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Local H I: Constraints on the Evolution of the H I Content of the Universe

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Abstract: Analyses of QSO absorption lines show that the H I content has evolved over the redshift range $z = 5$ to $z = 0$. The 21-cm line measurements of the $z = 0$ H I content avoid several biases inherent in the absorption-line technique, such as the influence of evolving dust content in the absorbers, and will produce a reliable measure to anchor theories of galaxy evolution. Examples of important questions to be addressed by local H I surveys are: (1) Is there a significant population of gas-rich galaxies or intergalactic clouds that is missing from the census of optically selected galaxies? (2) Is there an adequate reservoir of neutral gas to substantially prolong star formation at its present rate? (3) Are there massive objects of such low HI column density that they can have escaped detection in the 'unbiased' H I surveys that have been conducted so far?

Keywords: galaxies: distances and redshifts — galaxies: compact — galaxies: formation — radio lines: galaxies

1 Evolution of the H I Content

A measurement of the total H I content contained in nearby galaxies and H I clouds is an important constraint in the bigger picture of galaxy evolution on cosmological timescales. Although the neutral gas in large galaxies at present is often considered to be a minor component that is used as a tracer for kinematics or as a dwindling source of fuel for star formation, there is now strong evidence from studies of QSO absorption lines that the present HI content of the Universe is but a fraction of what it was at redshift $z \approx 3$. This finding comes from the statistics of the 'damped Lyman-α' class of absorption line that is identified with dynamically cold layers akin to the disks of familiar nearby spiral galaxies (Wolfe et al. 1986; Lanzetta, Wolfe & Turnshek 1995; Storrie-Lombardi et al. 1996). Figure 1 summarises the presently available measurements of the neutral gas content as a function of z (Storrie-Lombardi et al. 1996), alongside a plot of the incidence of C IV absorption lines, which provide an indication of the cross section presented by clouds of ionised, metal-rich gas (Steidel 1990; Bahcall et al. 1993), and the comoving density of luminous optically selected QSOs (Schmidt, Schreider & Gunn 1994; Hewett, Foltz & Chaffee 1993). Taken literally, the evidence points to an epoch around $z \approx 3$ when the neutral gas mass density, Ω_g, hit a maximum, at roughly the same time that the C IV cross section for strong absorption lines ($W_{\rm rest}(\lambda1548) > 0{\cdot}15$ Å) began a sharp increase. This is also a time when luminous QSOs were most abundant. These indicators testify that we are seeing substantial redistribution of gas, as witnessed by the formation of ionised metal-rich galaxy halos and the efficient fueling of active galactic nuclei. The surge in neutral gas content indicates that protogalactic gravitational potentials were deep enough that gas was confined to sufficiently high density that it was at least momentarily immune to ionisation by starbursts and ionising background radiation. This may be the epoch at which disk galaxies formed as secondary infall of gas occurred into galactic potentials formed in the first round of galactic bulge formation. The disk formation would be accompanied by halo enrichment, either by in situ star formation or by metal pollution of the extended halo region by winds from the new star-forming regions of the disk. An alternative view is that this is also likely to be an epoch when small protogalactic lumps are merging vigorously, and starburst within the lumps would be effective in ejecting metals into an extended region that would at later times constitute the 'halo' region of the merger product.

Figure 1 summarises only the neutral atomic and ionised gas components. A complete balance requires an accounting for all the Universe's baryons, as gas is exchanged between neutral, ionised, and molecular phases, as well as the path of stellar evolution leading to the current state where far more baryons are contained in stars than in neutral gas. Although the present H I content is only ~10% of the mass in stars, there was a period at $z \approx 2{\cdot}5$ when the H I content apparently was of order half of the

