SMALL SCALE FLUCTUATIONS IN THE MICROWAVE BACKGROUND RADIATION ASSOCIATED WITH THE FORMATION OF GALAXIES

R.A. Sunyaev
Space Research Institute, USSR Academy of Sciences,
Moscow, USSR.

According to current ideas, massive extragalactic systems such as galaxies and clusters of galaxies formed as a result of the growth of small fluctuations in density and velocity which were present in the early stages of expansion of the Universe under the influence of gravitational instability. According to the hot model of the Universe at the epoch corresponding to a redshift $z \approx 1500$, recombination of primaeval hydrogen took place and as a result the optical depth of the Universe to Thomson scattering decreased abruptly from about 1000 to 1 - the Universe became transparent. Therefore the observed angular distribution of the microwave background radiation (MWBR) contains information about inhomogeneities in its spatial distribution at a redshift $z \sim 1000$. Silk (1968) was the first to note that this "photograph" of the Universe at the epoch of recombination must be enscribed with fluctuations associated with perturbations in the space density and velocity of motion of matter which will later lead to the formation of galaxies and clusters of galaxies.

Detailed investigations of this question show that the real picture is much more complicated and, in particular, that the fact that recombination is not instantaneous (Zeldovich et al 1968, Peebles 1968) changes significantly the result; the recombination of the primaeval plasma takes place over a period of time and so a real "photograph" is not obtained. Furthermore, the possibility of secondary non-equilibrium heating of the matter in the Universe at redshifts $z \ll 100$ leading to re-ionisation of the matter could lead to a large optical depth to Thomson scattering and to damping of primaeval temperature fluctuations. Nevertheless, observations of small-scale fluctuations in the MWBR seem to be one of the few methods of determining the amplitude and nature of perturbations of velocity and density at the epoch of recombination. Knowledge of the amplitude of the fluctuations and the laws according to which they evolve with time enable the epoch of formation of galaxies and clusters to be determined - and this is one of the most important questions of contemporary cosmology.

D. L. Jauncey (ed.), Radio Astronomy and Cosmology, 327-334. *All Rights Reserved.*

1. PRIMAEVAL FLUCTUATIONS IN THE MICROWAVE BACKGROUND RADIATION

In the following discussion we will introduce the mass $M = \frac{4\pi}{3}\rho\lambda^3 = \frac{4\pi}{3}\Omega\rho_{cr}\lambda^3 z^3$ corresponding to the mass of a fluctuation of scale λ ; the angular diameter of this fluctuation θ for $z \gg 1$ is

$$\theta = \Omega z \frac{4\lambda H_0}{c} \approx 6' \Omega^{2/3} h^{7/4} (M/10^{15} M_\odot)^{1/3}$$

Here and below $\Omega = \rho/\rho_{cr} = 8\pi G\rho/3H_0^2$; $h = H_0/(50 \text{ km s}^{-1} \text{Mpc}^{-1})$ where H_0 is the present value of the Hubble constant.

1.1 Adiabatic perturbations

Before the epoch of recombination these fluctuations were stationarysound waves in which the fluctuation in density is uniquely related to the perturbation in the temperature of the background radiation $\Delta T/T = \frac{1}{3}\Delta\rho/\rho$. If recombination were instantaneous, we would observe such fluctuations of brightness temperature $\Delta T/T(\theta)$. The fact that recombination is not instantaneous leads to an abrupt decrease in ΔT on small scales as was shown by Sunyaev and Zeldovich. The point is that during recombination small scale perturbations have optical depth less than 1 to Thomson scattering at a much earlier stage than the Universe as a whole because $\lambda \ll ct$. As a result the fluctuations in the MWBR are much reduced. By the epoch of recombination this effect gives rise to the damping of adiabatic temperature fluctuations on all scales $M < 10^{15} M_\odot$. The other reason why relatively small temperature fluctuations are expected on small scales is damping up to and during the epoch of recombination of density and velocity perturbations with masses $10^{12} - 10^{14} M_\odot$ because of the effects of radiative thermal conductivity and viscosity (Silk 1968, Chibisov 1972, Weinberg 1975).

The principal effect which leads to temperature fluctuations on scales $10^{12-15} M_\odot$ is scattering of photons by moving electrons (Sunyaev and Zeldovich 1970). According to the equation of continuity $\partial(\Delta\rho/\rho)/\partial t = -\operatorname{div} \underline{u}$ perturbations of density are uniquely related to velocity perturbation which in this case are a function of spatial coordinates. As a result of Doppler scatterings,

$$\frac{\Delta T}{T} = \int \frac{u(z)}{c} \cos\theta \, e^{-\tau(z)} d\tau(z)$$

the factor $\cos\theta$ taking account of the fact that only the radial component of velocity gives contributions to the fluctuations. Detailed computations have been made by Sunyaev and Zeldovich (1970) and by Peebles and Yu (1970). The results of the calculations of Doroshkevich et al are as follows. The spectrum of initial fluctuations is taken to be of power-law form

$$\overline{\left(\frac{\Delta\rho}{\rho}\right)_k^2} \propto k^n$$

Damping and phasing of the perturbations leads to spectrum at the moment of recombination of the form

$$\overline{\left(\frac{\Delta\rho}{\rho}\right)_k^2} = A\,(kR_c)^n e^{-kR_c} \frac{\sin^2 kR_J}{k^2R_J^2} R_c^3$$

where R_J is the Jeans' wavelength and $R_c = \frac{6\times10^{24}}{\Omega h^2(1+z)}\left(1+(40\Omega h^2)^{-3/4}\right)^{1/2}$ cm is the dissipation length at the epoch of recombination. Combining this result with observation provides a method for estimating the epoch of formation of clusters of galaxies. Estimates of the magnitude of the expected temperature fluctuations in the MWBR suggest that $\Delta T/T \approx 10^{-4}$ on angular scales $\approx$ 1 - 10 arc min. If the spectrum of fluctuations is not of power law form but is rather narrow, the predicted amplitudes of the fluctuations for the same $\Delta\rho/\rho$ are less than 10^{-4}.

1.2 Entropy fluctuations

In the case of entropy fluctuations the adiabatic relation $\Delta T/T = \frac{1}{3}\Delta\rho/\rho$ does not apply and temperature fluctuations arise because of Doppler scatterings by inhomogeneities in the velocity distribution (Sunyaev and Zeldovich 1970). Velocity perturbations generate density inhomogeneities after perturbations on a given scale have become transparent on a time scale of the order of the hydrodynamical timescale. The temperature fluctuations $\Delta T/T$ should be of the same order of magnitude as in the case of adiabatic fluctuations if the amplitude and initial spectra of the perturbations are the same. They may be much greater on small scales because there is no damping of density or velocity perturbations before or during recombination.

1.3 Whirl perturbations

In this model the turbulent "whirl" velocities are much greater than the velocities predicted according to the theory of adiabatic and entropy fluctuations. Again the most important effect in producing temperature fluctuations is Doppler scattering. The computations of Chibisov and Ozernoi (1969) and Anile et al (1976) show that the fluctuations expected according to this theory exceed by a considerable factor the existing experimental limits of Conklin and Bracewell (1967), Parijskij (1973), Carpenter et al (1973) and Stankevich (1974). Agreement with the observations can, however, be obtained if it is supposed that secondary heating of the Universe took place which leads to damping of the fluctuations. However, Anile et al (1976) note that the large velocities of matter during the period of secondary heating also lead to significant fluctuations.

2. OTHER SOURCES OF FLUCTUATIONS

2.1 Radio sources

Longair and Sunyaev (1969) noted that radio sources radiating at short wavelengths (1 - 10 cm) lead to fluctuations in the MWBR. In addition there should also be present a large number of compact radio sources associated with the nuclei of galaxies and quasars. A simple extrapolation of the Cambridge counts of radio sources at 408 MHz to a wavelength of 4 cm with a radio source spectrum $F_\nu \propto \nu^{-0.75}$, ie $\alpha = 0.75$ shows that the radio sources contributing to the source counts guarantee fluctuations at a level ≈ 1 to 3×10^{-5} on angular scales 1 arc min to 1 degree. The most important contribution to the fluctuations is due to sources which have surface density roughly one per beam-width of the radio telescope.

2.2 Clusters of galaxies

Sunyaev and Zeldovich (1970, 1972) showed that in the direction of rich clusters of galaxies containing hot intergalactic gas, there should be a decrease in the brightness temperature of the MWBR

$$\frac{\Delta T}{T} = -4 \frac{kT_e}{m_e c^2} \sigma_T N_e R$$

Such an effect was discovered in the Coma cluster by Parijskij (1973) and recently confirmed by Gull and Northover (1976); $\Delta T/T$ is roughly 3×10^{-4}. If it is supposed that the effect does not depend on redshift and that the number of rich clusters (with richness classes greater or equal to that of Coma) along the line of sight to a redshift $z \approx 4 - 5$ is roughly 1, it is clear that clusters of galaxies can give a significant contribution to fluctuations of the MWBR on angular scales of the order of a few min arc.

2.3 Perturbations originating during secondary heating of the intergalactic gas

The formation of observed objects in the Universe is apparently accompanied by the ionisation and reheating of the intergalactic gas. Inhomogeneities in the heating must lead to fluctuations in the MWBR for the same reasons described in 2.2. As is well known, under the influence of gravitational instability, velocities corresponding to slowly growing perturbations of density also increase with time. Therefore scattering by moving ionised matter must also lead to temperature fluctuations of the MWBR.

