PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Evidence from the 21 cm Line Relating to Intergalactic Gas [and Discussion]

R. D. Davies and C. J. Hogan

Phil. Trans. R. Soc. Lond. A 1980 **296**, 407-414
doi: 10.1098/rsta.1980.0185

Phil. Trans. R. Soc. Lond. A **296**, 407–414 (1980) [407]
Printed in Great Britain

Evidence from the 21 cm line relating to intergalactic gas

By R. D. Davies
University of Manchester, Nuffield Radio Astronomy Laboratories, Jodrell Bank, Macclesfield SK11 9DL, U.K.

No evidence has been found for *distributed* H I at red shifts $z < 2$, although clumped H I is found in the absorption spectra of quasars. Observations of nearby groups of galaxies indicate the presence of substantial amounts of H I lying outside the optical confines of the galaxies. Some of this material is in the form of tidal bridges and tails and some is condensed into discrete intergalactic clouds. H I observations have also been used to investigate with higher precision than hitherto the virial mass of groups of galaxies. Two such groups have a lower mass and a lower mass light ratio than obtained from equivalent optical studies. The origin of this difference is not fully understood, but it may have consequences for the conventional methods of determining the mass density of the Universe. Finally, searches for H I in the epoch of galaxy formation ($z = 3$–10) are described. Limits have been set on the masses and the volume density of protoclusters at $z = 3.3$ and 4.9. This appears to be an important area for further observational and theoretical study.

1. Introduction

The possiblity that neutral atomic hydrogen might be a major component of the mass of the Universe has provided a stimulus for observation over many years. A Hubble constant of 75 km s^{-1} Mpc^{-1} would require a closure density of $n_c = 6.4 \times 10^{-6}$ hydrogen atoms/cm^3. The earliest experiments searched for a uniformly distributed gas which would be seen as a step in the emission or absorption at wavelengths longer than 21 cm. (Field 1962; Davies & Jennison 1964; Penzias & Scott 1968). The most sensitive measurement is of the absorption against a strong extragalactic radio source where the absorption will extend from zero velocity to the recession velocity of the radio source. Penzias & Scott find an upper limit to the optical depth of the absorption in front of Cygnus A of $\tau < 5 \times 10^{-4}$. This corresponds to $n_H < 6 \times 10^{-7}$ cm^{-3} for an H I excitation temperature of 18 K (Field 1972), implying $n_H < 0.1\, n_c$. A much more sensitive limit on the density of uniformly distributed intergalactic H I is provided by observations of the Lyman α absorption trough of a quasar with a large red shift. For 3C9, Gunn & Peterson (1965) failed to detect any H I absorption at a limit of $n_H < 5 \times 10^{-6}\, n_c$.

These results apply to widely distributed H I only and leave the possibility that the H I might be clumped in angle and velocity. Searches over wide angles in the sky with high velocity resolution are required to detect material on the scale of galaxies or clusters of galaxies. Several search strategies have been employed by a number of authors. Shostak (1977) looked for H I emission on the general field and absorption against extragalactic continuum sources; he was sensitive to objects of galactic dimensions having velocity widths of 11–600 km/s and angular dimensions less than 10′ at distances out to 200 Mpc. No individual extragalactic objects were found and Shostak concluded that H I in galaxy-type objects with masses greater than $10^5\, M_\odot$ was no greater than $0.02\, \rho_c$, where ρ_c is the closure density of the Universe. Haynes *et al.* (1978) searched for H I in clusters of galaxies by looking for absorption lines in the spectra of background continuum sources. No absorption was found to a typical limit of 0.1 in optical depth and the authors conclude that the possibility that clusters of galaxies are bound by isolated clouds of H I is remote. In a related study Roberts & Steigerwald (1977) find that discrete H I clouds in front of radio galaxies contribute less than 0.07 ρ_c.

The existence of H I at large red shifts has been established by searches of the absorption spectra of quasars. Brown & Roberts (1973) discovered absorption at $z = 0.692$ in 3C 286 for which the emission red shift is $z = 0.849$. Roberts *et al.* (1976) also found H I absorption at the optical absorption red shift of $z = 0.524$ in AO 0235+164 for which there is no emission red shift, it being a BL Lac type object. The column density of H I in absorption for these objects lies between 2 and $20 \times 10^{21}/\text{cm}^2$ for an assumed excitation temperature of 100 K. The velocity spread is *ca.* 50 km/s with individual features having a width at half-power of *ca.* 10 km/s. These parameters are consistent with absorption in the spiral arm of a galaxy. The presence of Mg I and Mg II in AO 0235+164 also agrees with this picture.