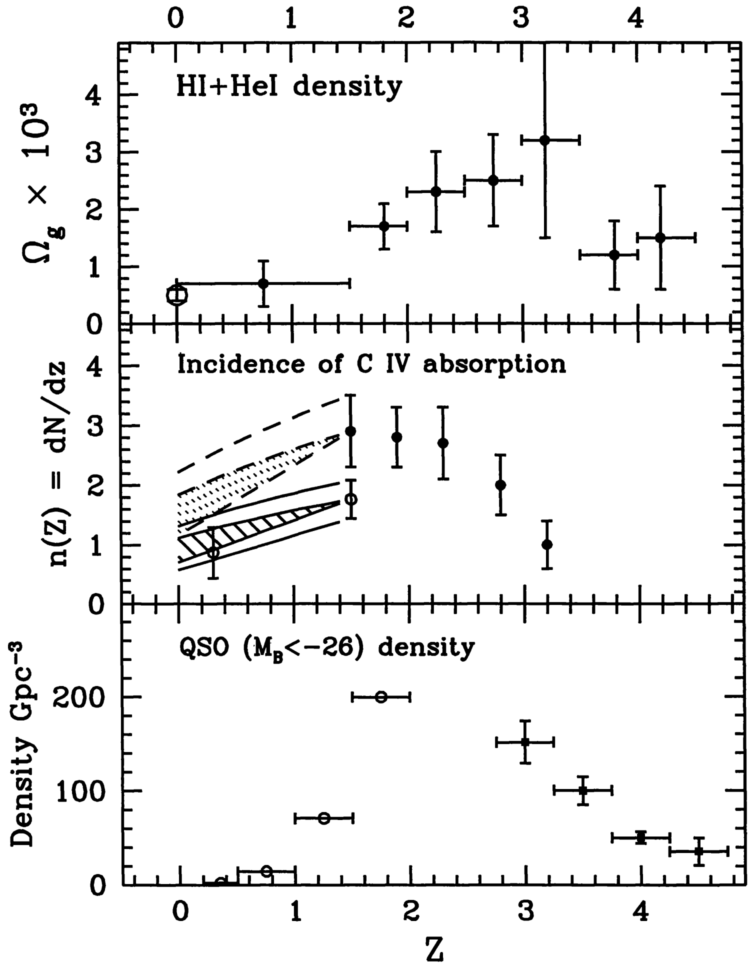

Figure 1—Cosmological density of neutral gas, incidence of C IV absorption, and comoving density of luminous QSOs as a function of redshift. (*Top*) Mean cosmological density of neutral gas, Ω_g, normalised to the critical density (Storrie-Lombardi et al. 1996; Rao, Turnshek & Briggs 1995 ($z = 0$); Storrie-Lombardi & Wolfe, private communication). (*Middle*) Number of C IV metal-line absorption systems per unit redshift, $n(z)$ (Steidel 1990); $z = 0 \cdot 3$ point from Bahcall et al. (1993). Filled points from Steidel indicate rest-frame equivalent widths $W_{rest}(\lambda 1548) > 0 \cdot 15$ Å; open points are for $W_{rest}(\lambda 1548) > 0 \cdot 3$ Å. Hatched areas indicate the range ($0 < q_0 < \frac{1}{2}$) for unevolving cross sections since $z = 1 \cdot 5$, beyond which redshift C IV can be measured with ground-based telescopes. (*Bottom*) Comoving density of optically selected QSOs: filled squares from Schmidt et al. 1994; open circles from Hewitt et al. (1993). $H_0 = 50$ km s^{-1} Mpc^{-1}, $q_0 = \frac{1}{2}$.

present stellar mass. Estimates of the mass content in ionised halos suggest that they probably contain about ten times the mass contained in the damped Lyman-α absorbers at their peak (Petitjean et al. 1993). This interpretation of the C IV data relies on theoretical modelling, with large uncertainties due to ionisation level and carbon abundance. It is striking that the recent HST observations (Bahcall et al. 1993) are consistent with no evolution in the absorption cross section presented by high column density C IV systems from $z \approx 1 \cdot 3$ (Steidel 1990) to $z \approx 0 \cdot 3$, implying that large quantities of ionised gas may still be present, either in the form of extended halos or in intergalactic clouds whose mass could far exceed the visible stellar mass in galaxies. It has been argued that the C IV systems, together with the more diffuse clouds of the Lyman-α forest, may contain a substantial fraction of the baryon content of the Universe (Rauch & Haehnelt 1995; Haehnelt, Steinmetz & Rauch 1996). The hydrogen neutral fraction of these ionised clouds would provide column densities of H I well below the regime ordinarily probed by 21 cm line observations. At present, the molecular gas mass content of galaxies appears to be roughly equal to the neutral atomic mass (cf. Kennicutt, Tamblyn & Congdon 1994).

