schechter function with $\alpha = -1.37$. The histogram shows the number of galaxies as function of HI mass in the HIPASS sample (see Zwaan et al. 2005a).

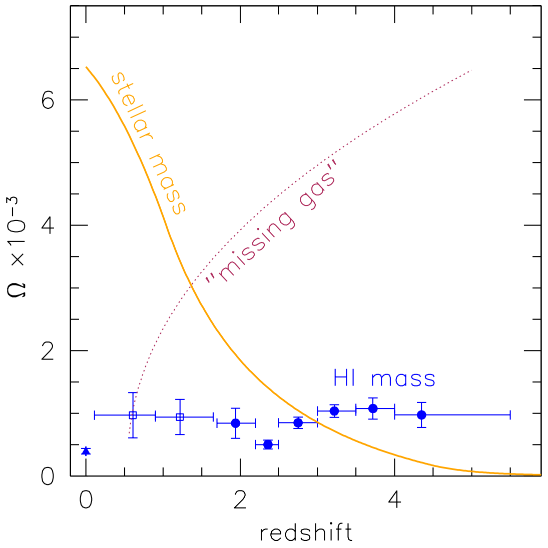

Fig. 2. The cosmic evolution of HI gas mass density compared to the build up of stellar mass. The latter was calculated by integrating the star formation rate density as parametrized by Hopkins & Beacom (2006).

HI mass ($M_{\mathrm{HI}} = 10^7\mathrm{M}_\odot - 10^{11}\mathrm{M}_\odot$), and its shape can be fitted satisfactorily with a Schechter function with a low-mass slope of $\alpha = -1.37$. Somewhat flatter and steeper slopes were reported previously by Zwaan et al. (1997) and Rosenberg & Schneider (2002), respectively, based on smaller scale surveys.

This relatively flat slope of the HI mass function has important implications for future 21-cm surveys at intermediate redshifts. A flat slope implies that L* galaxies contribute most to the total HI gas mass density and therefore surveys sensitive to HI masses just below that of an L* galaxy will probably be able to capture most of the cosmic HI gas. Unless the slope increases dramatically toward higher redshifts, SKA 21-cm emission line surveys at intermediate redshifts probably should be able to determine Ω_{HI} reliably without having to probe far below the knee of the HI mass function. However, actually measuring the change of the shape of the HI mass function as function of redshift is an important science goal too, of course.

4. The cosmic HI gas mass density evolves slowly

Much observational effort is directed to measuring the rate at which galaxies convert their gas content into stars over cosmic time. Ultraviolet and far-infrared observations of galaxies at various redshifts indicate that the cosmic star formation rate density increases in the young Universe, then reaches a peak around $z = 2.5$ (some 2.7 Gyr after the Big Bang), after which it slowly declines to the present value, a factor 10 lower than that at the peak (e.g. Hopkins & Beacom 2006). In a closed box model, the star formation rate density is the first time derivative of the HI gas mass density, Ω_{HI}. Therefore, based on the evolution of the star formation rate density, one would naively expect that Ω_{HI} evolves strongly too. Precise measurements of Ω_{HI} as function of look-back time are required to understand the processes that govern gas consumption.

A good measurement of the HI mass density in the $z = 0$ Universe is obtained by taking the integral over the HI mass function. Using the HIPASS data, we arrive at a value $\Omega_{\mathrm{HI}} = (3.5 \pm 0.4) \times 10^{-4} h_{75}^{-1}$ (Zwaan et al. 2005a). In our current pre-SKA time, HIPASS-like surveys are only feasible at $z = 0$, so we need other probes than 21-cm to get some handle on Ω_{HI} at redshifts $z > 0$. The Ly α absorption lines seen in the spectra of bright background quasars provide good tools to study neutral gas at higher redshift. The absorption technique allows detection of HI at any redshift out to which quasars are found: the signal strength depends on the brightness of the background lighthouse and the HI column density only, not on the mass of the HI cloud. The strongest Lyα absorption lines known as damped Lyα (DLA) systems have HI column densities in excess of $2 \times 10^{20}\mathrm{cm}^{-2}$, and are proven to contain some 80% of the neutral hydrogen atoms in the Universe (Péroux et al. 2005). These DLAs have been used to determine Ω_{HI} over the redshift range from $z = 1.7$ (above which the Lyα line is observable through the Earth's atmosphere) to $z \sim 5$ (Prochaska et al. 2005). Below the atmospheric cut-off at $z = 1.7$, Rao et al. (2006) used HST UV observations of the Lyα line in MgII-systems and the incidence rate of these systems to estimate Ω_{HI}. Together, the surveys of DLAs at high z, studies of MgII systems at intermediate z, and 21-cm surveys at $z = 0$ provide the data to chart the cosmic evolution of Ω_{HI}.