The present paper describes H I observations of groups of galaxies to determine both the extent of distributed hydrogen and the total mass of the group. Searches for primordial H I at large red shifts will also be described.

2. H I in groups of galaxies

The major body of H I in most groups of galaxies lies within the confines of the galaxies themselves. It is principally restricted to the Holmberg dimensions. However, a fraction of all galaxies, whether in pairs or groups, have extended H I filaments associated with them which are almost certainly of tidal origin. These filaments may extend for several galaxy diameters and have widths of at least 10% of the galaxy diameters. Well known examples of tidally interacting systems which show tidal bridges and tails of H I and optical material are NGC 5194/5195, NGC 4038/4039 (van der Hulst 1978) and NGC 4631/4656 (Weliachew 1977). The geometry and the velocities of the H I bridges and tails are consistent with tidal interactions similar to those considered by Toomre & Toomre (1972). The Magellanic Stream H I distribution and velocity configuration can also be interpreted as a tidal interaction between our Galaxy and the Magellanic Clouds (Davies & Wright 1977; Lin & Lynden-Bell 1977). The H I clouds near NGC 55 and NGC 300 are sometimes considered to be similar associated objects (Mathewson *et al.* 1975); they are more likely to be foreground clouds in the Magellanic Stream which lies projected against the Sculptor group of galaxies.

Another method for searching for H I in groups of galaxies is to measure the absorption spectrum of a continuum radio source lying behind the group. Haschik & Burke (1975) found absorption in the spectrum of the background source 4C 32.33 as its radiation passed through regions lying approximately two Holmberg radii from the centre of NGC 3067. The H I absorption line had a width of not more than 6 km/s at a velocity only 76 km/s different from the systemic velocity and of NGC 3067. Boksenberg & Sargent (1978) subsequently detected the H and K lines of Ca II in absorption in the optical spectrum of 4C 32.33. All of these observed characteristics are consistent with the absorption occurring in metal-enriched gas in the outer halo of NGC 3067. Peterson (1978) unsuccessfully tried to detect H I absorption against 17 quasars lying in rich clusters of galaxies. The lack of success in this type of observation arises from the low probability of a galaxy containing H I lying in front of a small angular diameter radio source such as a quasar.

Observations at Jodrell Bank aimed at detecting this intra-cluster material have been made in nearby groups of galaxies where pencil beams sensitive to low surface brightness H I emission can be located around and between the galaxies of small groups. Such techniques have a much greater chance of detecting diffuse low density H I; the sensitivity achieved in this work regularly approaches an equivalent surface density of $1-3 \times 10^{18}$ atoms/cm^2, a value two orders of magnitude more sensitive than the absorption experiments.

The intergalactic material likely to be found in small groups falls into two categories. The first consists of tidal bridges and/or tails that have been gravitationally pulled from the interacting galaxies. The second is primordial hydrogen that is in the form of stable protogalaxies that are members of the group and as yet have no detected stellar constituents. The first category of intergalactic material is in the form of filaments of gas continuous in velocity and structure with the parent galaxy while the second is detached from any galaxy and, if seen at appropriate angles, shows velocity gradients characteristic of rotation.

The best studied example of tidal interactions is the Magellanic Stream which is seen only in H I which lies in a band some 5° wide extending from either side of the Magellanic Clouds and is 150° in total length (Mathewson *et al.* 1974). Emission is brightest near the Magellanic Clouds where it is clearly a continuous filament of gas. High sensitivity observations with the the Mk II telescope at Jodrell Bank show that the gas is also continuous to the faint end of the Stream at $l = 90°$, $b = -30°$. Such a continuity is characteristic of a tidal feature which has been drawn from a continuous gas distribution, such as an outer spiral arm, in the perturbed galaxy. There is some branching structure in the main Stream. Further, a number of apparently isolated clouds and extended features have been identified in the Southern Sky that have similar galactocentric velocities to the Stream and are most probably additional tidal debris of the encounter between our Galaxy and the Magellanic Clouds. A characteristic feature of all this Stream material is the elongated substructure of cloudlets that are individually aligned with the main structure. The surface density of H I in these cloudlets ranges from 2 to 40×10^{19} atoms/cm^2. The surface density in the main Stream between the cloudlets is typically greater than *ca.* 5×10^{18} atoms/cm^2.

