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A search for neutral hydrogen in primordial protoclusters at $z = 3.33$ and 4.92

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Summary. A search has been made for the redshifted neutral hydrogen emission from primordial protoclusters at early epochs in the history of the Universe. A system with 2.5-MHz bandwidth was used to investigate 20 intermediate-latitude fields at frequencies of 328 and 240 MHz which correspond to neutral hydrogen redshifts of $z = 3.33$ and 4.92. Upper limits of peak flux density as low as 50 and 11 mJy have been set in fields at the two frequencies. These results are used to derive a limit to the properties of protoclusters in the early Universe on the model proposed by Sunyaev & Zeldovich; either their masses are $\lesssim 3 \times 10^{15} M_\odot$ or the number of such objects in the early Universe $\lesssim 10^6$

1 Introduction

The presence of old Population II stars in most galaxies indicates that the collapse of primeval hydrogen into galaxies must have occurred early in the history of the Universe. The range of epochs at which galaxy formation occurred is of topical interest in astronomy. If quasars are at cosmological distances, then it can be argued that those at highest redshift ($z \sim 3.5$) indicate that galaxy formation was occurring at least until $z \sim 3.5$. Optical searches for the super-luminous phase of primeval galaxies have been proposed by Partridge & Peebles (1967a, b). Such searches for diffuse galaxy images at epochs corresponding to $z = 4$–8 have been made by Partridge (1974) and by Davis & Wilkinson (1974), but without success. However, recent models of galaxy formation by Larson (1975); Meier (1976) and others suggest that the brightest phase at optical wavelengths occurs when galactic nuclei are formed; this phase may continue to $z \sim 0.5$.

An alternative approach towards the detection of early condensations of matter as it passes through a neutral hydrogen phase has been proposed by Sunyaev & Zeldovich (1972, 1975) and Doroshkevich, Sunyaev & Zeldovich (1974). They suggest that a large fraction of the mass of protoclusters ($M = 10^{13}$–$10^{15} M_\odot$) at $z \sim 3$–10 would be neutral hydrogen at a temperature of $<10^4$ K. Such massive neutral clouds might condense at the centre of a cluster in a pancake form and should be detectable in surveys with adequate sensitivity.

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We report here a search for the redshifted 21-cm emission from primordial protoclusters. One series of observations was made in a band (partially reserved for radio astronomy) at 328 MHz, which corresponds to a redshift of $z = 3.33$. A second series was made at 239.9 MHz ($z = 4.92$) in a band which is relatively free from continuous wave (CW) interference. The antenna temperatures expected for a typical protocluster 10 arcmin in diameter are 0.06 K at 328 MHz and 0.03 K at 240 MHz. Although these signals are a small fraction (10^{-3}–10^{-2}) of the background continuum emission from the Milky Way and extragalactic sources, they can be distinguished by their structure in frequency.

2 The observations

For these experiments the Mk IA radio telescope was equipped to receive simultaneously both horizontally and vertically polarized radiation in two independent transistor-amplifier receivers. In both the 328 and 240 MHz observations, a band 2.5-MHz wide centred on the receiving frequency was observed with the Jodrell Bank 1024-channel autocorrelation spectrometer (Pointon 1977) using 512 channels for each polarization. The use of orthogonal polarizations and a high frequency resolution relative to the expected Doppler width of the predicted astronomical signals enabled CW interference to be identified because of its high polarization and its narrow width; it would then be eliminated from the analysis.

The full-width half-power beamwidths of the Mk IA radio telescope are 50 and 68 arcmin at 328 and 240 MHz respectively. The system noise at both frequencies was in the range 200–250 K, depending on the galactic background contribution. Both systems gave an antenna temperature of 1 K for a point source flux density of 1 Jy ($10^{-26}\,\mathrm{W\,m^{-2}/Hz}$). Observations at 328 MHz were made in 1976 June and at 240 MHz from 1976 December to 1977 January.

