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Neutral Hydrogen at High Redshifts as a Probe of Structure Formation

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Abstract. Structure formation at $z \lesssim 10.0$ can be detected and studied using the 21 cm line emission from the neutral hydrogen. Two of us (Subramanian & Padmanabhan 1993, Paper I) had earlier computed the expected abundance of protoclusters as a function of the flux density at various redshifts, in the Cold dark matter (CDM) and the Hot dark matter (HDM) models. Here we work out in detail how the HI line profile from a single spherically symmetric protocluster evolves as it decouples from hubble expansion and collapses. We find peak fluxes of the HI line profile to be typically of order 0.4–0.8 mJy while the widths (FWHM) are of order 0.6–1.5 Mhz. Such protoclusters could be detectable by the Giant Metrewave Radio Telescope (GMRT) which is being built in India.

Key words: Structure formation—protoclusters—GMRT.

1. Introduction

Galaxies and large scale structures in the universe may originate by the growth of small initial perturbations via gravitational instability. In this picture it should be possible to detect neutral hydrogen in the protocondensates by observing the redshifted 21 cm line (Sunayaev & Zeldovich 1972, 1974). The GMRT presently being constructed in India is expected to provide a sensitive instrument for detecting such protocondensates (Swarup 1984). It is, therefore, interesting to work out the expected flux of redshifted 21 cm emission in various models of structure formation and compare the results with the expected sensitivity limits of future instruments like GMRT.

In Paper I two of us had computed the expected abundance of protocondensates which will emit a flux higher than S, at various redshifts, in the CDM and HDM models, normalised using the COBE results. Here we complement the study in Paper I by working out in detail how the HI line profile from a single protocluster evolves as it decouples from hubble expansion and collapses. Our calculations assume that: (i) The protocluster consists of small scale clumps of HI gas, as is likely in hierarchical clustering theories of galaxy formation (Paper I and Subramanian & Swarup 1992). (ii) The density profile of the protoclusters is spherically symmetric and the density contrast is a decreasing function of the radius. We will also test the sensitivity of the results to changes in the assumed density profile.

2. Evolution of the line profile

Consider a spherically symmetric perturbation with excess density contrast $\delta_i(r_i)$ monotonically decreasing with r_i. As the protocluster evolves, shells at larger and larger radii decouple from the hubble expansion, turn around and collapse. The 21 cm line emission from different volume elements will be redshifted differently because of the peculiar velocity of the elements and hence will be observed at different frequencies. By properly adding them, we can obtain the energy emitted by such a condensate as a function of the observed frequency.

In the spherical model the time evolution of a shell of radius r in the condensate is given by $r(t) = (3x/10\bar{\delta}_0(x))\,(1 - \cos\psi)$ where $t = (3/5)^{3/2}(3/4)\,(t_0/\bar{\delta}_0(x)^{3/2})\,(\psi - \sin\psi)$. Here $x = [a(t_0)/a(t_i)]r_i = (1 + z_i)r_i$ is the comoving radius of the shell and $\bar{\delta}_0(x) = \langle \delta_0(x) \rangle = (3/5)\,(1 + z_i)\bar{\delta}_i(r_i)$ is the average excess density contrast within the shell, extrapolated to the present epoch t_0. (We have also assumed a flat universe with $\Omega = 1$.) From these equations it is simple to work out how the velocity and density profile of the protocluster evolves (Peebles 1980; Padmanabhan & Subramanian 1992).

The energy emitted per unit time in 21 cm line radiation from a small volume $\mathrm{d}x\mathrm{d}y\mathrm{d}z$ of the protocondensate is $\mathrm{d}E = (3/4)A_{21}\,h\nu_e(\rho_{\mathrm{HI}}(x,y,z)/m_p)\mathrm{d}x\mathrm{d}y\mathrm{d}z$. Here A_{21} is the spontaneous emission rate, ν_e is the frequency of the 21 cm photon, m_p the proton mass and ρ_{HI} the neutral hydrogen density which we take to be a fraction, f say, of the total mass density. To compute the luminosity per unit frequency interval, $\mathrm{d}u(\nu)/\mathrm{d}\nu$, from the protocondensate, we transform $\mathrm{d}E$ from (x,y,z) to the (x,y,ν) (sky-frequency) co-ordinates, and integrate the emission over the sky. This transformation introduces a Jacobian factor of $\partial\nu/\partial z \propto \partial v_z/\partial z$ in the denominator. Knowing the expressions for $\rho(x,y,z,t)$, and $v_z(x,y,z,t)$, we can explicitly compute the evolution of the line profile at various redshifts.

In particular we have taken here the spherically symmetric form for $\rho(r,t)$ and $v(r,t)$ calculated as above. In this case it is more convenient to use (r,ϕ,θ) co-ordinates and transform θ to ν using $\nu = (\nu_e/(1 + z_c))\,(1 - (v(r,t)\cos\theta/c))$ where z_c is the redshift of the protocluster. We then have

$$\frac{\mathrm{d}u(\nu)}{\mathrm{d}\nu} = \frac{3\pi}{2}A_{21}hc(1 + z_c)\int \frac{\rho_{\mathrm{HI}}(r,t)r^2\mathrm{d}r}{m_p v(r,t)}. \tag{1}$$

In evaluating $\mathrm{d}u/\mathrm{d}\nu$ we should keep in mind that (at a fixed ν), only those values of r satisfying the above ν–θ relation for some θ will contribute to the integral in (1). We can also compute the observed flux as a function of frequency by dividing (1) by $4\pi D_L^2$, where D_L is the luminosity distance of the $\Omega = 1$ FRW Universe.

For explicit computations we have adopted an initial density profile of the form: $\delta_0(x) = \delta_0(0)\,[1 + (x/a)^2]^{-\alpha}$ for $x < R$ and zero for $x > R$. We have chosen $R = 15.09$ Mpc corresponding to a protocluster of mass $10^{15}\,M_\odot$, and $a = 3$ Mpc. We have calculated the line profile for three different density profiles $\alpha = 1, 3/2, 5/2$ and also for the top hat profile $\delta_0(x) =$ constant. The central density contrast $\delta_0(0)$ is chosen so that the excess density contrast of the protocondensate is $n \times \sigma_{\mathrm{CDM}}(R)$ where $n = 1.0, 2.5$, and $\sigma^2_{\mathrm{CDM}}(R)$ is the mean square fluctuation in the sphere of radius R in the CDM model normalised to the COBE results (note that this is the only model we consider here). The neutral fraction f is somewhat uncertain and we have taken it to be 0.025 (see also Paper I and Subramanian & Swarup 1992). Further we have cut off the contributions to the flux from shells which have collapsed to a radius more than half their turn around radius. This is to take account of the possible ionisation of HI once collapse and virialisation occurs.

In Fig. 1 we plot the emitted luminosity per unit velocity range (v_z) (in units of 10^{25}ergs s^{-1}Hz^{-1}) at different stages of the evolution ($z = 8.5, 5.1, 3.34$) of the protocondensate for $\alpha = 1$ and taking it to be a 1σ fluctuation. As shells at larger and larger radii turnaround, the peak luminosity increases, while the half width decreases. Indeed, the peak flux can become arbitrarily high, since there could be a caustic in the velocity space. However, the internal velocities of the small scale clumps in the protocluster will in general lead to the smoothening of the line and so a peak of finite height. To take this into account, we convolve the emission profile with a gaussian of dispersion $\sigma_v = 100 - 200$ kms^{-1}, velocity widths typical of luminous galaxies.

The raw and the convolved ($\sigma_v = 200$ kms^{-1}) line profiles (flux vs frequency) are shown in Fig. 2 for $z = 3.34$, one of the redshifts which will be probed by the GMRT, for both a 1σ and a 2.5σ fluctuation (solid and dashed lines correspond to the

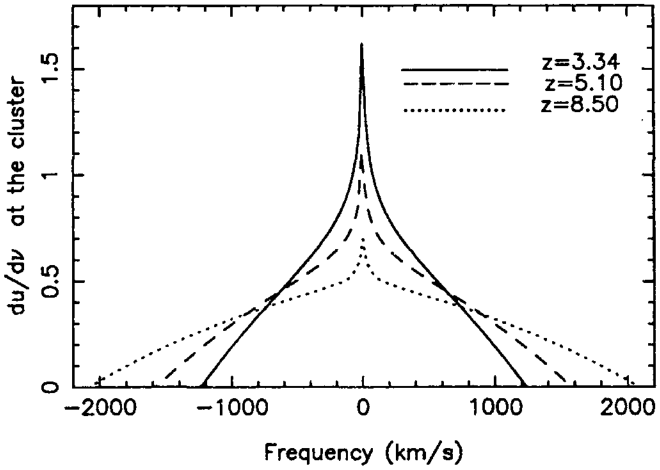

Figure 1. The emissivity line profile at different stages of the evolution ($z = 8.5, 5.1, 3.34$) of the protocondensate for $\alpha = 1$ and taking the protocondensate to be a 1σ fluctuation.

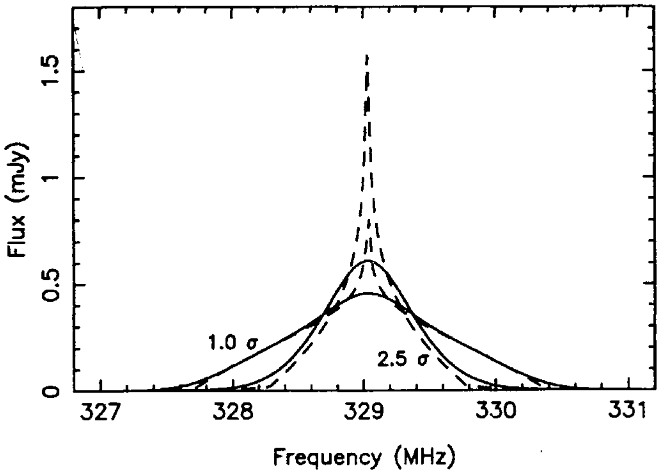

Figure 2. The raw and the convolved ($\sigma_v = 200$ kms^{-1}) line profiles (flux vs frequency) for $z = 3.34$, for both a 1σ and a 2.5σ fluctuation. Solid and dashed lines correspond to the convolved and raw profiles respectively.

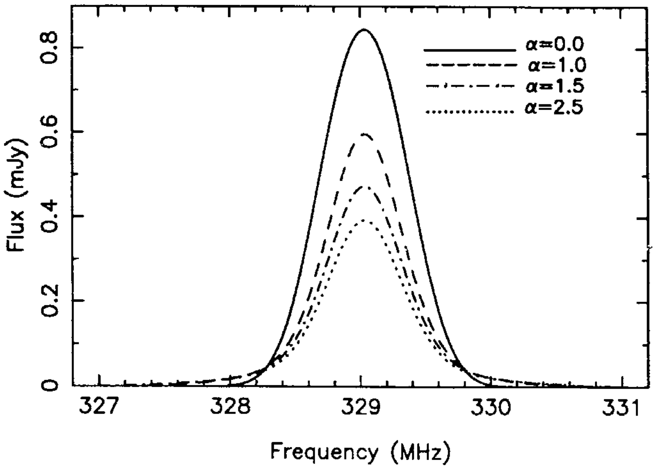

Figure 3. The convolved line profile for different initial density profiles ($\alpha = 0, 1, 3/2, 5/2$) taking the protocluster to be a 3σ fluctuation.

convolved and raw profiles respectively). The peak fluxes of the convolved line profiles that we have looked at are typically of order 0.4 – 0.8 mJy while the widths (FWHM) are of order 0.6 – 1.5 Mhz, depending on σ_v and the value of n. If one considers a protocondensate with twice the mass adopted above the fluxes also correspondingly increase by a factor ~ 2. Note that the expected σ_{rms} due to the thermal noise in GMRT at the corresponding frequency (327 MHz), for 10 hour integration and say a bandwidth of 300 Khz is about 0.16 mJy. This assumes the source to be within the synthesised beam, which typically encompasses a mass $\sim 5 \times 10^{14} M_\odot$. Also σ_{rms} increases very little for a factor of two increase in the beam size (R. Subrahmanyan, private communication). So typical protoclusters could indeed be detectable by the GMRT. Finally in Fig. 3 we illustrate the effect of assuming different initial density profiles ($\alpha = 0, 1, 3/2, 5/2$) for a protocluster which is a 3σ fluctuation. One sees that changing α from 0 to 5/2 leads to a decrease of the peak flux by a factor ~ 2.

The parameters of a protocluster which we have adopted here appear to us to be quite reasonable. We have taken a protocondensate with the mass corresponding to a rich cluster and considered $1 - 3\sigma$ fluctuations in a COBE normalised CDM model. The major uncertainty in our calculations is the neutral fraction f which we have taken here to be 2.5% of the total mass. For a different value of f one has to simply scale the flux in Figs. 2 and 3 by $f/(0.025)$. Our results indicate that typical protocondensates in the CDM model could be detectable by the GMRT.

References

Peebles, P. J. E. 1980, *Large Scale Structure of the Universe*, (Princeton: Princeton University Press).
Padmanabhan, T., Subramanian, K. 1992, *Bull. Astr. Soc. India*, **20**, 1.
Sunayaev, R. A., Zeldovich, Ya. B. 1972, *Astr. Astrophys.*, **20**, 189.
Sunayaev, R. A., Zeldovich, Ya. B. 1974, *Mon. Not. R. astr. Soc.*, **171**, 375.
Swarup, G. 1984, *Giant Metre-Wavelength Radio Telescope – Proposal*, Radio Astronomy Cenre, TIFR, India.
Subramanian, K., Swarup, G. 1992, *Nature*, **359**, 512.
Subramanian, K., Padmanabhan, T. 1993, *Mon. Not. R. astr. Soc.*, **265**, 101 (paper I).