Observations with the 12′ beam of the Mk 1A telescope have been made of the distributed H I in a number of small nearby groups with well separated galaxies. Clearly identified tidally produced streams of H I have been found in the majority of such groups. In the NGC 4725 group (the Coma I cloud of de Vaucouleurs) the smaller companion Sc galaxy NGC 4747 has an H I bridge towards NGC 4725 and a tail pointing away. The blue plate taken with the Mt Palomar 48 inch Schmidt telescope also reveals substantial tidal distortion of the optical image of NGC 4747. Similarly in the NGC 5713 group (the Virgo III cloud of de Vaucouleurs) the Sab galaxy NGC 5719 shows an H I bridge and tail almost certainly produced by NGC 5713. Extensive optical tidal debris is revealed in a deep IIIaJ plate taken with the U.K. 48 inch Schmidt telescope. The nearby galaxy M101 shows extended low surface brightness H I to the south which has probably been stripped from the tidally distorted dwarf companion NGC 5474 (Davies *et al.* 1979).

The galaxy with most extensive distributed H I in its immediate vicinity is M81 (Roberts 1972; Cottrell 1977; van der Hulst 1978; Appleton *et al.* 1979). New high sensitivity observations with the Mk IA telescope reveal tidal connections with NGC 3077, M82 and NGC 2976.

In our work on groups of galaxies, two clouds have been discovered that could be intergalactic rather than tidal in origin. They are both distinct H I concentrations that are not on the velocity and density gradient of a tidal bridge or tail. One is an extended cloud lying between

M81 and NGC 2976. The other is a cloud 6′ in extent lying 14′ from the centre of the S0 galaxy NGC 1023 (Hart & Davies 1979). The difference in velocity between these two galaxies is 275 km/s, a value so high as to make it unlikely to be of tidal origin. No optical features can be seen on the Mt Palomar Sky Atlas prints at the position of this interesting object.

Materne *et al.* (1979) have searched for emission from intergalactic clouds in the two de Vaucouleurs groups NGC 1023 and C VnII and found no emission which corresponded to upper limits of 4 and $2.6 \times 10^8\ M_\odot$ for individual clouds in each group. Their search was of lower sensitivity than ours and avoided the dominant galaxies. Consequently they did not detect the intergalactic cloud near NGC 1023 described above, nor would they have found any tidal material which extends from the outer boundaries of the galaxies.

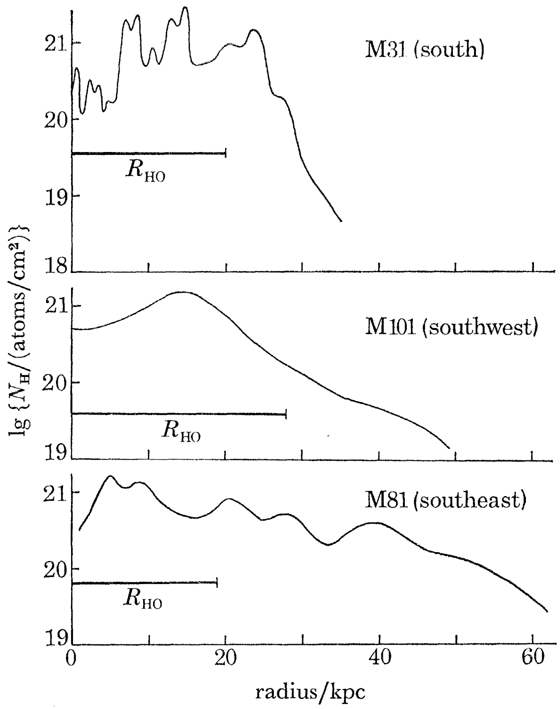

FIGURE 1. The neutral hydrogen surface density as a function of radial distance in M31, M101 and M81. The optical (Holmberg) radius R_{HO} is given for comparison.