As a monitor of the performance of the receiving system, recombination lines were measured in each band. The 271α line at 328.596 MHz was detected in Sgr A, W35 and W43, while the 300α line at 242.347 MHz was detected in Sgr A and W43 (Pedlar *et al.* 1977).

The observing technique involved beam switching between pairs of fields separated by about 2° in the sky. The difference in signal between each field in a pair was recorded; the emission from a protocluster in one or other field would be seen as a positive or negative feature in the 2.5-MHz bandwidth difference spectrum. As will be shown below, the probability of a protocluster lying in any one beam is low, and in consequence it would be highly unlikely that a null result would be produced by the cancellation of the emission from a protocluster lying in each beam and having at the same time similar values of z.

The regions chosen for the protocluster search lay in areas of low metre-wave galactic background emission at intermediate latitudes. Typical values of background brightness temperature were 30 K at 328 MHz and 60 K at 240 MHz. One group of positions was centred at $l = 110°$, $b = -40°$ and the other at $l = 170°$, $b = 50°$. The beam centres for the 10 pairs of fields are listed in the first columns of Tables 1 and 2.

The results of the 328 MHz ($z = 3.33$) observations are given in Table 1 which contains the range of z searched at each position and upper limits to the signals expressed in units of aerial temperature and flux density (1 K of T_a is equivalent to 1 Jy in the present experiments where the expected diameter of the protocluster is smaller than the beamwidth.) Two upper limits are given, one of which corresponds to a width of 660 km/s (722 kHz) and the other to 200 km/s (219 kHz), which represent a likely range of protocluster velocity widths as will be discussed in Section 3. In each case the upper limits represent the maximum amplitude of the Gaussian profile, having the half-power width specified, that could be fitted anywhere within the observing band. The values given for the 660 km/s width are

Table 1. 328 MHz (z = 3.33) upper limits.

l (°)	b (°)	$\Delta T_{\max}$ (200 km/s) (K)	$\Delta T_{\max}$ (660 km/s) (K)	Range of redshift (Δz)
90.0	−40.0	0.19	0.16	−0.012 to +0.015
91.5	−38.3	0.19	0.13	
100.0	−40.0	0.16	0.10	−0.015 to +0.010
101.1	−38.1	0.12	0.09	
110.0	−40.0	0.11	0.09	−0.010 to +0.014
110.5	−38.0	0.09	0.07	
120.0	−40.0	0.13	0.06	−0.015 to 0.010
120.1	−38.0	0.11	0.05	
131.0	−40.0	0.11	0.13	−0.013 to +0.015
130.6	−38.0	0.13	0.07	
150.0	+ 50.0	0.16	0.15	−0.013 to +0.015
147.6	+ 48.5	0.23	0.16	
160.0	+ 50.0	0.15	0.13	−0.012 to +0.012
157.3	+ 49.2	0.18	0.11	
170.0	+ 50.0	0.21	0.11	−0.015 to +0.015
167.1	+ 49.5	0.15	0.09	
180.0	+ 50.0	0.15	0.13	−0.013 to +0.014
177.0	+ 49.8	0.15	0.15	
190.0	+ 50.0	0.15	0.09	−0.012 to 0.008
186.9	+ 50.0	0.16	0.07	

Table 2. 240 MHz (z = 4.92) upper limits.