Surveys of nearby volumes in the 21 cm line are important in anchoring the $z = 0$ point of Figure 1. A complete inventory of neutral gas in the nearby Universe, of the sort that is being provided by

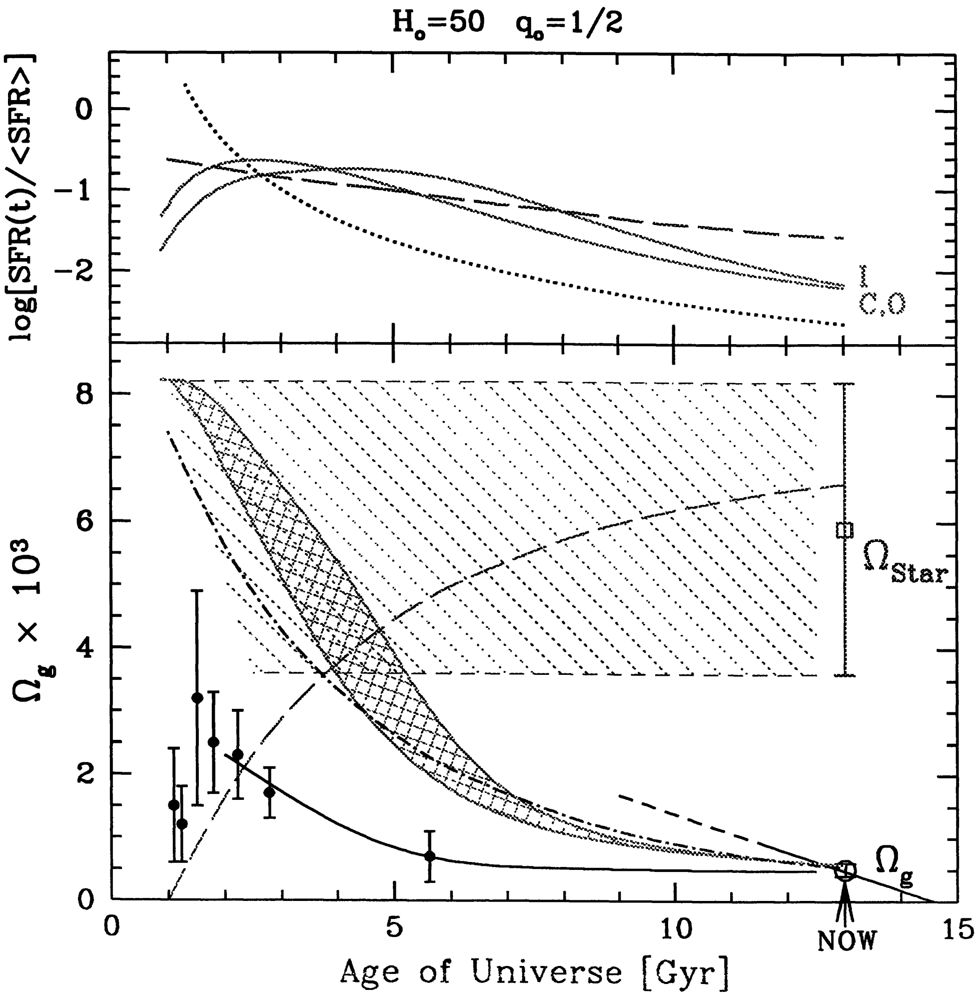

Figure 2—Star formation rate (SFR) and density $\Omega_g(t)$ of neutral gas as a function of time compared with $\Omega_{stars}(z=0)$. (*Bottom*) $\Omega_g(t)$ from references in Figure 1; Ω_{stars} $(z=0)$ from Lanzetta et al. (1995). Rising dashed curve is the KTC model for increasing stellar mass; the dot–dash is the KTC model for declining cold gas content, adjusted as described in text to indicate only the atomic fraction. The cross-hatched band indicates the range of models proposed by Pei & Fall for the true $\Omega_g(z)$, corrected for selection effects caused by dusty damped Lyman-α absorbers. (*Top*) Relative star formation rate for models by Lanzetta et al. (1995) (dotted), KTC (dashed), and Pei & Fall (1995) (solid: I = model with infall; C,O = 'closed box' and outflow models).

