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ON THE POSSIBILITY OF RADIOASTRONOMICAL INVESTIGATION OF THE BIRTH OF GALAXIES

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SUMMARY

During the prestellar epoch, protogalaxies were composed mainly of neutral hydrogen with mass approximately 100 times the mass of interstellar gas in galaxies today. Protogalaxies and protoclusters of galaxies therefore radiated strongly in the 21-cm line of neutral hydrogen. Due to cosmological redshift this line will be shifted to the metre wavelength band, so detection of red-shifted 21-cm lines from protogalaxies may provide the possibility of finding the epoch of galaxy formation and the properties of protogalaxies.

The birth of galaxies and clusters of galaxies is far from being clear and an observational approach to this problem is of the utmost importance, both for determining the parameters of the process and also for distinguishing between different theoretical schemes. For instance, were globular clusters born first and did they then join into galaxies? Or did the first step consist of the separation and compression of giant gas clouds (with $M \sim 10^{13}$–$10^{15}\, M_{\odot}$)—protoclusters of galaxies—which later disintegrated into smaller structural units: galaxies, globular galaxies, individual stars? At what redshift z did these processes occur? What was the density and temperature of the gas which transformed into galaxies?

The achievements and difficulties of various theories are discussed in many papers and we shall not mention them here. Instead, we propose radioastronomical observations which can give, at least in principle, answers to the questions mentioned above. These observations are very difficult and substantial improvement of existing equipment will be needed to fulfil the task, but the importance of the problem seems to us to warrant discussion in order to attract the attention of experimentalists. The paper does not pretend to give substantially new results, the underlying idea having been already stated by us (Sunyaev & Zel'dovich 1972a).

If gas clouds (protoclusters of galaxies) condensed first, their birth occurred at some redshift $z \leqslant 10$. To obtain this estimate, compare the actual dimensions of clusters of galaxies with the distance between neighbouring clusters.Accounting for the expansion of the Universe and going backwards in time, it is easy to find that clusters overlapped when $z \sim 5$–10. At the present day only a minute fraction (~ 1 per cent) of the overall mass of galaxies is in the form of neutral atomic hydrogen; most is in the form of stars. But the stars did not exist from eternity. Theory (at least one theory, Doroshkevich, Sunyaev & Zel'dovich 1974) shows that every cluster of galaxies passed through a rather short period when all the matter was gaseous. The gas consisted of two distinct phases: a cold and dense one with $T \sim 10^4$ K, $n_H \sim 0.1$–1 cm^{-3}, and a hot, rarefied one with $T \gtrsim 10^6$ K, $n_H \sim 10^{-4}$–10^{-3} cm^{-3}, $n_H \ll n_e$. The rather sharp division depends on the strong dependence of the cooling time t_{cool} as a function of temperature T at a given pressure, i.e. $t_{cool} \propto T^{3/2}$, for $T > 3 \times 10^5$ K; whereas at low temperatures, $T < 10^4$ K, after hydrogen recombination, the cooling is once more slowed down. The cold gas fragmented into galaxies and ultimately into stars, while the hot gas remained forever in the form of hot intergalactic gas. The time of fragmentation t_{fr} of the cold gas into galaxies and stars is estimated to be several ' hydrodynamic time units ' $t_h = (4\pi G\rho_c)^{-1/2}$. But the density ρ_c of the cold gas is many times greater than the mean cosmological density of matter. One can estimate that $t_{fr} \approx 0.1\, t_{cosm}$, t_{cosm} being the age of the Universe at the moment of formation of the gas cloud (i.e. the protocluster of galaxies).

Every cluster of galaxies experienced once in the past a period when the concentrated mass of neutral atomic hydrogen was equal to the mass of all the galaxies now existing in this cluster. This mass, $M \sim 10^{13}$–$10^{15}\, M_\odot$, is 4 to 6 orders of magnitude greater than the mass of neutral hydrogen in contemporary galaxies, which raises the possibility, pointed out in an earlier paper (Sunyaev & Zel'dovich 1972a), of detecting the 21-cm line radiation from a cluster of protogalaxies at cosmological distances. Measurement of the redshift of this line would give the most important characteristic of the process—the time of formation of protogalaxies. Following our earlier paper, the intensity was calculated by Novokreshchenova & Rudnitsij (1973) and here the calculations are made more exact and for a wider variety of initial assumptions.