l (°)	b (°)	rms (10 channels) (K)	$\Delta T_{\max}$ (200 km/s) (K)	$\Delta T_{\max}$ (1000 km/s) (K)	Range of redshift (Δz)
90.0	−40.0	0.033	0.044	0.064	−0.028 to +0.027
91.5	−38,3		0.055	0.035	
100.0	−40.0	0.046 (0.028)	0.097 (0.048)	0.073	−0.028 to +0.027
101.1	−38.1		0.097 (0.059)	0.068	
110.0	−40.0	0.033	0.053	0.015	−0.028 to +0.026
110.5	−38.0		0.040	0.015	
120.0	−40.0	0.037	0.057	0.022	−0.026 to +0.027
120.1	−38.0		0.062	0.015	
131.0	−40.0	0.035	0.055	0.013	−0.028 to +0.022
130.6	−38.0		0.035	0.013	
150.0	+ 50.0	0.055	0.088	0.044	−0.027 to +0.022
147.6	+ 48.6		0.066	0.051	
160.0	+ 50.0	0.096	0.183	0.053	−0.028 to +0.027
157.3	+ 49.2		0.114	0.031	
170.0	+ 50.0	0.037	0.051	0.046	−0.028 to +0.026
167.1	+ 49.5		0.035	0.026	
180.0	+ 50.0	0.028	0.031	0.011	−0.027 to +0.026
177.0	+ 49.8		0.057	0.022	
190.0	+ 50.0	0.084 (0.022)	0.037 (0.020)	0.037	−0.028 to +0.028
186.9	+ 50.0		0.059 (0.020)	0.048	

(   ) = parabolic baseline removed.

approximately a factor of 1.8 smaller than the values for the 200 km/s, as would be expected from the reduction in noise averaged over the larger bandwidth. Integration times used in the various fields were in the range 3–7 hr.

Table 2 and Fig. 1 give the results at 240 MHz of a similar series of observations at the same field centres but with 1.8 times larger beam area, as a consequence of the lower frequency of observation. Integration times were in the range 2–5 hr. A more comprehensive analyses was made of these data because of their greater freedom from interference. The large number (512) channels used in these observations permitted the removal of narrow-band interference. An estimate is given of rms noise measured over 10 spectrometer channels, which corresponds to 49 kHz (=60 km/s). This noise was calculated relative to a straight-line fit through the entire spectrum. In most cases it represents the rms noise expected from the receiver and galactic background contributions. In two cases ($l = 100°$, $b = -40°$ and $l = 190°$, $b = 50°$) a higher value of rms noise resulted from a curved baseline. A lower value was calculated relative to a parabolic baseline; it is also tabulated, along with a more realistic lower limit for the 200 km/s protocluster width. These curved baselines cannot be removed, of course, before fitting the broad profile. A 1000 km/s width was taken from the broad component, since a larger velocity width (3125 km/s) is available in the 2.5-MHz bandwidth at this frequency. Table 2 includes the upper limits to the antenna temperature in each field for a Gaussian of width 1000 km/s. A histogram of the upper limits observed is given in Fig. 2 which will be compared with the theoretical model predictions in the next section.