unbiased 21 cm line surveys, will have tight error bars and thus will carry large statistical weight in models that describe the evolution of Ω_g. Note that the statistical errors of the $z > 1 \cdot 6$ measurements of Ω_g are so large that these high-z points are consistent with no evolution at all. In principle, the low-z regime $(0 < z < 1 \cdot 6)$ of the diagram can be measured using QSO absorption-line methods in much the same way as the high-z points. However, the observations are difficult since the Lyman-α line is not redshifted into the optical window until $z \geq 1 \cdot 6$, so the low-z absorption-line work must be done from space observatories such as IUE and HST (Lanzetta et al. 1995; Rao et al. 1995).

When the data points are plotted as a function of time, as in Figure 2, it is clear that the single low-z QSO absorption-line point applies to a time span much longer than half the age of the Universe. Several selection effects make it difficult to obtain a reliable sampling of damped Lyman-α absorbers at low z. Cosmological factors, as well as the apparent shrinking of the damped Lyman-α absorption cross section, $\sigma(t)$, with increasing age of the Universe (Lanzetta et al. 1995), act to make them very rare at recent times: $dN/dt \propto \sigma(t)t^{-k}$, where $k = 2$ for $q_0 = \frac{1}{2}$ and $k = 3$ for $q_0 = 0$. There are also selection effects that are likely to influence the QSO absorption-line measurements and that affect the low-z measurement most strongly: (1) The presence of dust in disk galaxies is expected to become increasingly important as they evolve, and may act to selectively attenuate the light from QSOs behind them, causing these lines of sight to be under-represented in QSO samples (Fall & Pei 1989; Pei & Fall 1995; Webster et al. 1995) although this view is contested (Boyle & Di Matteo 1995). (2) Gravitational lensing may act to selectively amplify background objects into QSO samples, but also may bend the light path so as to dodge the high HI column densities of the disk (Bartelmann & Loeb 1996; Smette et al. 1995*a*, 1996).

Figure 2 includes curves to indicate trends in stellar evolution relative to the decline in Ω_g with time. Recent analyses of the depletion of the neutral gas content of galaxies over cosmological times due to star formation have been presented by Lanzetta et al. (1995) and Pei & Fall (1996). A related study by Kennicutt et al. (1994, KTC) addresses the prolonging of the current star formation rate in $z \approx 0$ disks due to delayed gas return as stellar populations age. An example of the KTC models is presented in Figure 2 to illustrate both the rise of stellar mass with time and the decline of neutral gas content with time for a disk system without added inflow or allowing mass to escape. For this display, the KTC model has been scaled so that the final stellar mass and the final H I mass are consistent with the observations at $z \approx 0$; the relative proportion of H I to H_2 has been adjusted for this display to vary linearly with time from $\rho_{HI}/(\rho_{HI}+\rho_{H2}) = 1$ at high z to $\frac{2}{3}$ at the present time. The slope of the KTC model at the time marked 'Now' in Figure 2 can be compared with the steeper slope drawn to indicate the rate at which the current star formation rate would consume the present atomic hydrogen content, exhausting the supply in only ~1·5 Gyr if there were no additional reservoirs of molecular gas or contribution from delayed stellar return.

The models of Lanzetta et al. require a balance between the decline of Ω_g and a rise in stellar mass; along with assumptions that stellar return occurs instantaneously as each generation of stars is formed, this constrains the mean star formation rate history of the Universe. In this picture, the star formation rate as a function of time has a surge at early epochs (see top panel in Figure 2) when little metal enrichment has occurred. A consequence is that their models produce uncomfortably large numbers of stars at $z \approx 0$ with low metal abundances. Pei and Fall suggest that this problem can be solved with a family of dusty models, which implies that the damped Lyman-α statistics drastically underestimate the neutral gas content at all redshifts. In the Pei and Falls models, the peak star formation rate is delayed to an epoch at $z \approx 1$ to 2 when the ISM has acquired higher metal abundances. The KTC models that are tuned to describe the ecology of large galaxy disks have a more nearly uniform, gently declining star formation rate. The current generation of radio telescopes is not sensitive enough to resolve this controversy by simply looking back to measure the H I density at $z \approx \frac{1}{2}$. On the other hand, choosing complete samples of radio-selected high-z quasars for background probes would remove possible selection effects due to dust.