Up to a few years ago, the Ω_{HI} data were interpreted in such a way that all the baryons locked up in stars today, were once contained in neutral hydrogen reservoirs associated with DLAs (e.g. Lanzetta et al. 1995). This idea was supported by the observation that the HI mass density in DLAs at $z \sim 4$ was equal to the mass density in stars today (Storrie-Lombardi et al. 1996). Furthermore, the cosmic HI supply slowly declined in time, consistent with a gradual conversion of gas to stars. This convenient interpretation was troubled by *i)* more modern cosmological parameters (Spergel et al. 2003) that caused the high redshift gas density measurements to drop, and *ii)* a better measurement of the stellar mass density at the present epoch, which came out higher than before (e.g. Rudnick et al. 2003). This now indicates that there was not nearly enough HI mass at earlier times to make up for all today's stellar mass (see Fig. 2).

Obviously, the closed-box model does not work. A large fraction of the gas at high z is hot and ionized and therefore undetectable as Ly-α or 21-cm absorption (see e.g. Davé et al. 1999). This gas can cool and condense onto galaxies thereby generating a continuous flow of fuel for the build up of stellar mass.

Secondly, we might still miss some of the HI gas at high redshift due to a dust bias in QSO absorption lines studies where obscuration in the foreground absorbing cloud causes the apparent luminosity of the background QSO to drop below the detection limit of the QSO survey. The jury is still out on the importance of this effect. For example, Vladilo & Péroux (2005) argue that the dust bias could lead to an underestimation of the gas mass density at high z of at least a factor two. On the other hand, DLA surveys in radio-selected quasars, in which optical dust extinction should not play a role, do not yield a significantly higher $\Omega_{\rm HI}$ measurement (Ellison et al. 2001; Jorgenson et al. 2006). An analysis of reddening in SDSS quasars spectra with and without DLAs (Murphy & Liske 2004) also points to an insignificant dust bias.

And finally, some fraction of the "missing" gas might be locked up in molecules. Molecules are very easy to hide in surveys. Zwaan & Prochaska (2006) recently showed that in the local Universe the redshift number density of H_2 absorbers with column densities $> 10^{21}\rm cm^{-2}$ is approximately a factor 150 lower than that of DLAs. Still these column densities contain some 97% of the cosmic H_2 mass density. Furthermore, we showed that these very rare systems are associated with the bulk of the star formation in the Universe. Also, since the volume averaged star formation rate density was obviously higher by a factor of ten at the time corresponding to redshifts $z = 2.5$, we might expect a larger mass density of molecules at these times.

In order to understand the relative importance of each of these solutions, it is essential to know exactly the amount of gas – both atomic and molecular – at all redshifts. Deep SKA 21-cm redshift surveys will measure the HI content, and possibly also the molecular mass density through surveys of the CO(1-0) and HCO$^+$(1-0) lines at high redshift.

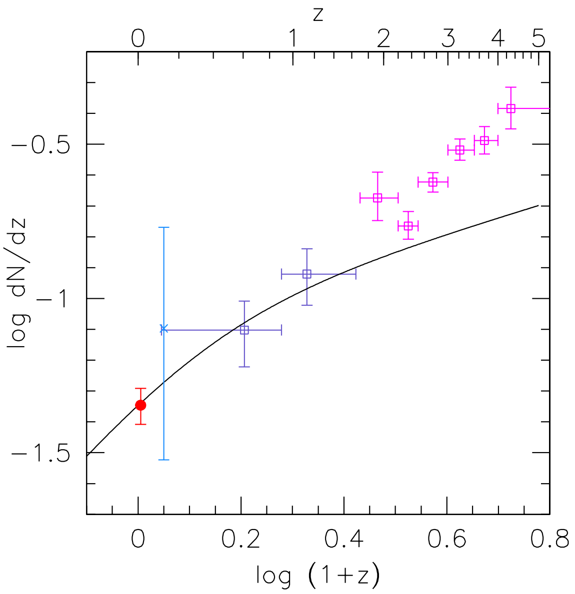

Fig. 3. The redshift number density dN/dz of damped Lyα systems. The line corresponds to "no evolution in the product of cross section and co-moving space density". See Zwaan et al. (2005b) for references to the various measurements.