Our data on the H I distribution in the vicinity of some nearby galaxies can be related to the origin of optical quasar absorption lines. A fraction, possibly as much as a half, of the absorption lines have properties that are consistent with an origin in the outer regions of intervening galaxies along the line of sight (Bahcall & Spitzer 1969). The clouds contain metals as well as the dominant hydrogen, their velocity widths are typically 30–60 km/s and the surface density is commonly in the range $4\text{–}80 \times 10^{13}$ hydrogen atoms/cm² (Morton & Morton 1972). The H I observations do not reach within three or four orders of magnitude of these surface densities; nevertheless it is of interest to examine the trend of density with distance from the centre of some galaxies in our sample. The radial distribution of surface density is shown for M31, M101 and M81 in figure 1. The inner part of the plot for each galaxy is taken from aperture synthesis observations while the outer regions are from pencil beam observations. In each case the Holmberg radius (out to the 26 magnitudes per arcsec² contour) is also given for comparison. Both M101 and M81 show a slower fall-off in density than does M31. Extrapolation of the surface density plots to 3×10^{14} cm^{-2}, a value in the mid-range of quasar absorption densities, would suggest radii of 55, 130 and 170 kpc for M31, M101 and M81 respectively. Of course there is no way of telling from the present data whether the run of surface density will follow these trends, but it does give an indication of the possible radii at these densities. Radii of this magnitude would lead to the number of quasar absorption lines of the type that occur in intervening galaxies. Moreover the velocity width of the H I emission found in the tidal filaments, 25–50 km/s, is characteristic of the optical absorption line widths. The true intergalactic H I clouds or protogalaxies should also be included (Aarons 1972). Our observations suggest that, although they are a component of the intracluster medium, they make less of a contribution than the tidal bridges and tails.

3. The H-line as a probe of the mass of groups of galaxies

H-line observations of the rotation curves of individual galaxies of a group and of the systemic velocity of the galaxies enables the masses of individual galaxies and the mass of the group as a whole to be estimated from the virial theorem. It should then be possible to determine whether there is invisible matter in the groups, for example material in extended halos as suggested by some authors. At the same time the mass:luminosity ratio M/L can be derived for the group, given the optical luminosity of the member galaxies. The contribution of groups of galaxies to the total mass of the Universe can also be estimated.

The reason why H I measurements are so useful is that they give very accurate systemic velocities, established from emission over the full dimensions of the galaxy. Systemic velocities are readily determined to an accuracy of 10 km/s or better. The total mass of a galaxy can be determined from the full rotation curve or the line of centroids procedure of Dean & Davies (1975).

The mass of the total system can be derived from the virial theorem on the assumption that it is gravitationally bound when the kinetic energy (T) is equal to the potential energy (Ω), where

$$T = \tfrac{3}{2} \sum m_i v_i^2$$

and

$$\Omega = -\frac{2G}{\pi} \sum_{\text{pairs}} \frac{m_i m_j}{r_{ij}};$$

v_i is the observed radial velocity of the i galaxy relative to the barycentric velocity of the group and r_{ij} is the projected distance between the galaxies of mass m_i and m_j. In this case we propose that all the mass has been identified. If it is found that $T > -\Omega$ then we may conclude that there is mass in the group not associated with identified optical or H I objects; it is still assumed that the system is bound, a condition that is confirmed if the crossing-time of the group members is substantially less than the age of the Universe.

In an H I study of 14 members of the NGC 1023 group it was found that 11 (including NGC 1023) had velocities clustered within $\pm$ 60 km/s of 735 km/s while the remaining 3 objects are clustered 350 km/s higher in velocity (Hart & Davies 1979). For the 11 galaxies that we consider to be a coherent group, $T \approx -2\Omega$, a result which has two interesting implications: first, the group of 11 galaxies is bound, within the errors of measurement; secondly, no large amounts of extra mass are required to bind the group, either in the halos of the galaxies themselves or in the intergalactic medium. At most, a factor of two in mass could be accommodated within the group to a distance of 200 kpc from the group centre. This result contradicts the suggestion that galaxies may contain a factor of up to 10 more mass in extended halos than is deduced from measured rotation curves (Turner & Ostriker 1977; Yahil 1977; Gott & Turner 1977). Furthermore the mass:luminosity ratio (M/L) of the group can be determined and compared with other estimates from pairs, groups and clusters of galaxies. For the 11 galaxies in the NGC 1023 group, $M/L \approx 20$, compared with $M/L = 60$–200 from optical studies of pairs, groups and clusters of galaxies.

A similar series of H I measurements has been made of the M101 inner group of galaxies where $T \approx -\Omega$, again indicating no excess mass in this group. M/L was found to be 8. This work is being extended to other small groups to determine why there is so little evidence for hidden masses on these groups compared with other studies. Clearly some of the higher masses determined optically arise from the larger velocity errors which contribute an additional spread to the adopted galaxy velocities. Another difference may arise from the definition of group membership. We have been restrictive in our choice of group membership and have chosen those galaxies that exhibited a marked bunching in velocity.