At $z = 0$, recent 21 cm line measurements indicate that the bulk of the atomic hydrogen content of the nearby Universe is bound into galaxies with optical counterparts (Zwaan, Sprayberry & Briggs 1997, present issue p. 117; Schneider 1997, present issue p. 99; Szomoru et al. 1994; Henning 1995; Briggs 1990). Furthermore, the normalisation of the HI mass function seems to be well understood (cf. Zwaan et al. 1997; Rao & Briggs 1993), although there is still concern over the normalisation of even the optically determined luminosity function (cf. Ellis et al. 1996; Glazebrook et al. 1995). Clearly the determination of the integral H I content of the local Universe is a measurement that the Parkes Multibeam Survey will clarify, since it will be complete, unbiased by extinction and optical surface brightness, and will have well understood sensitivity limits.

2 Distribution of N_{HI} Column Densities

Another place where future surveys can play an important role will be in exploring lower H I column densities than have been observed in the 21 cm line in the past. QSO absorption-line statistics over a wide range of Lyman-α line strengths specify that the incidence of absorption becomes increasingly prevalent toward lower column densities, so that along a randomly chosen sight line, the probability of interception rises by roughly a factor of 10 for every decrease by a factor of 100 in N_{HI}. This behaviour is quantified by the $f(N_{HI})$ distribution, defined so that $f(N_{HI})\,dX/dN_{HI}$ is the number of lines detected within a range dN_{HI} centred on N_{HI} over a 'normalised absorption distance' dX, where $X = \frac{1}{2}[(1+z)^2 - 1]$ is the normalised absorption distance from zero redshift to z for $q_0 = 0$. The function $f(N_{HI})$ is roughly proportional to $N^{-1\cdot 5}$ over the range $N_{HI} = 10^{13}$–10^{22} cm^{-2}, although there is evidence for subtle structure possibly related to opacity in the Lyman continuum that occurs for layers with $N_{HI} > 3{\times}10^{17}$ cm^{-2} (Petitjean et al. 1993). At high redshift, the frequency of absorption for these optically thick absorbers is ~0·9 per unit X (Petitjean et al. 1993); for $N_{HI} > 10^{18}$ cm^{-2}, the frequency is roughly halved. The derivation of the $f(N_{HI})$ at these N_{HI} is especially uncertain, since the entire Lyman series is heavily saturated in the regime where the Lyman continuum is optically thick, and the damping wings, which permit an unambiguous measure of column density, do not become readily observable until N_{HI} is well in excess of 10^{20} cm^{-2}. Thus column density measurements in this regime are very uncertain, leading Petitjean et al. to plot only one point on their $f(N_{\rm HI})$ diagram for $10^{17\cdot 7}$–$10^{20\cdot 5}$ cm^{-2}.

Recent large H I surveys with filled-aperture telescopes are routinely capable of detecting column densities below 10^{19} cm^{-2} (Schneider 1997; Zwaan et al. 1997; Briggs et al. 1997, following paper p. 37), provided the emission fills the telescope beam. The Arecibo survey by Sorar (1994; see also Briggs & Sorar 1996) was optimised to be sensitive to $N_{\rm HI} = 10^{18}$ cm^{-2} (5σ), and the survey observed over 5000 independent beam areas to a depth of 7500 km s^{-1}, covering a total absorption path $\Delta X \approx 120$. The Arecibo beam subtends ~3 kpc at 3 Mpc and 70 kpc at 75 Mpc, which is a reasonable match to the cloud sizes deduced for the Lyman-α forest (cf. Smette et al. 1992, 1995*b*). To date, only one of the 61 detections (Zwaan et al. 1997) has not been identified with a high column density layer of the type associated with the neutral intergalactic medium of a galaxy, implying that a separate population of low column density objects can add only a small fraction of the current HI content already identified with galaxies.