5. The HI column density distribution does not evolve much

In the previous section I discussed the evolution of the Universe's total HI content. Before the SKA becomes operational, we have no means of determining how this HI is divided between galaxies of different mass, except for at $z = 0$. There are, however, other statistics that can tell us something about the properties of HI gas over cosmic time. One such measurement is dN/dz, the redshift number density of HI gas above the DLA limit, i.e., the number of HI clouds per unit z encountered along a random sightline through the Universe. Figure 3 shows this measurement at various redshifts, together with a curve representing "no evolution in the product of cross section and co-moving space density". Obviously, this diagram suggests that the number of HI systems above the DLA threshold per comoving unit of length does not evolve after the time corresponding to $z \sim 1$, or more than half the age of the Universe. At present, it is difficult to ascertain whether this should be interpreted as no evolution in the DLA population—meaning no change in the space density and size of DLA absorbing systems—or as a combined effect where an evolving space density is compensated by a change in mean absorber size. SKA deep 21-cm surveys will help answering this question.

Another measurement is the HI column density distribution function $f(N_{\rm HI})$, which describes the relative abundance of different HI column densities per normalized interval dX. This dX is calculated such that $f(N_{\rm HI})$ is expressed per co-moving path length so that it can be compared directly at all redshifts. Zwaan et al. (2005b) recently calculated $f(N_{\rm HI})$ at $z = 0$ by analyzing HI 21-cm

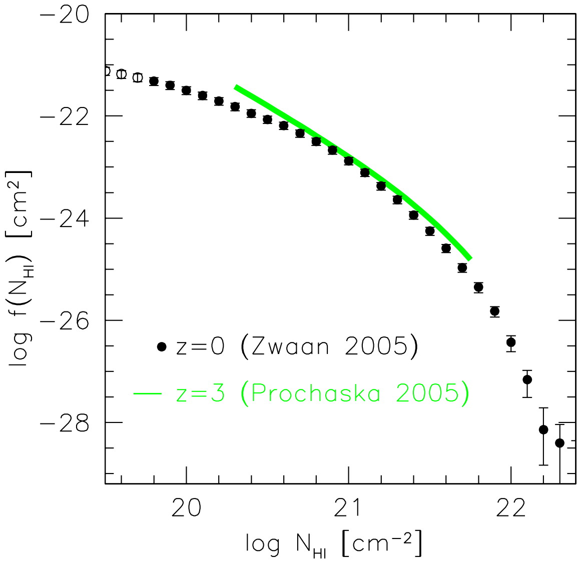

Fig. 4. The HI column density distribution function $f(N_{\rm HI})$ at $z = 0$ (black dots) compared to the measurement from DLAs at a median redshift of $z = 3$.

emission line maps of $\sim$ 350 galaxies from the WHISP survey. In Figure 4 we reproduce the result and also show the $f(N_{\rm HI})$ measurement from Prochaska et al. (2005), based on DLA systems identified in SDSS quasar spectra.

The surprising result from this figure is that there appears to be only very mild evolution in the intersection cross section of H I from redshift $z \sim 4$ to the present. Furthermore, the shape of the $f(N)$ distribution is identical at high redshift and at $z = 0$. This is particularly remarkable given the completely independent observational techniques that were used to derive the two distributions: 21-cm emission line maps of galaxies at $z = 0$ versus Lyα absorption line profiles of DLAs at high z. This similarity must at least be telling us that the processes that shape the $f(N)$—ionization of H I at the low N end and formation of H_2 at the high N end—must be very similar at these different moments in the history of the Universe. This diagram is also telling us that the local galaxy population explains the incidence rate of low and intermediate z DLAs and there is no need for a population of hidden very low surface brightness (LSB) galaxies or isolated H I clouds (dark galaxies).

6. Concluding remarks

The results of local 21-cm surveys, combined with those of quasar absorption line studies, provide a rough picture of the evolution of the cold gas. However, many questions related to the role of gas in galaxy evolution remain unanswered until the SKA opens up a new window on the Universe by enabling deep 21-cm surveys at high z. This paper discussed some aspects related to the general topic of the evolution of neutral gas, but ignored some other very important topics, such as the study of very low column density HI and HI absorption observations.

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