4. Primordial neutral hydrogen at high red shifts

Of particular interest is a search for H I in the earliest epoch of condensation from the hot gas phase of the Universe. After recombination at $z \approx 1000$, when the temperature is less than 3000 K, the hydrogen is neutral but still essentially uniformly distributed. The first recognizable fluctuations occur in this distribution when gravitational perturbations grow to be sufficiently large and further cooling of the gas occurs (the gas is decoupled from the cosmic radiation field also at $z \approx 1000$). In the present state of theory it is not yet clear which scale of mass (more than $10^5\ M_\odot$) will condense first – globular clusters ($10^5\ M_\odot$), galaxies ($10^{11}\ M_\odot$) or clusters ($10^{15}\ M_\odot$). In all cases, the formation of these mass concentrations occurs at $z = 3$–10 when they first become gravitationally bound. C. J. Hogan & M. J. Rees (1979) have suggested that red-shifted 21 cm emission might be searched for in masses of galaxy dimensions. These signals would occur in regions of the order of 1′ and have a velocity width of a few hundred kilometres per second. The emission would be very weak and difficult to detect.

The alternative picture in which large protocluster masses condense first has been presented by Sunyaev & Zeldovich (1972, 1975) which leads to the prediction of more readily detectable red-shifted H I signals because of the larger mass concentrations. In their theory about 10% of the mass of a protocluster of total mass $10^{15}\ M_\odot$ will be in the neutral state in the form of a flattened pancake. Observations made in a particular frequency band Δf corresponds to a sampling of the Universe in a range of red shift Δz such that $\Delta f/f = \Delta z/(1+z)$. The red-shifted signals from the protoclusters will give antenna temperatures of *ca.* 1 K in a region 10′ in diameter. Davies *et al.* (1978) made a search for these protoclusters at frequencies of 328 and 240 MHz corresponding to red shifts of 3.3 and 4.9. Upper limits comparable with the magnitude of signals predicted by the theory were set on 20 intermediate latitude fields at both frequencies. These results were used to derive limits to the properties of protoclusters in the early Universe. In particular it was concluded that their masses are less than *ca.* $3 \times 10^{15}\ M_\odot$ or the number of such objects in the early Universe was less than *ca.* 10^6. It would clearly be of interest to push the observations to even lower limits to bring them well within the range of parameters predicted by Sunyaev & Zeldovich. Our most recent efforts in this field have been directed towards a search at 151 MHz (z = 8.4) where a sensitivity comparable to the two previous searches has been attained. Analysis of these observations is proceeding.

It is possible that protoclusters might surround high red shift quasars with large red shifts or be responsible for absorption lines with large red shifts in quasars. One candidate for such a search was the z = 2.3099 absorption line in the radio-quiet quasar PHL957. This absorption system has a high column density of neutral hydrogen as indicated by its broad Lyman α line. A radio search at the corresponding red shifted H I frequency of 429.139 MHz did not reveal any H I mass greater than a limit of $3 \times 10^{13}\,M_{\odot}$ (Davies *et al.* 1977).

5. Conclusions

Intergalactic H I is not the major mass component of the Universe at $z \lesssim 2$ although it is found in isolated regions as shown by the low excitation absorption lines in quasars. This latter gas is probably low density material in the outer regions (50–100 kpc from the centre) of galaxies and is of the kind detected in groups of galaxies. However at earlier epochs, say $3 < z < 10$, a substantial proportion of the matter of the Universe will be in the form of H I condensed into protogalaxies or protoclusters. The first searches for this primordial H I have been made.

References (Davies)