The high redshift $f(N_{\rm HI})$ distribution would imply of order 50 interceptions in the range 10^{18} to 10^{19} cm^{-2} for the pathlength X explored by the Arecibo survey. Where are they? At least a part of the discrepancy is likely due to evolution of the Lyman-α forest cloud population. An additional observational problem is that the high column density end of the forest cloud distribution (around 10^{17} cm^{-2} and above) has associated metal lines, such as C IV and Mg II, which has historically caused them to be identified with hypothetical galaxy halos; single-dish observations seldom have the resolution to reliably separate the HI signal from a halo of a spiral galaxy from the bright signal originating in the main body of the galaxy, unless there are strong kinematic effects that create a difference in gas velocity as a function of radius and the halo gas is very extended.

Further considerations in the study of this intermediate column density range are the theoretical models that consider ionisation of extended gas around galaxies by the extragalactic ionising background (Sunyaev 1969; Corbelli, Schneider & Salpeter 1989; Maloney 1993; Charlton, Salpeter & Linder 1994). Many of these models predict a strong dip in $f(N_{\rm HI})$ between $10^{17\cdot 5}$ and $10^{19\cdot 5}$ cm^{-2}. If similar arguments apply to a population of intergalactic clouds or super-LSB galaxies, then an interesting experiment now coming into the realm of possibility will be to push the sensitivity limits of the local H I emission observations down to ~10^{17} cm^{-2} where ionised layers of high column density might be detected.

3 Where to Find 'HI Clouds' Now

Some very interesting examples of H I without coincident optical emission have turned up by chance in 'off-scans' from 21 cm line studies (Schneider 1989; Giovanelli & Haynes 1989; Giovanelli & Maynes Chengalur 1995; Giovanelli et al. 1995), although all of these detections appear to be associated in some way with nearby visible galaxies. For example, the protogalaxy of Giovanelli & Haynes (1989) now appears in VLA observations to more closely resemble a galaxy with tidal remnant (Chengalur et al. 1995) than a single large cloud. An interesting consequence of high-sensitivity VLA surveys of H II galaxies and LSB dwarfs (Taylor, Brinks & Skillman 1993; Taylor, Thomas & Skillman 1996) is an apparent increased probability of finding dim H I-rich companions to the H II galaxies as compared with the LSBs. This kind of study will not be possible with the crude resolution of single-dish surveys. The tendency of small galaxies to be found in the vicinity of large ones rather than in isolated regions (cf. Szomoru et al. 1996) will complicate the derivation of a H I-mass function that extends to faint masses when survey observations are made with a large beam. On the other hand, isolated HI clouds (if they exist) and HI clouds associated with early-type galaxies, such as polar rings and fresh examples of the Leo Ring (Schneider 1989), should be readily identified if confusion with other galaxies in the same field is not too much of a problem.

4 Conclusion

Large sky surveys in the 21 cm line will improve the measurement of the $z \approx 0$ H I content of the Universe, and this value will find immediate use in anchoring theories of galaxy evolution. Telescopes with large beams will suffer from confusion, which will complicate the determination of the faint-end slope of the H I-mass function. Observation of the low column density regime with $N_{\rm HI} < 10^{18}$ cm^{-2} is a new frontier that awaits exploration in the local universe and may be capable of sensing the tip of the ionised intergalactic cloud distribution.

Bahcall, J. N., et al. 1993, ApJS, 87, 1
Bartelmann, M., & Loeb, A. 1996, ApJ, 457, 529
Boyle, B. J., & Di Matteo, T. 1995, MNRAS, 277, L63
Briggs, F. H. 1990, AJ, 100, 999
Briggs, F. H., & Sorar, E. 1996, in Cold Gas at High Redshift, ed. M. N. Bremer et al. (Dordrecht: Kluwer), p. 285
Briggs, F. H., Sorar, E., Kraan-Korteweg, R. C., & van Driel, W. 1997, PASA, 14, 37
Charlton, J. C., Salpeter, E. E., & Linder, S. M. 1994, ApJ, 430, L29