Observations of the redshifted 21-cm line are very difficult. But other methods proposed for the search for protoclusters and protogalaxies are also difficult and complicated. Among these proposals are:

(i) a search for Lα λ 1216 Å and He II λ 304 Å radiation redshifted to the visible region (Sunyaev & Zel'dovich 1972a),

(ii) a search for the characteristic decrease of the 2·7 K background radiation temperature in the Rayleigh–Jeans part of the spectrum, due to Compton scattering by hot electrons of the hot gas phase (Sunyaev & Zel'dovich 1972a, b),

(iii) optical observation of the superluminous phase due to massive star formation in the newborn galaxies (Partridge & Peebles 1967), and

(iv) X-ray and γ-ray observations of the multiple accreting binary sources in newborn galaxies (Sunyaev, in preparation).

To be exact, these proposals are aimed at the detection of different components and phases of protogalaxies, namely hot neutral gas at $T \sim 10^4$ K, stars, partially ionized gas, very hot electron gas, and massive stars. Therefore they complement one another and one experiment does not make another unnecessary.

We now return to the 21-cm line emission. In order to obtain a definite estimate, let us visualize the clusters of galaxies as spheres with mass $M = 3 \times 10^{14}\, M_\odot$, diameter $D = 2$ Mpc, and each at a distance of 30 Mpc from its neighbour. We assume further that in the time $t_{form} < t < (t_{form} + t_{fr}) = 1.1\, t_{form}$ the absolute dimension of the cloud was the same (2 Mpc) as it is now, although the distance between clouds was less. Further, one half of the total mass was in the form of hot (7000 K) neutral gas, 70 per cent H I and 30 per cent He I by mass, uniformly distributed. In this case the maximum column density of neutral hydrogen is

$$n_{\rm H}l = \frac{0 \cdot 7}{2}\left(\frac{M}{m_{\rm p}}\frac{6}{\pi D^3}\right) D \approx 2M/3D^2 m_{\rm p} \approx 10^{22}\ {\rm cm}^{-2}.$$

The velocity dispersion in the protocluster is $\sim v \lesssim (GM/R)^{1/2} \sim 10^3$ km s^{-1} which is much greater than the thermal velocity, ~ 10 km s^{-1} at $T = 7000$ K. Corresponding to the hydrodynamic velocity there is Doppler broadening of the line $\Delta\nu/\nu \sim v/c \leqslant 1/300$. It is quite possible that the profile of the line will consist of several narrow lines. The optical depth in the 21-cm line depends on the Doppler broadening and is given (van de Hulst *et al.* 1954) by

$$\tau = 2 \cdot 6 \times 10^{-15}\, n_{\rm H}l/T_{\rm s}\Delta\nu \gtrsim 10^{-3},$$

with $T_{\rm s}$ being the spin temperature of hydrogen, which is practically equal to the electron temperature $T_{\rm e} = 7000$ K at the density $\langle n_{\rm H}\rangle \sim 0 \cdot 1$–$1$ cm^{-3}. The 21-cm line must be in emission, because $T_{\rm s}$ is greater than the background radiation brightness temperature even at a redshift $z \sim 5$–10. The brightness temperature of the 21-cm emission, or, to be exact, the increase over the background temperature, is $\Delta T_{\rm b} = T_{\rm e}\tau \geqslant 7$ K. As is well known, it does not depend upon $T_{\rm e}$ and $T_{\rm s}$ as long as $n_{\rm H}l$ and $\Delta\nu$ are given.

This value of $\Delta T_{\rm b}$ is for an observer co-moving with the protogalaxy. Due to the cosmological redshift all temperatures are diminished in the ratio $(1+z)^{-1}$ so the expected value of the line brightness temperature as seen from the Earth is $\Delta T_{\rm b}(z = 0) = \Delta T_{\rm b}/(1+z_{\rm form}) \geqslant 1$ K. The line is shifted to the region $\lambda = \lambda_0(1+z_{\rm form})$, i.e. 100–200 cm, a region where the overall background has an effective brightness temperature ranging approximately from 20 to 200 K.

The possibility of detecting the redshifted 21-cm line is connected with its narrow spectral form, since the background due to galactic emission and to unresolved extragalactic discrete sources is stronger but has no sharp spectral features. Radio emission of interstellar molecules in our Galaxy comes from cold clouds and is much narrower than $\Delta\nu/\nu \sim 1/300$.

The angular dimension of a cluster of protogalaxies with diameter D is given by

$$\theta = \frac{DH_0}{2c}\frac{\Omega^2(1+z)^2}{[\Omega z - (2-\Omega)(\sqrt{1+\Omega z} - 1)]}.$$

It depends on the time of formation of galaxies, which gives $z_{\rm form}$, and on the dimensionless density of the matter in the Universe

$$\Omega = \rho/\rho_{\rm crit} = 2q_0 = 8\pi G\rho/3H_0^2,$$

H_0 being the Hubble constant. Taking $H_0 = 75$ km s^{-1} Mpc^{-1}, the average angular dimensions are ~ 10 arcmin.

TABLE I

Ω	z	θ (arcmin)	ω (10^{-6} sr)	λ (cm)	F_ν (10^{-29} W m^{-2} Hz^{-1})	F (10^{-21} erg cm^{-2} s^{-1})	β
1	5	9	5	126	$\geqslant 10$	100	0·07
	10	14	10	231	$\geqslant 4$	20	0·1
0·1	5	4	1	126	$\geqslant 2$	20	0·2
	10	5	2	231	$\geqslant 0 \cdot 6$	3	0·3

In Table I we give values for θ and Ω together with ω, the solid angle subtended; λ, the shifted wavelength; F_ν, the flux density; $F = \int F_\nu \, d\nu$, the energy flux in the line; and β, the number of protoclusters of galaxies on the line of sight. The flux density in the centre of the observed line due to one protocluster is equal to

$$F_\nu = 2kT_b(z = 0)\,\omega/\lambda^2 = 2kT_b(z = z_{form})\,\omega/\lambda_0^2(1+z)^3.$$

The table shows that this quantity lies in the range 10^{-28}–10^{-29} W m^{-2} Hz^{-1}. The values quoted are for the maximum line-width $\Delta\nu/\nu \sim 1/300$; if the width is smaller, the flux densities will be greater.

In the non-linear theory of the formation of galaxies (see Sunyaev & Zel'dovich 1972a and references therein) the neutral hydrogen in the protocluster is first condensed into a rather thin cloud familiarly known as a ' pancake '. In this case ΔT_b and the angular dimensions depend upon the orientation of the pancake relative to the observer. When seen from the side, the protocluster may have ΔT_b up to 10 K, but the solid angle is 10 times less than when the pancake is seen face-on. The energy flux integrated over frequency and angle does not depend on the orientation of a protogalaxy, nor on its velocity dispersion, since the optical depth in the line is small and self-absorption is negligible. The integrated flux depends upon z and the total atomic hydrogen mass in the cloud, and this mass is 10^4–10^6 times the atomic hydrogen mass in a single contemporary galaxy.

The overall number of protoclusters which are sources of redshifted 21-cm line radiation is of great importance. It depends on their lifetime, which we take to be one-tenth of their cosmological age. The average number of protoclusters along the line of sight is given by

$$\beta = \frac{\pi D^2}{4}\int_{t_{form}}^{t_{form}+t_{fr}} N(t)\,c\,dt = \frac{\pi D^2}{4} N_0 c H_0 \int_{z_{form}-\Delta z_{fr}}^{z_{form}} \frac{1+z}{(1+\Omega z)^{1/2}}\,dz$$

where $N(z) = N_0(1+z)^3$ is the density of protoclusters in the expanding Universe, the contemporary density* being taken as $N_0 = 3\times10^{-5}$ Mpc^{-3}.

The data collected in Table I suggest that, together, massive gas clouds can occupy up to 10 per cent of the celestial sphere. With an average solid angle $\omega = 5\times10^{-6}$ sr this gives $(4\pi\times0{\cdot}1)/5\times10^{-6} = 2\times10^5$ for the number of clouds in the whole sky. Each cloud radiates its own narrow line with a different $\lambda = \lambda_0(1+z_{form})$ and $\Delta\nu/\nu = \Delta\lambda/\lambda \leqslant 3\times10^{-3}$. Assuming that the redshift of formation has a large dispersion $\Delta z_{form} \sim (1+z_{form})$, we conclude that with fixed wavelength the number of observable protoclusters does not exceed $2\times10^5\times10^{-3} = 200$ over the whole sky, with the best choice of wavelength. Observations with a variable wavelength are essential, both in order to augment the number of protoclouds observed and also to distinguish them from sources of different type with continuum spectra.

There are even more difficult experiments we can suggest, such as a search for highly-excited hydrogen lines (Kardashev 1959) or for the radioline of He^3 II λ 3·5 cm (Sunyaev 1966; Goldwire & Goss 1967) shifted into the decimetre wavelength band. These lines could be emitted by the intermediate region in the massive gas cloud surrounding the neutral gas where recombination occurs. Their

* The density of massive ' pancakes ' can exceed the observed density of clusters of galaxies because part of the gas is not bound by gravitation and can escape to form field galaxies and small groups of galaxies.

redshift must coincide with that of the 21-cm line of the cold core. The recombination lines and He^3 II lines are expected to be weak, and a search for them is only possible after detection of the 21-cm line and determination of the redshift of a protocluster.

Finally, if a protocloud occurs on the line of sight between a QSO and the observer, the hydrogen $L\alpha$, β absorption lines with protocloud redshift must be imprinted on the QSO emission. This situation is not excluded even if QSO themselves are born in pancakes, due to the statistical character and large z dispersion of pancake formation.

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