Implications of 21cm observations for damped Ly-α systems

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ABSTRACT

We present Giant Metrewave Radio Telescope HI 21cm absorption observations, of candidate and confirmed damped Lyman-α systems. The derived spin temperatures $T_{\text{spin}}$ are high, in all cases, $\sim 1000$ K or higher. We have also collated from the published literature a list of damped absorbers for which 21cm observations exist, and discuss the implications of the observations for the nature of these systems.

A cross-comparison of the HI 21cm profiles (which trace the cold gas) with the low ionization metal profiles (which trace all the neutral HI, both cold and warm) shows that in all cases for which both spectra are available, the 21cm absorption coincides in velocity with the deepest metal line feature. This is consistent with models in which the deep metal line features arise from discrete clouds but not with models where the deepest features are the result of velocity crowding.

We also find that the typical derived spin temperatures of damped Lyman-α systems are considerably higher than those in the Milky Way or nearby spiral galaxies. The only exceptions are systems which are known to be associated with the disks of spirals; these do, in fact, show low spin temperature. In a multi-phase medium the derived spin temperature is a weighted average of the temperatures of the individual phases. High apparent $T_{\text{spin}}$ values are hence to be expected from small, low metallicity objects since these objects should (as per existing theoretical models of the formation of a multi-phase ISM in the Milky Way and high redshift proto-galaxies) have a lower fraction of the cold phase in their ISM as compared to large galaxies. The high $T_{\text{spin}}$ is hence consistent with the observed low metallicities of damped Lyman-α absorbers as well as with recent findings that damped absorption is associated with a variety of galaxy types (as opposed to being confined to the disks of large spirals).

Finally, although the number of systems for which observations are available is small, we suggest that the following trend may be identified: at low redshift, damped Lyman-α absorption arises from a range of systems, including spiral galaxy disks, while, at high redshift, absorption occurs predominantly in smaller systems.

Key words: quasars: absorption lines – cosmology: observations.

1 INTRODUCTION.

A gas cloud with a column density $N_{\text{HI}} > 10^{20}$ atoms/cm$^{-2}$ produces a broad Lyman–α absorption profile with characteristic Lorentzian damping wings. Such systems can hence be easily identified from even modest resolution spectra of distant quasars. Although these high column density...
absorbers are extremely rare compared to the ubiquitous Lyman-α forest lines, they nonetheless make the dominant contribution to the observed neutral hydrogen at high redshifts.

At \( z = 0 \), the cross section for damped Lyman-α absorption is dominated by the disks of spiral galaxies (Rao & Briggs 1993). It is thus plausible that the damped systems seen at high redshift are either spiral galaxies or the precursors of spiral galaxies. In support of this hypothesis, large surveys of these objects have established that the mass density of neutral gas in damped Lyman-α systems at \( z \sim 3 \) is comparable to the mass density of stars in luminous galaxies at \( z \sim 0 \) (e.g. Wolfe, 1988, Lanzetta et al. 1991, Storrie-Lombardi et al. 1996). Further, the mass density in neutral gas today is far smaller than that at high redshift. The evolution of \( \Omega_{HI} \) with redshift thus matches the pattern expected from gas depletion due to star formation.

While the motivation for the original damped Lyman-α surveys was to find disk galaxies at high redshift (Wolfe et al. 1986), the nature of the systems in which this absorption arises remains as yet controversial. Absorption line surveys principally establish the probability of finding an absorber along a random line of sight. This probability is proportional to the product of the volume number density of the absorbers and their typical cross-section; neither of the two is separately constrained. The observed frequency of occurrence of damped Lyman-α lines in QSO spectra at high \( z \) is about 5 times larger than that expected from a population in which both the HI disk cross-section and the galaxy number density remain constant (Wolfe et al. 1986, Smith, Cohen & Bradley 1986, Lanzetta et al. 1991). The nominal conclusion is that, if damped absorption traces the precursors of spiral galaxies, then either the typical galaxy disk was somewhat larger in the past than it is now, or there were considerably more galaxies in the past than there are today.

Prochaska & Wolfe (1997,1998) attempted to settle the issue of the nature of damped absorbers in a purely observational manner, using high resolution spectra of low-ion metal transitions, to investigate the velocity structure of 31 transitions, to investigate the velocity structure of 31 systems. These low-ionization metals co-exist with neutral HI; their absorption profiles, however, are unsaturated and hence trace the kinematics of the neutral gas along the narrow line of sight to the background QSO. The authors found that the metal line profiles are systematically asymmetric (in that the deepest absorption preferentially occurs at the profile edge). Such asymmetries arise naturally in absorption from a spinning disk due to two effects (i) a “radial effect”, where the strongest absorption occurs at the tangent point, i.e. due to velocity crowding, and (ii) a “perpendicular effect” in which the strongest absorption takes place in the midplane, if the line-of-sight intersects the midplane more than a few scale heights away from the major axis. The metal line profiles thus appear to support the hypothesis that damped Lyman-α absorption arises primarily in spiral galaxy disks. This is controversial, however, since the observed asymmetries can also be explained by merging proto-galactic clumps in hierarchical models (Haehnelt et al. 1998) and even by randomly moving clouds in a spherical halo (McDonald & Miralda-Escude 1999).

At low and intermediate redshifts, there have been a number of ground-based, as well as HST, observations to try and directly image the systems responsible for the absorption (see, for example, le Brun et al. 1997). From these observations, it appears that, contrary to predictions based on the HI content of \( z = 0 \) galaxies, damped Lyman-α absorption is not associated predominantly with bright \((L > L_\star)\) spiral galaxies, but appears to arise in galaxies spanning a wide range of morphological types. Interestingly, even in quasar-galaxy pairs at very low redshift, systems which show HI absorption appear to be predominantly disturbed or interacting galaxies (Carilli & van Gorkom 1992).

If the quasar against which the Lyman-α absorption is seen is radio loud, one can also attempt to detect redshifted 21cm absorption from the damped Lyman-α system (e.g. Wolfe & Davis 1979, Wolfe, Briggs & Jauncey 1981, Wolfe et al. 1985, de Bruyn et al. 1996, Carilli et al. 1996, Lane et al. 1998, Chengalur & Kanekar 1999). Observing the 21cm line yields a number of interesting physical parameters. Firstly, since the 21cm line is not saturated, the absorption profile reflects the kinematics of the cold gas in the system. Further, (under suitable assumptions) the 21cm optical depth can be used along with the total HI column density (obtained from the damped Lyman-α profile) to yield the average spin temperature of the gas. Under a variety of astrophysical conditions (Field 1958), the spin temperature of the 21cm transition is identical to the kinetic temperature of the gas; it is hence a useful diagnostic. Finally, if the background source is extended, one can attempt to determine the transverse extent of the absorbing gas. This cannot be done using UV absorption lines since the background quasar is unresolved at these wavelengths.

We present, in this paper, Giant Metrewave Radio Telescope (GMRT) HI 21cm observations of candidate and confirmed low redshift damped Lyman-α systems. We have also collated from the published literature earlier 21cm studies of a set of such objects, and discuss the implications of these observations for the nature of the absorbers.

2 OBSERVATIONS & RESULTS

The observations were carried out in April and October 1999 as part of the commissioning of the first sideband of the 30 station correlator at the GMRT. The number of antennas available was typically \( \sim 10 \) because of various on-going debugging and maintenance activities. Both linear polarizations were observed. The GMRT correlator is an FX correlator which provides a fixed number (128) of spectral channels (per sideband) over a bandwidth that can be varied from 16 MHz to 64 kHz. The current observations used bandwidths of 1 and 2 MHz and no online spectral windowing.
3C446 & PKS 1451-375: Both PKS 1451-375 and 3C 446 are listed as candidate damped Lyman-α absorbers on the basis of their IUE spectra (Lanzetta et al. 1995). The present observations used a total bandwidth of 2 MHz, centred at the frequency of the optically determined redshift (See Table 1 for details). No statistically significant absorption was detected in either case. The RMS noise levels in the spectra after a single Hanning smoothing (i.e. an effective velocity resolution of ∼ 50 km s⁻¹ from z = 0.3127, not detected in the WSRT data. This feature is present in more than one observing run, with the correct Doppler shift. The total velocity range over which the absorption is seen is ∼ 120 km/s.

VLBI observations at 1667 MHz of PKS 1127-145 (Bondi et al. 1996) have shown that it has a core-jet structure, with a total size less than ∼ 20 milli-arcseconds. This small size implies that the covering factor of the absorbing system is likely to be close to unity. Assuming a covering factor of unity results in a spin temperature $T_s$ of ∼ 910 ± 160 K, consistent within the error bars with the value of 1000 ± 200 K obtained by Lane et al. (1998).

3 DISCUSSION

We were able to collate from the published literature eighteen 21cm observations of damped Lyman-α absorbers, including cases where only upper limits have been obtained on the optical depth. This is probably not an unbiased sample since it is unlikely that all non-detections have been published. The relevant parameters of the sample are summarised in Table 2. Note that although 3C 446 and PKS 1451-375 are included in Table 2 and Figure 2, their status as bona fide damped Lyman-α systems remains to be confirmed.

The optical depth in the 21cm transition is a function of both the column density, $N_{\text{HI}}$, of the gas as well as its spin temperature, $T_s$. For an optically thin, homogenous cloud the exact relation is:

$$N_{\text{HI}} = \frac{1.823 \times 10^{18} T_s}{f} \int \tau_{21} dV$$

where $\tau_{21}$ is the 21cm optical depth, $N_{\text{HI}}$ is the neutral hydrogen column density and $f$ is the covering factor; $T_s$ is in K and $dV$ in km s⁻¹. For an inhomogeneous absorber, the temperature $T_s$ in equation (1) should be replaced by the column density weighted harmonic mean of the temperatures of the different components (assuming all components are optically thin). Thus, for example, if one has an absorber in which 50% of the gas is at 80 K and 50% at 8000 K, the measured spin temperature would be ∼ 160 K, while if 10% is at 80 K and 90% at 8000 K, the measured spin temperature would be ∼ 730 K.

In the case of damped systems, the column density $N_{\text{HI}}$ is known from the damped Lyman-α profile; this can be used in conjunction with the measured 21cm optical depth to obtain the spin temperature of the absorbing gas, if the covering factor $f$ is known. Many of the background sources listed in Table 2 are extremely compact making it likely that the covering factor is close to unity. Further, as discussed in more detail in Carilli et al. (1996), although the covering factor $f$ is sometimes poorly constrained, it is unlikely to

![Figure 1. GMRT HI spectrum towards PKS 1127-145. The velocity axis is centred at $z = 0.3127$.](image)
lead to a systematic bias for the systems discussed here. We also emphasise that the sample of Table 2 does not contain unpublished non-detections of absorption; since \( T_s \) and \( \tau_21 \) are inversely related, the bias in the sample (if it exists) is thus towards lower \( T_s \) values. As we will see below, damped Lyman-\( \alpha \) systems tend to have \( T_s \) values higher than those observed in local spiral galaxies; the results from our sample are hence conservative since the bias tends to reduce this discrepancy.

3.1 Kinematics of damped systems

A more fundamental consequence of the inverse relationship between \( \tau_21 \) and \( T_s \) is that 21cm absorption typically traces the cold gas (\( T_s \sim 100 \) K) in the absorber. For example, in our galaxy, the warm neutral medium (WNM) has been detected in absorption only towards the very bright radio source Cygnus A (Carilli et al. 1998), while, in extra-galactic systems, there has been only one claim of 21cm absorption that could arise from warm (\( T_s \sim 5000 \) K) gas (Lane et al. 1999). Low ionization metal lines, on the other hand, trace both the warm and the cold neutral gas. A comparison between 21cm profiles and the profiles of metal lines can thus be used to glean further information on the phase structure and kinematics of the absorbing system. Unfortunately, there are only four known 21cm absorbers for which high resolution (\( \sim 8 \) km s\(^{-1}\)) optical spectra are available. These are discussed individually below.

1. 1229-021 (\( z_{abs} = 0.3950 \)) The metal lines of this system were studied by Lanzetta & Bowen (1992), using the AAT with a velocity resolution of 7 km s\(^{-1}\). The 21cm spectrum (Brown & Spencer 1979; Briggs 1998) shows a narrow component centered at the redshift of the deepest part of the metal line profile. The metal lines show two more components at +100 km s\(^{-1}\) and +200 km s\(^{-1}\), relative to \( z = 0.395 \). While the 21cm profile has a broad shallow component with a total width between nulls of 180 km s\(^{-1}\) there is no absorption associated with the +200 km s\(^{-1}\) metal line component nor a separate discrete component at +100 km s\(^{-1}\).

2. 3C286 (\( z_{abs} = 0.69215 \)) The velocity structure of the damped system at \( z \sim 0.692 \) towards 3C286 is exceedingly simple in both the 21cm and low-ion (FeII, CaII) transitions. Each consist of a single narrow component with b values of 5.2 km/s for the 21cm line (Davis & May 1978) and 6.5 km/s for the FeII line (Meyer & York 1992). The metal lines occur at \( z = 0.69218 \pm 0.00007 \) while the 21cm line is at \( z = 0.692154 \pm 0.000002 \); thus, the locations are coincident in velocity, within the error bars.

3. 1331+170 (\( z_{abs} = 1.7764 \)) The SiII 1808 line detected from this system (resolution \( \sim 6.6 \) km/s) is clearly asymmetric (Prochaska & Wolfe 1997), with its deepest feature at \( z = 1.77636 \pm 0.00006 \). The 21cm profile (Wolfe & Davis, 1979) has a single component at \( z = 1.77642 \pm 0.0001 \), the deepest part of the SiII line coincides with the 21cm line, again within the error bars. However, once again there are discrete components in the SiII spectrum which have no counterparts in 21cm absorption.

4. 0458-020 (\( z_{abs} = 2.039 \)) The 21cm line (Wolfe et al. 1985) has two clear components, at \( z = 2.03937 \) and \( z = 2.03955 \). The two deepest features of the CrII 2056 profile (Prochaska & Wolfe 1997) coincide with the 21cm features (within the error bars); however, the deeper CrII feature corresponds to the weaker 21cm feature (see Figure 2, in Prochaska (1999), for an overlay of the two profiles). There are also several weaker CrII features which have no corresponding features in the 21cm spectrum.

Four systems are clearly too small a sample to draw any far-reaching conclusions regarding the general kinematics of damped absorbers. It is, however, revealing that the strongest metal line absorption coincides in velocity with a 21cm absorbing component, in every case for which high-resolution optical spectra are available. This points to a physical coincidence between the cold gas responsible for the 21cm absorption and the (not necessarily cold) gas giving rise to the deepest features in the low-ion profiles. This is consistent with any model for which the absorption arises in discrete clouds, but not with models for which the deep features in the low-ion profiles are the result of velocity crowding.

The other noteworthy feature is that the low ionization metal lines are in general much broader than the 21cm profiles, and often contain discrete velocity components which have no analogues in the 21cm spectrum. For example, if one assumes that the neutral hydrogen column density scales with the depth of the low ionization lines (which is not necessarily a good assumption), the noise levels on the 21cm spec-

| Source     | \( z_{abs} \) | \( N_{HI} \) cm\(^{-2}\) | Resolution km s\(^{-1}\) | \( \tau \) | \( T_s \) K |
|------------|-------------|----------------|-----------------|--------|--------|
| PKS 1451-375 | 0.2761 | 1.3e20\(^a\) | 4.2 | \( < 0.006 \) | 1400 |
| PKS 1127-145 | 0.3127 | 5.1e21\(^b\) | 2.17 | 0.092 | 910 |
| 3C446      | 0.4842 | 6.3e20\(^a\) | 4.8 | \( < 0.02 \) | 1600 |

Limits are 3\( \sigma \).

\(^a\) Lanzetta et al. (1995), \(^b\) Rao & Turnshek (1999)
Table 2. Damped Ly-\(\alpha\) Systems with 21cm Observations

| Name           | \(z_{abs}\) | \(N_{HI}\) cm\(^{-2}\) | No. of Components | \(\Delta V_{21}\) km s\(^{-1}\) | \(T_s\) K | Absorber ID | Ref   |
|----------------|------------|-------------------------|------------------|-------------------|---------|-------------|-------|
| PKS 0735+314   | 0.4011     | 2.5e20                  | 1                | 6                 | 190     | Group 20    | 5.6   |
| PKS 0735+314   | 0.4011     | 2.5e20                  | 1                | 6                 | 190     | Group 20    | 5.6   |
| PKS 1229-021   | 0.3949     | 5.6e20                  | 2                | 180               | 170     | Spiral      | 7-10  |
| PKS 0289+387   | 0.2883     | 6.3e20                  | 3                | 250               | -       | Barred Spiral | 11-13 |
| PKS 0536-017   | 0.0514     | 6.3e20                  | -                | -                 | >1600   | -           | 5.6   |
| PKS 0536-017   | 0.0514     | 6.3e20                  | -                | -                 | >1600   | -           | 5.6   |
| PKS 0536-017   | 0.0514     | 6.3e20                  | -                | -                 | >1600   | -           | 5.6   |
| PKS 0536-017   | 0.0514     | 6.3e20                  | -                | -                 | >1600   | -           | 5.6   |
| PKS 0536-017   | 0.0514     | 6.3e20                  | -                | -                 | >1600   | -           | 5.6   |
| PKS 0536-017   | 0.0514     | 6.3e20                  | -                | -                 | >1600   | -           | 5.6   |

\(\Delta V_{21}\) values are computed from the published data using equation (1), and the latest available values for all parameters in the equation. In certain instances, this value may differ slightly from that quoted by the authors in the original reference. The only exception is PKS 0201+113, for which multiple and quite different values are quoted in the literature. We use the value from Kanekar & Chengalur (1997). * Candidate damped Lyman-\(\alpha\) systems, based on IUE spectra.

3.2 The spin temperature of damped absorbers

Figure 2 shows a plot of spin temperature \(v/s\) redshift for 17 systems from Table 2 (excluding 3C196, for which the background source is extended, making the column density uncertain). It can be clearly seen that the majority of systems tend to have \(T_s\) values much larger than 500 K. For comparison, spin temperatures in the disc of the Galaxy or Andromeda are typically between 100 and 200 K (Braun & Walterbos 1992; Braun 1997). Similarly, Carilli & van Gorkom (1992) find that when the line-of-sight passes through the disc of a galaxy, the spin temperatures derived from 21cm emission-absorption arising in nearby quasar-galaxy pairs are also low, i.e. within 1 \(\sigma\) of 300 K, (although the error bars are admittedly large). Further, as discussed by Carilli et al. (1996), the difference in \(T_s\) values between damped systems and local discs is probably not due to the different methods used for the measurements in the two cases.

Interestingly enough, however, all the absorbers in Table 2 which have been identified as spiral galaxies either have low (\(<200\) K) spin temperatures or, where the column density is not independently known (in the case of the extended source, 3C196), have absorption profiles consistent with low \(T_s\) values for moderate values of column density (de Bruyn et al. 2000). It thus appears that low spin...
temperatures do occur in damped Lyman-α systems, when the line-of-sight passes through the disk of a spiral galaxy. This indicates that the discrepancy in spin temperature between the majority of damped absorbers and local spirals is a real one, which may well arise from a true difference in the physical characteristics of the two classes of systems. The likely explanation for the high spin temperatures in damped systems is (as suggested earlier, eg. Carilli et al. 1996) that their fractional content of warm gas is larger than that of local spirals.

In the Milky Way, neutral gas can exist in pressure equilibrium in two stable phases, the warm neutral medium (WNM) at T \(\sim 10^4\) K and the cold neutral medium (CNM) at T \(\sim 60\) K. At high pressures (such as those obtained in the midplane of the Galaxy), only the cold phase exists, while, at low pressures (as obtained at large scale heights, far away from the midplane), only the warm phase is found. At intermediate pressures, the two phases co-exist in pressure equilibrium. Detailed models of heating and cooling processes in a two-phase neutral medium (Wolfire et al. 1995) have shown that the pressure required to produce the cold phase increases with a decrease in metallicity. The cold phase should hence be rare in smaller galaxies which have both lower midplane pressures and lower metallicities. Since the fractional contribution of the CNM to the total column density would be smaller in such systems, they would (as detailed earlier) have higher average \(T_s\) values than spiral galaxies.

The metallicity evolution of damped Lyman-α systems is currently controversial. Damped absorbers typically have low metallicity (\(\sim 0.1\) solar) and there is little direct evidence for evolution of metallicity with redshift (Pettini et al. 1999). However Savaglio & Panagia (1999) find that if one assumes, and fits for, depletion using depletion patterns observed in the Milky Way, the metallicity does appear to increase with decreasing redshift. If the absorbers were indeed spirals, one would have expected to see metallicity evolution. If, on the other hand, damped systems typically arise in smaller galaxies, a consistent picture can be seen to emerge. Smaller galaxies have lower levels of star formation and are hence generally metal poor. Further, their midplane pressures are lower than those of large galaxies, making it doubly difficult to create the conditions for the formation of the CNM. Thus, both the low metallicity and the high spin temperature of damped systems can be consistently explained if damped Lyman-α absorption occurs predominantly in small rather than large galaxies. Finally, a detailed analysis of the formation of a multi-phase medium in protogalaxies (Spaans & Norman 1997, Spaans & Carollo 1997) indicates that the epoch of formation of a multi-phase ISM is a strong function of the galactic mass; while galaxies with baryonic mass \(\sim 5 \times 10^{11}\ M_\odot\) form the cold phase of the ISM by redshifts of \(\sim 3\), dwarf galaxies with mass \(\sim 3 \times 10^{9}\ M_\odot\) typically form the cold phase only by redshifts \(\sim 1\).

It can be seen from Figure 2 that low spin temperatures are not obtained at high redshift (\(z \gtrsim 2\)), while both low and high \(T_s\) values are found at low redshift. Further, Table 2 indicates that large velocity widths (\(\Delta V_{21} > 100\ km\ s^{-1}\)) are not found for \(z \gtrsim 2\), while both large and small widths are seen at low redshift. This is qualitatively consistent with what is expected in hierarchical merging models, (eg. Kauffmann 1996). Interestingly, 1127 – 145 is the only system which has both a large 21cm velocity spread and a high temperature; all other systems with large velocity widths are identified with low \(T_s\) spirals. There are, however, at least three galaxies at the redshift of the damped Lyman-α absorber (Lane et al. 1998). It is possible that they are interacting and that some of the HI in this system is associated with tidal features and has a high spin temperature.

Hence, although the numbers are small, the general trends in \(T_s\) and \(\Delta V_{21}\) are consistent with scenarios in which damped Lyman-α absorbers are typically small systems at high redshifts, while at low redshifts, they are a composite population including both spiral galaxies as well as smaller systems. This would be consistent both with hierarchical models of galaxy formation and narrow band imaging observations (Fynbo et al. 1999), which show that high redshift damped Lyman-α systems often have several Ly-α emitting objects at the redshift of the absorber.

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**Figure 2.** Plot of \(T_s\) for all damped systems for which published 21cm absorption measurements exist. Upper limits are shown by upward pointing arrows. Absorbers identified as spiral galaxies are shown as hollow squares.
REFERENCES

Bondi M., Padrielli L., Fanti R., Fiearra A., Gregorini L., Mantonvani F., 1996, A&AS, 120, 89.
Boissé P., le Brun V., Bergeron, J., Deharveng, J.-M., 1998, A&A, 333, 841.
Braun R., Walterbos R., 1992, ApJ, 386, 120.
Braun R., 1997, ApJ, 484, 637.
Briggs F. H., Wolfe A. M., 1983, ApJ, 268, 120.
Briggs F. H., Turnshek D. A., Wolfe A. M., 1984, ApJ, 287, 549.
Briggs F. H., Wolfe A. M., Liszt H. S., Davis M. M., Turner K. L., 1989, ApJ, 341, 650.
Briggs F. H., Brinks E., Wolfe A. M., 1997, AJ, 113, 467.

Briggs F. H., 1998, in Highly Redshifted Radio Lines, C. L. Carilli et al. eds, PASP Conf. Ser. vol 156.
Brown R. L., Roberts M. S., 1973, ApJ, 184, L7.
Brown R. L., Spencer R. E., 1979, ApJ, 230, L1.
Brown R. L., Mitchell K. J., 1983, ApJ, 264, 87.

le Brun V., Bergeron J., Boissé P., Deharveng J-M., 1997, A&A, 321, 733.
de Bruyn A. G., O’Dea C. P., Baum S. A., 1996, A&A, 305, 450.
de Bruyn A. G., Briggs F. H., Vermulien R., 2000, in preparation.
Buridge E. M., Beaver E. A., Cohen Ross D., Junkkarinen V. T., Lyons R. W., 1996, AJ, 112, 2533.
Carilli C. L., van Gorkom, J. H., 1992, ApJ, 399, 373.
Carilli C. L., Perlman E. S., Stocke J. T., 1992, ApJ, 400, L13.
Carilli C. L., Lane W., de Bruyn A. G., Braun R., Miley G. K., 1996, AJ, 111, 1830.
Carilli C. L., Dwarkanath, K. D., Goss, W. M., 1998, ApJ, 502, L79.

Carswell R. F., Hilliard R. L., Strittmatter P. A., Taylor D. J., Weymann R. J., 1975, ApJ, 196, 351.
Cohen R. D., Barlow T. A., Beaver E. A., Junkkarinen V. T., Lyons R. W., Smith H. E., 1994, ApJ, 421, 453.
Cohen R. D., Beaver E. A., Diplas A., Junkkarinen V. T., Barlow T. A., Lyons R. W., 1996, ApJ, 456, 132.

Cohen R. D., Burbridge E. M., Junkkarinen V. T., Lyons R. W., Madejski G., 1999, BAAS 194.7101.

Chengalur J. N., Kanekar N, 1999, MNRAS, 302, L29.
Davis M. M., May L. S., 1978 ApJ, 219, 1.
Field G. B., 1958, Proc. IRE, 46, 240.
Fynbo J. U., Thomsen B., Møller P., 1999, to appear in Proceedings of the Vatican Symposium on Astrophysical Research and Science Education, Rome, 1998.
Huchne M. G., Steinmetz M., Rauch M. 1998, ApJ, 495, 64.
Kanekar N., Chengalur J. N., 1997, MNRAS, 292, 831.
Kauffmann G., 1996, MNRAS, 281, 475.
Lane W., Smette A., Briggs F., Rao S., Turnshek D., Meylan G., 1998, AJ, 116, 26.
Lane W., Briggs F., Smette A., 2000, ApJ, 532, 146.
Lanzetta K. M., Wolfe A. M., Turnshek D. A., Lu L., McMahon R. G., Hazard C., 1991, ApJS, 77, 1.
Lanzetta K. M., Bowen D. V., 1992, ApJ, 391, 48.
Lanzetta K. M., Wolfe A. M., Turnshek D. A., 1995, ApJ, 440, 435.
Lu L., Wolfe A. M., Turnshek D. A., Lanzetta K. M., 1993, ApJS, 84, 1.

McDonald P., Miralda-Escude J., 1999, ApJ, 519, 486.
Meyer D. M., York D. G., 1992, ApJ, 399,121.
Møller P., Warren, S. J., 1993, A&A, 270, 43.
Møller P., Warren, S. J., 1998, MNRAS, 299, 661.

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