Chengalur, J. N., Giovanelli, R., & Haynes, M. P. 1995, AJ, 109, 2415
Corbelli, E., Schneider, S. E., & Salpeter, E. E. 1989, AJ, 97, 390
Ellis, R. S., Colless, M., Broadhurst, T., Heyl, J., Glazebrook, K. 1996, MNRAS, 280, 235
Fall, S. M., & Pei, Y. C. 1989, ApJ, 337, 7
Giovanelli, R., & Haynes, M. P. 1989, ApJ, 346, L5
Giovanelli, R., Scodeggio, M., Solanes, J. M., Haynes, M. P., Arce, H., & Sakai, S. 1995, AJ, 109, 1451
Glazebrook, K., Ellis, R., Santiago, B., & Griffiths, R. 1995, MNRAS, 275, L19
Haehnelt, M. G., Steinmetz, M., & Rauch, M. 1995, ApJ, 465, L95
Henning, P. A. 1995, ApJ, 450, 578
Hewett, P. C., Foltz, C. B., & Chaffee, F. H. 1993, ApJ, 406, L43
Kennicutt, R. C., Tamblyn, P., & Congdon, C. W. 1994, ApJ, 435, 22 (KTC)
Lanzetta, K. M., Wolfe, A. M., & Turnshek, A. M. 1995, ApJ, 440, 435
Maloney, P. 1993, ApJ, 414, 41
Pei, Y. C., & Fall, S. M. 1995, ApJ, 454, 69
Petitjean, P., Webb, J. K, Rauch, M., Carswell, R. F., & Lanzetta, K. M. 1993, MNRAS, 262, 499
Rao, S. M., & Briggs, F. H. 1993, ApJ, 419, 515
Rao, S. M., Turnshek, D. A., & Briggs, F. H. 1995, ApJ, 449, 488
Rauch, M., & Haehnelt, M. G. 1995, MNRAS, 275, L76
Schmidt, M., Schneider, D. P., & Gunn, J. E. 1994, AJ, 107, 1245
Schneider, S. E. 1989, ApJ, 343, 94
Schneider, S. E. 1997, PASA, 14, 99
Sorar, E. 1994, PhD thesis, University of Pittsburgh
Smette, A., Surdej, J., Shaver, P. A., Foltz, C. B., Chaffee, F. H., Weymann, R. J., Williams, R. E., & Magain, P. 1992, ApJ, 389, 39
Smette, A., Claeskens, J. F., & Surdej, J. 1995*a*, in Astrophysical Implications of Gravitational Lensing, Proc. IAU Symp. 173, ed. C. S. Kochanek & J. N.
Hewitt (Dordrecht: Kluwer), p. 99
Smette, A., Robertson, J. G., Shaver, P. A., Reimers, D., Wisotski, L., & Koehler, T. 1995*b*, A&AS, 113, 199
Smette, A., et al. 1997, A&A, submitted
Steidel, C. C. 1990, ApJS, 72, 1
Storrie-Lombardi, L. J., McMahon, R. G., Irwin, M. J., & Hazard, C. 1996, ApJ, 468, 121
Sunyaev, R. A. 1969, ApJ, 3, 33
Szomoru, A., Guhathakurta, P., van Gorkom, J. H., Knapen, J. H., Weinberg, D. H., & Fruchter, A. S. 1994, AJ, 108, 491
Szomoru, A., van Gorkom, J. H., Gregg, M. D., & Strauss, M. A. 1996, AJ, 111, 2150
Taylor, C. L., Brinks, E., & Skillman, E. D. 1993, AJ, 105, 128
Taylor, C. L., Thomas, D. L., Brinks, E., & Skillman, E. D. 1996, ApJS, 107, 143
Webster, R. L., Francis, P. J., Peterson, B. A., Drinkwater, M. J., & Masci, F. J. 1995, Nature, 375, 469
Wolfe, A. M., Turnshek, D. A., Smith, H. E., & Cohen, R. D. 1986, ApJS, 61, 249
Zwaan, M., Sprayberry, D., & Briggs, F. H. 1997, PASA, 14, 117