SEARCH FOR PROTO-CLUSTERS AT METER WAVELENGTHS

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Although current models of galaxy formation differ widely, it seems likely that just prior to their formation, a significant fraction of the matter in the Universe was in the form of neutral hydrogen (HI) clouds at redshifts z greater than about 3, beyond which the quasar density decreases rapidly. In this paper we have taken a semi-empirical approach for estimating values of measurable parameters for a variety of scale sizes and masses expected in the epoch prior to galaxy formation and have compared these with the results of searches made so far.

Searches for the redshifted 21-cm line radiation from HI clouds have been carried out by the Jodrell Bank group at z = 3.28 and 4.92 (Davies et al. 1978) and by the Cambridge group at z = 8.4 (Bebbington 1986). The observations indicate upper limits for the masses of the proto-clusters of about $1 - 10 \times 10^{15} M_{\odot}$, or that the number of such objects in the early Universe is $\lesssim 10^6$.

According to the adiabatic perturbation model considered by Sunyaev & Zeldovich (1972;1974), super-clusters of mass $\sim 10^{14} - 10^{16} M_{\odot}$ condense first and galaxies are formed later by fragmentation at $z \sim 5$ to 10. In their model, only a few thousand proto-clusters are observable over the entire sky in a bandwidth of a few MHz in the frequency range of about 150 (z = 8.5) to 327 MHz (z = 3.3). On the other hand, in the isothermal perturbation scenario or in the recent cold dark matter models, galaxies form first and aggregate hierarchically to form clusters at later epochs (Peebles 1980; Blumenthal et al. 1984). The observational strategies for the detection of HI clouds differ considerably for the two cases (Hogan and Rees 1979; Oort 1984). Since the HI condensations expected in the adiabatic model are relatively rare, a large region of the sky needs to be searched. However, for the hierarchical clustering scenario, where large scale clustering of relatively low mass condensates are expected, highly sensitive observations are desirable, but searches over only a few square degrees may suffice. In both cases we may have to search over a large redshift range. An extensive search for proto-clusters is one of the major objectives of a Giant Meterwave Radio Telescope being set up in India (Swarup 1984).

In our model a fraction β_z, of the total mass M contained in a cell of characteristic size d_z, condenses into a cloud of size a_z. At any epoch only a fraction f_z of these cells are observable in their 21-cm emission, depending upon their formation rates and lifetimes. It is assumed that 75% of the baryonic mass is hydrogen, of which half is neutral at the epoch of condensation. Hence,

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the neutral hydrogen mass $M_{HI} = 0.375\,\beta_z(\Omega_b/\Omega_o)M$, where (Ω_b/Ω_o) is the ratio of baryon to total density parameter. We take $(d_z/a_z) \sim 2$ at the epoch of formation. The relationship between d_z and M is given by

$$d_z = [M/\rho_c\,\Omega_o]^{1/3}\,(1+z)^{-1}$$

where $\rho_c = (3H_o^2/8\pi G)$ is the critical density and $H_o = 100\,h$ km s^{-1} Mpc^{-1}. Hence

$$d_z = 7.13\,[M\,(10^{14}M_\odot)]^{1/3}\,h^{-2/3}\,(1+z)^{-1}\,\Omega_o^{-1/3}\ \text{Mpc}.$$

The clouds being optically thin, the peak line flux density is given by

$$S_p = \frac{g_2}{g_1+g_2}\cdot A_{21}\cdot\frac{h\nu_e}{4\pi}\cdot\frac{M_{HI}}{m_p}\cdot\frac{1}{D^2(1+z)^2}\cdot\frac{1}{\Delta\nu_o}$$

where $D = (2c/H_o\Omega_o^2)\,[\Omega_o z + (\Omega_o - 2)\{(\Omega_o z + 1)^{1/2} - 1\}]\,/\,(1+z)$.

Thus, $$S_p = 56.17\,\frac{M_{HI}(10^{14}M_\odot)\,h^2\,\Omega_o^4\,[\Delta\nu_o^W(\text{MHz})]^{-1}}{[\Omega_o z + (\Omega_o - 2)\{(\Omega_o z + 1)^{1/2} - 1\}]^2}\ \text{mJy}.$$

The observed angular size of the condensate is

$$\theta_a = (a_z/D)\,(1+z)$$

$$= 0.573\,\frac{h\,\Omega_o^2\,a_z(\text{Mpc})\,(1+z)^2}{[\Omega_o z + (\Omega_o - 2)\{(\Omega_o z + 1)^{1/2} - 1\}]}\ \text{arcmin}.$$

The observed width, $\Delta\nu_o^W$, of the red-shifted 21-cm line ($\nu_e = 1420$ MHz) due to the virial motion of HI gas is

$$\Delta\nu_o^W = \alpha_z(2\beta_z GM/3a_z)^{1/2}\,\nu_e(1+z)^{-1}\,c^{-1}$$

$$= 2.54\,[\alpha_z/(1+z)]\,[\beta_z\,M(10^{14}M_\odot)/a_z(\text{Mpc})]^{1/2}\ \text{MHz}$$

where $\alpha_z = \Delta\nu_o^W/\Delta\nu_o^V$ is the degree of virialization in the condensate.

Table I gives the calculated values of the observed peak line flux density S_p, virial line-width $\Delta\nu_o^W$ and angular size θ of the HI cloud of size $a_z = 0.5\,d_z$ for $z = 3.34$ and 8.47. We have assumed $\Omega = 1$ and $H_o = 75$ km s^{-1} Mpc^{-1}. Taking $\beta_z = 0.5$ and $\Omega_b = 0.1$, the mass of neutral hydrogen in the condensate is $M_{HI} \simeq M/50$. The Observed line width may be smaller by a factor $\alpha_z < 1$, as the clouds may not be virialized at the epoch of formation. If the scale size of the clouds is smaller than $0.5\,d_z$ at the epoch of condensation, the observed angular size θ would be correspondingly smaller.

It is seen from Table I that the line flux densities for super-cluster size clouds with $M \gtrsim 10^{16}$ are expected to be $\gtrsim 5$ mJy, which should be observable using some of the existing large radio telescopes, provided searches are made over a sufficiently large area of the sky and at several redshifts. However, for

Table 1. Calculated values of measurable parameters from Proto-clusters

Mass($M_\odot$)		z = 3.34 (327 MHz)				z = 8.47 (150 MHz)			
M	M_{HI}	d_z (Mpc)	S_p (mJy)	$\Delta\nu_o^v$ (MHz)	θ (arcmin)	d_z (Mpc)	S_p (mJy)	$\Delta\nu_o^v$ (MHz)	θ (arcmin)
5×10^{16}	10^{15}	15.8	18.86	3.29	28.34	7.24	3.47	2.23	21.82
5×10^{15}	10^{14}	7.33	4.06	1.53	13.15	3.36	0.75	1.03	10.13
5×10^{14}	10^{13}	3.40	0.87	0.71	6.10	1.56	0.16	0.48	4.70
5×10^{13}	10^{12}	1.58	0.19	0.33	2.83	0.72	0.035	0.22	2.17

clumpiness on smaller scales, higher sensitivity and higher angular resolution is required as obtainable by a synthesis radio telescope. Even in the case of hierarchical clustering of small clouds, the HI lines are likely to be sufficiently separated in frequency as discussed below.

The observed separation between lines, $\Delta\nu_o^s$, depends on the redshift distribution of clouds :

$$\Delta\nu_o^s = H_o d_z f_z^{-1/3} (1 + \Omega_o z)^{1/2} \nu_e c^{-1}$$
$$= 0.473\, d_z(\mathrm{Mpc}) h\, f_z^{-1/3} (1 + \Omega_o z)^{1/2} \ \mathrm{MHz}.$$

Hence, the ratio of virial line width to the line separation is

$$\frac{\Delta\nu_o^w}{\Delta\nu_o^s} = 0.282\ \alpha_z \beta_z^{1/2} f_z^{1/3} \Omega_o^{1/2} \left(\frac{d_z}{a_z}\right)^{1/2} \left(\frac{1 + z}{1 + \Omega_o z}\right)^{1/2}$$

The maximum value of $\Delta\nu_o^w / \Delta\nu_o^s = 0.28\,(d_z/a_z)$ is <1, if $(d_z/a_z) \lesssim 3$ at the epoch of formation of condensates. According to our estimates, the values of the above parameters are likely to be : $f_z \sim 0.2$, $\alpha_z = 0.5$, $\beta_z = 0.5$, $\Omega_o = 0.3 - 1.0$, $d_z/a_z \sim 2$ to 3. Hence $\Delta\nu_o^w/\Delta\nu_o^s \sim 0.07$ to 0.10. Searches for the $\sim 10^{15-16}\ M_\odot$ super-clusters which are expected to form by the growth of adiabatic perturbations are perhaps best done at larger redshifts (~ 6 - 10), when these structures may start fragmenting. On the other hand hierarchical clustering of relatively low mass condensates are more likely to be detected at lower redshifts (~ 3 to 6) when large scale clustering of the smaller condensates might have occured.

Recently, the Westerbork group has put upper limits to the line flux density of about 10 mJy at 327 MHz (z = 3.34) at a resolution of about 1 arcmin (private communication). This corresponds to $M_{HI} \sim 10^{14}\ M_\odot$ over a scale size of $\lesssim 0.06$ Mpc. Since many such clouds may exist in the field of view of a few square degrees of the Westerbork synthesis radio telescope, it may be possible to increase the sensitivity for the detection of a hierarchical distribution of low mass clouds by appropriate power spectrum analysis.

The detection of primordial HI clouds is a challenging observational problem. The searches made at the Jodrell Bank and the Cambridge Observatories have constrained clumping only on the largest scales of epochs corresponding to $z \sim 3.3$, 4.9 and 8.5. The Westerbork observations have put a much lower limit of $\sim 10^{13}\ M_\odot$ for $z \sim 3.3$ but only over a few square degrees of the sky. For constraining various theoretical models and in order to have a detailed understanding of the evolution of the primordial gas and its condensation, it would be desirable to reach an order of magnitude higher sensitivity, say, a fraction of a mJy at several discrete frequencies corresponding to z in the range of about 3 to 10.

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DISCUSSION

DAVIES: Our recent Jodrell Bank measurements at 151 MHz (z = 8.4) were most sensitive to protoclusters with velocity widths in the range 200 to 800 km s^{-1}. Protoclusters with masses greater than 3 x 10^{14} solar masses would have been detected if they had a substantial fraction of their mass in this velocity range. No such protoclusters were detected, although we would have expected a few in the volume of space sampled. I would comment that ideally a velocity width of more than 2000 km s-1 should be sampled in this type of observation. Could I ask the theorists what they consider would be the best redshift interval for the protocluster search?

SWARUP: We are undertaking observations over bandwidths of ~10 MHz corresponding to $\gtrsim$ 10,000 km s^{-1}. Perhaps Dr. Silk may have a comment regarding your query.

SILK: We would expect to find protogalactic or protocluster hydrogen clouds at the redshifts of the most remote quasars. This is where we might expect to see galaxy formation. Indeed the only example of a primeval galaxy is an object at a redshift of 3.2 found by optical search adjacent to a quasar at the same redshift.