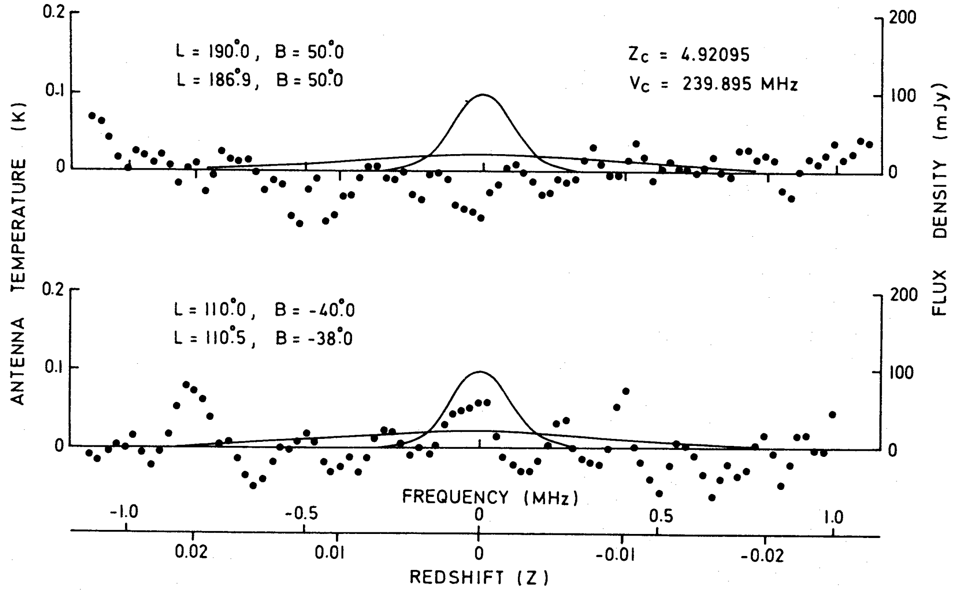

Figure 1. Mk IA observations of two pairs of fields in frequency bands centred at 239.895 ($z = 4.92095$); the beamwidth is 68 arcmin. The upper curve is the difference spectrum between fields centred at $l = 190°.0$, $b = 50°.0$ and $l = 186°.9$, $b = 50°.0$. The lower curve is the difference spectrum between the fields centred at $l = 110°.0$, $b = -40°.0$ and $l = 110°.5$, $b = -38°.0$. A signal in the first-named field of each pair will be positive while a signal in the second field will be negative. In each difference spectrum is plotted the Gaussian profile expected for a protocluster having a neutral hydrogen mass of $3 \times 10^{14} M_{\odot}$ and velocity widths of 200 and 1000 km/s.

3 Discussion

The results presented above will now be compared with the predictions of the protocluster model of Sunyaev & Zeldovich. They assume that the cluster parameters measured at the

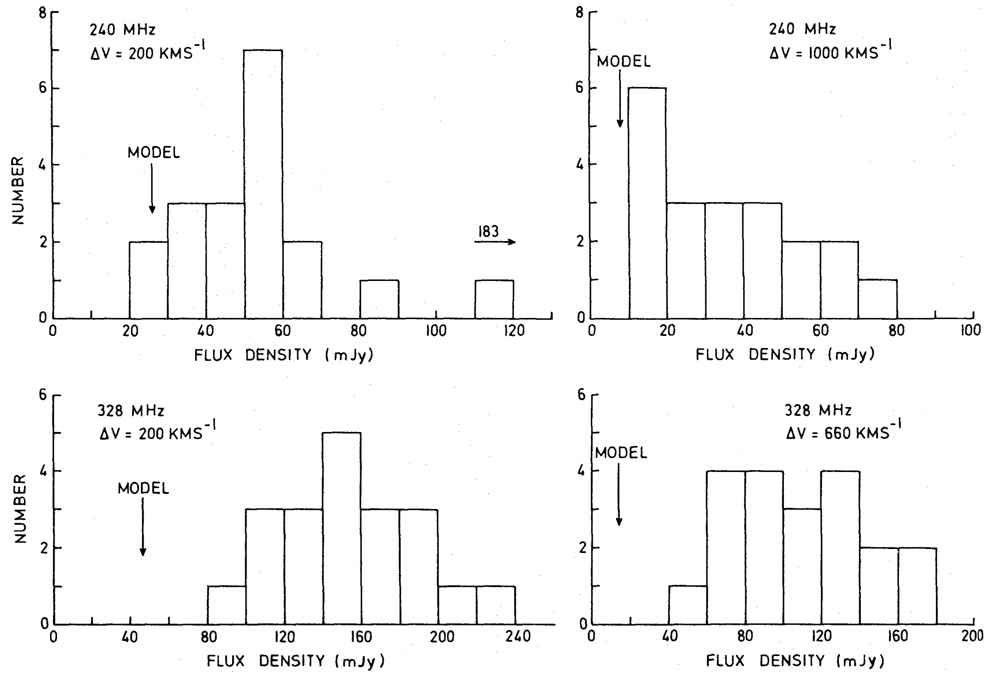

Figure 2. Histograms of the observational upper limits (2σ) to the neutral hydrogen emission from protocluster clouds. The upper two histograms are for 240 MHz ($z = 4.92$) where the halfwidths of the emission profiles are taken as 200 and 1000 km/s. The lower two histograms are for 328 MHz ($z = 3.33$) where the half-widths are 200 and 660 km/s. In each case the flux densities predicted from the Sunyaev & Zeldovich model are indicated by vertical arrows.

present epoch are also applicable to the earlier epochs investigated here. A mass of $3 \times 10^{14} M_\odot$ and a diameter of 2 Mpc are assumed. Half the total mass is taken to be neutral gas, of which 70 per cent by mass is hydrogen and 30 per cent is helium.

The line integral of neutral hydrogen through such a protocluster, having the proportion of neutral hydrogen discussed above, is 6.6×10^{21} atom cm^{-2}. The other important parameter in this discussion is the velocity dispersion v within the protocluster. An upper limit is provided by the virial condition, which leads to $v \lesssim 1100$ km/s. The *radial* component of this velocity will be $1100/\sqrt{3} = 660$ km/s. A total velocity width ΔV equal to this value would comfortably ensure that such a cluster is bound. A cluster could have a considerably lower velocity spread and the emission might consist of several narrow lines as indicated by Sunyaev & Zeldovich (1975). In the following we will consider the results in terms of a broad feature 660 km/s wide or a narrow feature 200 km/s wide, as might for example be characteristic of a pancake-shaped protocluster seen edge-on.

The parameters of the H I emission from protoclusters can be estimated using the equations given by Sunyaev & Zeldovich (1975) and are given in Table 3. The expected brightness temperature T'_b at the profile centre expected from the cluster is given by

$$T'_b = T_b/(1+z) = 5.14 \times 10^{-19} \int n_H \, dl / \Delta V \, (1+z),$$

where ΔV in km/s is the width at half intensity of the profile which is assumed Gaussian. Using $\int n_H \, dl = 6.6 \times 10^{21}$ atom/cm^2, the values of T'_b for $\Delta V = 200$ and 660 km/s lie in the range 0.9–3.9 K as shown in Table 3. The angular diameter of a cluster at redshift z was estimated from the expression

$$\theta = (DH_0/2c)\, \Omega^2 (1+z)^2 / [\![\Omega z - (2-\Omega)[(1+\Omega z)^{1/2} - 1]]\!],$$

where $H_0 = 75$ km/(s Mpc) is the Hubble constant, $\Omega = 2q_0 = 1$ is the ratio of the actual

Table 3. Predicted parameters of H I emission from protoclusters.

	$z = 3.33$		$z = 4.92$	
	$\Delta V = 660$ km/s	$\Delta V = 200$ km/s	$\Delta V = 660$ km/s	$\Delta V = 200$ km/s
Brightness temperature at observer (T'_b) in K	1.2	3.9	0.9	2.9
Angular diameter of cluster (θ) in arcmin	7.2	7.2	8.6	8.6
Flux density in mJy	14	45	8	26

density to the critical density of the Universe, and $D = 2$ Mpc is the linear diameter of the protocluster. The angular diameters are 7.2 and 8.6 arcmin at $z = 3.33$ and 4.92 respectively. These values are appreciably less than the beamwidths used here. The peak flux densities (S) predicted for the above values of T'_b and θ are given in Table 3 and range between 8 and 45 mJy.

These model predictions are indicated in Fig. 2 which is a plot of the upper limit of the peak flux density seen in each of the 20 fields at both 328 and 240 MHz. It can be seen that the observational limits closely approach the values expected from the model. Indeed, for the smaller values of ΔV some limits are less than the prediction.

In order to estimate the likelihood of observing a protocluster in a given beam it is necessary to estimate the number of protoclusters at early epochs. Using a present density of clusters of $3 \times 10^{-5}\,\mathrm{Mpc}^{-3}$ and assuming that protoclusters are in a condition to emit the 21-cm line for 10 per cent of their cosmological age, Sunyaev & Zeldovich estimate that there are $N = 2 \times 10^5$ protocluster clouds in the Universe. An observing bandwidth $\Delta\nu$ at a redshifted frequency ν will be able to detect $(\Delta\nu/\nu)N$ protoclusters which lie in a spherical shell of thickness $\Delta z/(1+z) = \Delta\nu/\nu$. Thus there will be 1.5×10^3 and 2.1×10^3 protoclusters detectable over the whole sky in the present observing bandwidth of 2.5 MHz at 328 and 240 MHz respectively. The number of beamwidths that have to be searched to find such a typical protocluster will then be

$$\left.\begin{array}{l}50 \text{ to } \tfrac{1}{2} \text{ power}\\ 27 \text{ to } \tfrac{1}{4} \text{ power}\end{array}\right\}\begin{array}{l}328\text{ MHz}\\ z = 3.32\end{array}$$

$$\left.\begin{array}{l}20 \text{ to } \tfrac{1}{2} \text{ power}\\ 11 \text{ to } \tfrac{1}{4} \text{ power}\end{array}\right\}\begin{array}{l}240\text{ MHz}\\ z = 4.92.\end{array}$$

The present survey contained 20 fields at each frequency. Accordingly, given sufficient sensitivity and the above estimate of the density of protoclusters, we would expect to see one cloud within the quarter-power beam of the 20 areas searched at 328 MHz and one within the half-power beam at 240 MHz.

We have indicated in the foregoing discussion that the sensitivity and sky coverage of the present search for primeval protoclusters at $z = 3.33$ and $z = 4.92$ are sufficient to be able to place significant limits on their flux density and volume density as predicted on the model proposed by Sunyaev & Zeldovich. Because of the great uncertainties in our knowledge of conditions in the early Universe, there is a wide choice of input parameters for the model. In particular (a) the mass of the protoclusters, (b) their space density and (c) the fraction of their lifetime spent in the neutral state could be uncertain by a half to one order of magnitude. The present observations provide limits close to the predicted values in a number of fields; at $z = 4.92$ nine out of 20 fields have emission limits $\leqslant 3$ times the prediction for $\Delta V = 1000$ km/s and all points have limits < 9 times the predicted value. A similar situation applies at each value of z and of ΔV. Although it is possible for individual protoclusters to have masses up to $\sim 3 \times 10^{15} M_\odot$ at the top end of the error (limit) distribution, a model in which all protoclusters have a substantially greater mass and have the space density and lifetime assumed is precluded by the data. Similarly a substantial fraction cannot have velocity dispersions much less than 200 km/s or else they would be correspondingly brighter and be visible.

4 Conclusions

Neutral hydrogen measurements appear to be able to contribute to our knowledge about early conditions of galaxy and cluster formation (Sunyaev & Zeldovich) and in this paper we have demonstrated that it is practicable to make an adequately sensitive search for the red-shifted neutral hydrogen emission from these objects. Observations at $z = 3.33$ and $z = 4.92$ show that either the number of protoclusters containing substantial amounts of neutral gas in the early Universe is $\leqslant 10^6$ or that their masses are $\lesssim 3 \times 10^{15} M_\odot$. Limits on the mass of a factor of 10 lower are set by the observations in some of the fields measured.

It should also be mentioned that the number of neutral protoclusters which we might expect to detect may exceed the number of protoclusters that eventually form clusters of galaxies, because the former group must include the field galaxies which will also have formed protocluster material. It is likely that the field galaxies were produced in an equal amount of protocluster material which presumably had a somewhat higher velocity dispersion and as a consequence were unbound gravitationally.

A further uncertainty in the predictions is the epoch of the neutral gas phase in the protoclusters. In their 1975 paper, Sunyaev & Zeldovich suggest $z = 5$–10 rather than $z = 3$–5 in their 1972 paper. We are planning searches at $z > 5$.

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