Aarons, J. 1972 *Astrophys. J.* **172**, 553.
Appleton, P. N., Davies, R. D. & Stephenson, R. J. 1979 In preparation.
Bahcall, J. N. & Spitzer, L. 1969 *Astrophys. J.* **156**, L63.
Boksenberg, A. & Sargent, W. L. W. 1978 *Astrophys. J.* **220**, 42.
Brown, R. L. & Roberts, M. S. 1973 *Astrophys. J.* **184**, L7.
Cottrell, G. A. 1977 *Mon. Not. R. astr. Soc.* **178**, 577.
Davies, R. D., Booth, R. S. & Pedlar, A. 1977 *Mon. Not. R. astr. Soc.* **181**, 1P.
Davies, R. D. & Jennison, R. C. 1964 *Mon. Not. R. astr. Soc.* **128**, 123.
Davies, R. D., Johnson, S. C. & Davidson, G. P. 1979 In preparation.
Davies, R. D., Pedlar, A. & Mirabel, I. F. 1978 *Mon. Not. R. astr. Soc.* **182**, 727.
Davies, R. D. & Wright, A. E. 1977 *Mon. Not. R. astr. Soc.* **180**, 71.
Dean, J. F. & Davies, R. D. 1975 *Mon. Not. R. astr. Soc.* **170**, 503.
Field, G. B. 1962 *Astrophys. J.* **135**, 684.
Field, G. B. 1972 *A. Rev. Astron. Astrophys.* **10**, 227.
Gott, J. R. & Turner, E. L. 1977 *Astrophys. J.* **213**, 309.
Gunn, J. E. & Peterson, B. A. 1965 *Astrophys. J.* **142**, 1633.
Hart, L. & Davies, R. D. 1979 In preparation.
Haschik, A. D. & Burke, B. F. 1975 *Astrophys. J.* **200**, L137.
Haynes, M. P., Brown, R. L. & Roberts, M. S. 1978 *Astrophys. J.* **221**, 414.
Haynes, M. P., Giovanelli, R. & Burkhead, M. S. 1978 *Astr. J.* **83**, 938.
Hogan, C. & Rees, M. J. 1979 *Mon. Not. R. astr. Soc.* **188**, 791.
van der Hulst, J. M. 1978 In *Structure and properties of nearby galaxies* (ed. E. M. Berkhuijsen & R. Wielebinski), p. 269. Dordrecht: D. Reidel.
Mathewson, D. S., Cleary, M. N. & Murray, J. D. 1974 *Astrophys. J.* **190**, 291.
Mathewson, D. S., Cleary, M. N. & Murray, J. D. 1975 *Astrophys. J.* **195**, L97.
Materne, J., Huchtmeier, W. K. & Hulsbosch, A. N. M. 1979 *Mon. Not. R. astr. Soc.* **186**, 563.
Morton, D. C. & Morton, W. A. 1972 *Astrophys. J.* **174**, 237.
Penzias, A. A. & Scott, E. H. 1968 *Astrophys. J.* **153**, L7.
Peterson, B. M. 1978 *Astrophys. J.* **223**, 740.
Roberts, M. S. 1972 In *External galaxies and quasi stellar objects* (*I.A.U. Symposium* no. 44) (ed. D. S. Evans), p. 12. Dordrecht: D. Reidel.
Roberts, M. S., Brown, R. L., Brundage, W. D., Rots, A. H., Haynes, M. P. & Wolfe, A. M. 1976 *Astr. J.* **81**, 293.
Roberts, M. S. & Steigerwald, D. G. 1977 *Astr. J.* **217**, 883.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

Shostak, G. S. 1977 *Astron. Astrophys.* **54**, 919.
Sunyaev, R. A. & Zeldovich, Y. B. 1972 *Astron. Astrophys.* **20**, 189.
Sunyaev, R. A. & Zeldovich, Y. B. 1975 *Mon. Not. R. astr. Soc.* **171**, 375.
Toomre, A. & Toomre, J. 1972 *Astrophys. J.* **178**, 623.
Turner, E. L. & Ostriker, J. P. 1977 *Astrophys. J.* **217**, 24.
Weliachew, L., Sancisi, R. & Guélin, M. 1978 *Astron. Astrophys.* **65**, 37.
Yahil, A. 1977 *Astrophys. J.* **217**, 27.

Discussion

C. J. Hogan (*Institute of Astronomy, Cambridge, U.K.*). M. J. Rees and I have considered (Hogan & Rees 1979) a way to observe directly the distribution of gas at large red shifts. The spectrum of non-uniform gas emitting or absorbing line radiation in an expanding Universe displays frequency structure on scales $\delta\nu/\nu \approx 10^{-3}$ if the scale of lumpiness is *ca.* $10^{-3}\,cH^{-1}$, but the detailed spectral structure is correspondingly uncorrelated on angular scales larger than *ca.* 10^{-3} rad (*ca.* 4′). Thus, lumpy large red shift gas may appear as a distinctive signature in the variation of the spectrum of background radiation across the sky, even if the bulk of the background comes from other sources. Emission at 21 cm, or 21 cm absorption of the microwave background, might be visible with present-day techniques out to $1+z \approx 10$ (150 MHz). Ly α emission might be visible out to $1+z \approx 5$ (6000 Å; 600 nm); Ly α absorption has probably already been observed in quasar absorption systems, and may be visible in any direction if there is a background to absorb. Observations of either type would be a valuable probe of the evolution of cosmic structure.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES