SEARCHES FOR PRIMORDIAL PANCAKES

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SUMMARY. The search for neutral hydrogen 21 cm emission from collapsing protoclusters at redshifts of 3-20 is an important technique for establishing the history of galaxy formation. Observations already place strong constraints on the largest mass scales. Future measurements should reach sensitivities adequate to detect individual massive galaxies.

1. PANCAKES AS PROTOCLUSTERS OF GALAXIES

The question of when and how galaxies formed is perhaps the most important problem in cosmology today, since its solution would change our view of virtually every type of astronomical object accessible to observation. The two principal observational attacks on the problem have been the searches for fluctuations in the microwave background at $z \sim 1000$, described by Bruce Partridge in this session, and for luminous protogalaxies at $z \sim 3$-5 reviewed recently by Koo (1985). A third method, the search for massive aggregates of neutral gas at the epoch of the gravitational condensation of galaxies, clusters and superclusters, is also one of the few methods which explore the Universe in the difficult range of redshifts $4 < z < 20$.

The picture of galaxy formation which motivates this last approach envisages collapse of gas clouds at least as massive as clusters of galaxies, say 10^{14}-$10^{16} M_{\odot}$, which fragment to form galaxies. Fluctuations which have densities slightly exceeding the critical density at the time of recombination at $z \sim 1000$ will continue to expand for some time but will eventually collapse like model universes with $\Omega > 1$. The gas pressure becomes negligible soon after recombination so that gravitational collapse, when it occurs, is initially free-fall. For many cloud geometries it will be principally along one axis, whilst expansion may continue along the other axis, giving rise to a thin dense gaseous disk or pancake. The density in the central layer may become high enough that radiative cooling is effective, keeping the gas there neutral and

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sandwiched between much hotter layers of shocked material. The neutral layer may then fragment into clouds with masses of groups or single galaxies.

The fraction of the whole cloud which is neutral during the collapse, the thickness of the resulting pancake, the lifetime of the gas in the neutral state and the redshift at which the collapse occurs depend on the detailed dynamics of the clouds and hence on their initial conditions. Here our ignorance is nearly total since we know nothing about the amplitudes of the fluctuations in density or their spectrum except what can be deduced from the microwave background studies. At present they provide us only with a useful set of upper limits which can be interpreted in several ways. But our knowledge that rich clusters of galaxies, having masses of typically a few x $10^{15}M_\odot$, do exist now enables us to make specific predictions about their precursors. If they formed from pancakes, then the absence of Lyα absorption in quasar spectra by such objects for z<3 shows that the collapse phase occured earlier. The upper limits on $\Delta T/T$ in the microwave background observations, if interpreted conservatively, suggest that scales with these masses must have collapsed later than z=20. The detection of the neutral hydrogen gas by its redshifted 21 cm line seems possible for this range of redshift (ν = 70-350 MHz) as pointed out first by Sunyaev and Zeldovich (1975).

2. 21 CM LINE EMISSION FROM PANCAKES

The physical parameters of the pancakes are easy to estimate, if difficult to predict precisely. The volume containing a mass M in a Friedmann Universe has a comoving diameter

$$D = 19\ (M/10^{15}M_\odot)^{1/3}\ \Omega_0{}^{1/3}\ h^{2/3}\ \mathrm{Mpc}$$

where Ho = 100h km/s Mpc.
ts angular diameter at redshift z is

$$\theta = DH_0\Omega_0{}^2(1+z)/2c[\Omega_0 z-(2-\Omega_0)(\surd(1+\Omega_0 z)-1]$$

For M = $10^{15}M_\odot$ and Ω_0=1, the angular diameter decreases slowly from 18' at z=5 to 14' at z=20, whilst for Ω_0=0.2 the corresponding range is 17' to 9'. These values are the appropriate ones if the incipient pancake continues to expand in directions in its plane at least until the collapse is complete. For such a model the velocities of collapse are

$$\pm(2GM(1+z)/D)^{1/2} = \pm\ 684(1+z)^{1/2}(M/10^{15}M_\odot)^{1/3}\Omega_0{}^{1/6}h^{1/3}\ \mathrm{km/s}$$

The model is probably not too poor a description since the pancake diameters at (1+z) = 10, when they may have collapsed, are ~ 2 Mpc for $10^{15}M_\odot$, the same as the current dimensions of rich clusters. Uncertainty in the correct model leads to corresponding uncertainty

in the velocities of collapse. But there will be in any case a large range in the observed radial velocities due to the differing orientations of the pancakes to the line of sight. That part of the hydrogen which remains unionised in the collapse will be heated to high temperatures so that the pancake will remain optically thin in the 21 cm line even with the large masses of HI involved.
The mean number density at redshift z is

$$11.4\Omega_0 h^2(1+z)^3 \ m^{-3}$$

giving a column density for a cloud of mass M of

$$N_H = 6.67 \times 10^{24}\Omega_0^{2/3}h^{4/3}(1+z)^2(M/10^{15}M_\odot)^{1/3} \ m^{-2}$$

The brightness temperature in the emitted line is then related to the HI column density by the standard relation

$$N_{HI} = 1.84 \times 10^{22}(T/k)(v/kms^{-1}) \ m^{-2}$$

For a face-on pancake, where the range of radial velocity is greatest, the observed brightness temperature in the 21 cm line is

$$T = 0.26\Omega_0^{1/2}h(1+z)^{1/2} \ k$$

$= 0.58\Omega_0^{1/2}\lambda^{1/2}$ k at an observing wavelength λ, independent of the mass of the pancake. Edge-on pancakes will have brightness temperatures several times larger since they both subtend smaller solid angles and exhibit a much smaller range of radial velocities. They are, however, likely to be only a small fraction of the mean galactic background brightness

$$T_{gal} \sim 40\lambda^{2.7} \ k$$

The corresponding total flux detected from a pancake is (for Ω_0=1)

$$S\Delta\nu = 1336 \ (1+z)^{-2}(M/10^{15}M_\odot) \ mJy \ MHz$$

Fig 1 shows curves of $S\Delta\nu$ as a function of M and z for different values of Ω_0, together with limits set by observation which we shall now review.

3. OBSERVATIONAL SEARCHES

Several searches for redshifted 21 cm emission have been carried out but few published, perhaps because of doubts about the value of negative results when predictions are also very uncertain. Observers are becoming less reticent and I think rightly so. The microwave background fluctuation problem highlights how sucessfully observers and theorists spur each other to greater heights of ingenuity in setting limits and explaining them.

The earliest experiment, rather than observing programme, that I know of was by Martin Ryle and Patricia Leslie at Christmas 1959 (always a good time for long integrations on speculative experiments) using parts of the 4C telescope at 178 MHz. They used a long path delay in one arm of an interferometer to remove the effects of continuum sources, whilst retaining full sensitivity to signals < 1 MHz in bandwidth. There was no theoretical background to this experiment except that at some time in the past most material must have been atomic hydrogen and its distribution might have been irregular. The pen records still exist and show that they saw nothing on scales of $\sim 1°$ with a limiting sensitivity of roughly $10^{18} M_{\odot}$ of HI.

The first serious observations were those of Davies et al (1978) in which the Mark IA telescope at Jodrell Bank was used at 240 and 328 MHz ($(1+z) = 5.9$ and 4.3) with a 1024-channel spectrometer. 20 fields were observed at each frequency with a beam switching technique giving good limits on the surface brightness of any line emission of about 0.1K at 328 MHz and between 0.01 and 0.1K, depending on bandwidth, at 240 MHz. The beamwidths of 50' and 68' were larger than any anticipated angular size for protoclusters. None were found at these levels which correspond to HI masses of $\sim 3 \times 10^{14} M_{\odot}$. The main shortcoming of the search was the small volume of space searched making the chance of detection rather low.

A recently published search carried out several years ago by one of my students, David Bebbington (1986) has set useful limits at a yet lower frequency (151 MHz; $(1+z) = 9.4$). The observations were made with the 6C Telescope at Cambridge on a region surrounding the North Celestial Pole identical to that mapped in the first part of the 6C Survey (Baldwin et al 1985). The telescope is an East-west aperture synthesis instrument with 446 simultaneous interferometer baselines at uniform increments of 1.5λ giving a resolution of $4' \times 4'$ over a field of view of $14° \times 14°$ and with good sensitivity to large scale strucutre. In the continuum the distribution of sky brightness is dominated by the extragalactic source population, so the search for pancakes was carried out by making difference maps from observations in two adjacent bands 800 KHz wide centred at 151 and 152 MHz. To overcome instrumental and ionospheric variations which affect differentially the data taken on different days, the observations at the two frequencies were interleaved by switching the local oscillator at intervals of 6s. On successive days the phase of the switch was reversed so that the data could be combined to give similar coverage of the aperture plane for each frequency band. Sources having the mean continuum spectral index of $\alpha \sim 0.75$ are eliminated in the difference map by suitable choice of the weights of the two maps. Sources with spectra differing from the mean show up as weak sources of positive or negative flux density at their known positions. More troublesome was the problem of distant and grating sidelobes from very strong sources (Cyg A and Cas A) at very large angles from the beam centre. Such sidelobes have radii which are frequency dependent and therefore mimic the signals which

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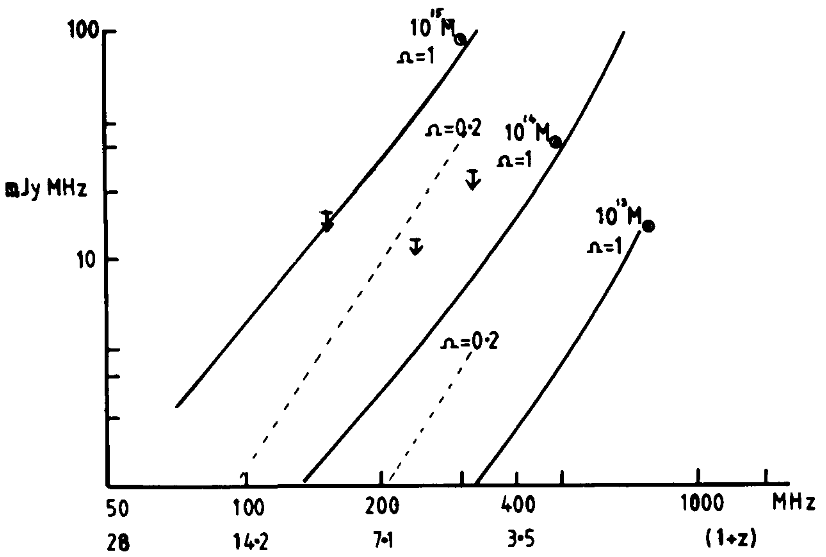

Fig 1. Limits on redshifted emission from neutral hydrogen as a function of observing frequency.

are being sought. Careful filtering of the data reduced their effects to near the noise level. Difference maps made with angular resolutions of 4' x 4' and 8' x 8' had noise levels of 5 and 10 mJy/beam area respectively. No significant features were seen above the noise level except, as anticipated, at the positions of several of the brightest continuum sources. The surface brightness limits at the two resolutions correspond to brightness temperatures of 5 and 2.5k. The predictions for Ω=1 for pancakes of 10^{15} M_{O} seen face-on at this frequency give angular sizes of 18' and brightness temperatures of 0.8k. The brightness increases, due both to the increased column density and the reduced line of sight velocity dispersion, to up to 10k for pancakes seen within 30° of edge-on, which statistically will occur in half the cases. The upper limits established here are plotted together with those of Davies et al in Fig 1. Their significance is discussed below.

Other searches which have been carried out or are in progress include that by Sullivan at 150 MHz using the Arecibo telescope, by observers with the Westerbork telescope at 327 MHz and by Subramanyan with the Ooty telescope also at 327 MHz. The latter searches give some hope of reaching interesting limits perhaps close to 1mJy MHz.

Whilst the limiting sensitivity in the searches is of prime importance, so too is the volume of space explored. The dimensions of the region surveyed in comoving coordinates are, in the radial direction.

$$c\Delta t(1+z) = c\Delta z/H_O(1+z)(1+\Omega_O{}^2)^{\frac{1}{2}}$$

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$$= (c/H_0)(\Delta\nu/\nu)/(1+\Omega_0{}^2)^{1/2}$$

and in the transverse direction.

$$2c\Theta[\Omega_0 z - (2-\Omega_0)(\sqrt{(1+\Omega_0 z)} - 1)]/H_0\Omega_0{}^2(1+z)$$

giving a comoving volume of

$$\Theta^2 \; (\Delta\nu/\nu)4(c/H_0)^3[\Omega_0{}^2-(\Omega_0{}^2-(2-\Omega_0)(\sqrt{(1+\Omega_0{}^2)}-1)]^2/\Omega_0{}^4(1+2)^2(1+\Omega_0 z)^{1/2}$$

which is almost constant at

$\sim 1.5 \times 10^{10}\ \Theta^2(\Delta\nu/\nu)h^{-3}$ Mpc^3 for $3<z<20$ for $\Omega_0 = 1$

and with more variation

$\sim (5-15)\times10^{10}\Theta^2(\Delta\nu/\nu)h^{-3}$Mpc^3 for $z = 3 - 10$ for $\Omega = 0.2$

In the searches described above the search parameters were (for Ω_0=1)

328 MHz	20 fields each with Θ=50'	$\Delta\nu$=2.5 MHz	Volume = $4.8\times10^5h^{-3}$Mpc^3
240 MHz	20 fields each with Θ=68'	$\Delta\nu$=2.5 MHz	Volume = $1.2\times10^6h^{-3}$Mpc^3
151 MHz	Θ=14°	$\Delta\nu$=1.6 MHz	Volume = $1.0\times10^7h^{-3}$Mpc^3

Rich clusters of galaxies, such as those in Abell's list, have total masses of 1-10x10^{15} $M_\odot$, comparable with the pancake masses discussed here. There are roughly 4000 within a redshift of 0.2, giving a space density of $4.4\times10^{-6}h^3$Mpc^{-3}. The expected number of such clusters in these searches, assuming Ω_0=1, are than 2,5 and 53. If the whole mass of clusters at that epoch were neutral gas, they would certainly have been detected. What fraction should be detectable as HI pancakes depends critically on what fraction of the total mass appears as HI, in particular, what fraction of the total mass is baryonic and what fraction of that is neutral. The lifetime of the gas in the neutral state is also uncertain.

The overall effect of assuming different values of Ω_0 is that, for Ω_0=1, the fluxes expected for pancakes are relatively large due to the large angular size for a given comoving diameter whilst for the same reason the search volume is relatively small. For small Ω_0 the reverse is true, the search volumes are large but the fluxes expected are small and 10^{15} $M_\odot$ lies below the present limits of detection.

4. FUTURE PROSPECTS

The present results do not allow a unique interpretation. Clusters may have only a small fraction of their mass as HI and for only a short period, or they may have condensed earlier than (1+z) = 9.4 or could be improved by a factor of, say, 100 a much clearer distinction might be made. Gas clouds of 10^{13} M_0 collapsing to form galaxies might be detected.

Such a goal needs very careful experimental design for two main reasons. First, the fluxes expected are weak [$S\Delta\nu \sim 13(1+z)^{-2}$ mJy MHz] spread over bandwidths $\Delta\nu \sim 1/(1+z)^{1/2}$ MHz and angular sizes of 3'-4'. Large collecting areas (> $10^4 m^2$) are required to achieve adequate sensitivity even with integration times of several days. Because of the variation of the mean galactic background brightness $T_{gal} \sim 50\lambda^{2.7}$, the area of telescope required increases very rapidly with increasing λ, ie increasing (1+z), (area $\propto \lambda^{4.5}$). Secondly the spectral signals from the HI must be discriminated from the much stronger continuum signals from many sources in the field. For instance at 150 MHz, where the fluxes expected are about 0.5 mJy over 0.3 MHz bandwidth, there are 12 sources deg^{-2} with flux densities of 50 mJy. Given good spectrometers, that may not seem a difficult problem, but it is essential that the spectral response of the telescope is smooth and that it is uniform over the field of view. The response to the brightest sources in the sky, ~ 10^4 Jy at this frequency, must also be kept exceptionally small (80dB rejection) which requires very careful design for narrow band work at low frequencies. A further source of frequency dependent sidelobes is provided by ionospheric path fluctuations which will need to be calibrated rather precisely. All of these problems are less severe at shorter wavelengths but the prospects there are somewhat less exciting given the failure of searches to find individual protogalaxies out to z=5 and the rather small amounts of galactic evolution seen out to z ~ 2 which also suggests an early time for galaxy formation.

At present the only telescope planned which might reach the necessary sensitivities is the Giant Metrewave Radio Telescope (GMRT) to be built by Govind Swarup and his group near Poona, India. The problems of detecting protoclusters are considerable, but so is their ingenuity and we wish them every success in achieving so important an objective.

REFERENCES

Baldwin, J.E., Boysen, R.C., Hales, S.E.G., Jennings, J.E., Waggett, P.C., Warner, P.J., and Wilson, D.M.A., 1985. Mon. Not. R. astr. Soc. 217, 717.

Bebbington, D.H.O., 1986. Mon. Not. R. astr. Soc. 218,

Davies, R.D., Pedlar, A. and Mirabel, I.F., 1978. Mon. Not. R. astr. Soc. 182, 727.

Koo, D.C., 1985. Erice Workshop on Spectral Evolution of Galaxies, eds C. Chiosi and A. Renzini, Reidel.

Sunyaev, R.A. and Zeldovich, Ya.B., 1975. Mon. Not. R. astr. Soc. 171, 375.

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