3. REHEATING OF THE INTERGALACTIC GAS

The optical depth of the Universe to Thomson scattering is equal to

$$\tau_T = \int_0^{z_{max}} \sigma_T N_e(z)\, c\, dt = \sigma_T \Omega N_{cr} c H_0^{-1} \int_0^{z_{max}} \frac{(1+z)}{(1+\Omega z)^{1/2}} x(z)\, dz$$

where $x(z) = N_e/(N_e+N_H)$ is the degree of ionisation of hydrogen. If for small $z < z_{max}$ the hydrogen is completely ionised and at $z > z_{max}$ it is neutral, $\tau_T = 0.025\, \Omega^{1/2} h\, z_{max}^{3/2}$. In order to damp out fluctuations effectively, it is necessary that $\tau_T \sim 5$, corresponding to weakening of the fluctuations by a factor of 150. Evidently, effective damping of temperature fluctuations can only take place if reheating of the intergalactic gas occurs sufficiently early at $z > 40\, \Omega^{-1/3} (\frac{\tau}{5})^{2/3} h^{-2/3}$
At redshifts $z > 10$, the most important cooling process for heated intergalactic gas is Compton scattering of photons by hot electrons, leading to an increase in the mean square frequency of photons and cooling of the electrons.

3.1 Shock waves

One possible method of secondary heating is dissipation of turbulent motions. Subsonic turbulent velocities decrease during the expansion as (1 + z). Turbulence which was subsonic before recombination becomes supersonic after recombination because of the abrupt drop in the velocity of sound i.e. shock waves are formed immediately after recombination. The time scale for Compton cooling of the plasma at a redshift $z \sim z_{rec} = 1000$ is much shorter than the cosmological timescale.

$$\frac{t_c}{t_{cosm}} = \frac{3}{4}\frac{m_e c}{\sigma_T \varepsilon_r} H(z) \approx 20\,\frac{\Omega^{1/2}}{z^{2.5}}$$

Consequently, hot ionised gas is only present in the shock front and behind it the gas cools rapidly and recombines. It is difficult to conceive that in this situation it is possible to obtain $\tau_T > 1$. Besides, the gas in the shock front has a large velocity and temperature and this must lead to strong fluctuations of the intensity of the MWBR. We also note that the rapid cooling must lead to the early appearance of dense objects of large mass. Apparently, early heating by shock waves does not seem to be an effective mechanism for damping primordial fluctuations.

3.2 Photoionisation

The other, more probable, possibility is that the secondary heating is due to the presence of strong sources of ulta-violet radiation.

The optical depth of the Universe for ionising photons is

$$\tau_{ph} = \sigma_0 N_H c\, t_{cosm} \approx 10^5 \cdot \Omega^{1/2} h\, z^{3/2} [1 - x(z)]$$

and is very high. Here and below $\sigma_{ph} = \sigma_0 \left(\frac{\nu_0}{\nu}\right)^3 = 6.3 \times 10^{-18} (\nu_0/\nu)^3\ cm^2$; $h\nu_0 = 13.6 eV$ is the ionisation potential of hydrogen. Therefore we can investigate the local ionisation balance

$$4\pi N_H \int_{\nu_c}^{\infty} \frac{J_\nu}{h\nu} \sigma_{ph}(\nu)\, d\nu = (\alpha_t - \alpha_1) N_e^2 \qquad (1)$$

where $(\alpha_t - \alpha_1) = 2.5 \times 10^{-13} T_4^{-1/2}\ cm^3 s^{-1}$ is the recombination coefficient to all levels except the first and $T_4 = T/10^4$ K.

The emissivitiy of sources per unit volume may be determined as follows

$$j_\nu = \frac{1}{4\pi} N(z) L_\nu \quad erg\ cm^{-3} s^{-1} Hz^{-1} sr^{-1}$$

where $N(z)$ is the mean space density of sources; $L_\nu = L_0 \left(\frac{\nu}{\nu_0}\right)^{-\alpha}$ is the mean spectral luminosity close to the Lyman limit. The total luminosity of the source is $L = \int L_\nu d\nu$. Absorption of photons takes place to a distance $D(\nu) \approx (\sigma_{ph} N_H)^{-1}$ from the object, corresponding to an optical depth $\tau_{ph} \approx 1$. The intensity of radiation at any point closer than $D(\nu)$ is

$$J_\nu = j_\nu D(\nu) = \frac{1}{4\pi} N(z) L_\nu \frac{1}{\sigma_{ph} N_H}$$

The temperature of a hydrogen plasma under the combined effects of photoionisation and cooling due to recombination and the excitation of lines by electron collisions cannot greatly exceed 10^4 K. At large redshifts Compton cooling of the plasma plays an important role but at redshifts $z < 30$ and for a power-law spectrum of ultraviolet radiation, the temperature of the electrons does not fall significantly below 10^4 K. Substituting for J_ν into (1), we find

$$\int_{\nu_c}^{\infty} \frac{N(z) L_\nu d\nu}{h\nu} \approx (\alpha_t - \alpha_1) N_e^2(z)$$

Complete ionisation of the gas takes place when the number of ionising photons being created per unit volume per unit time exceeds the number of recombinations in the same volume. Taking $N(z) = 0.03\,(1+z)^3$ Mpc^{-3}, a density of the order of that of galaxies such as our own, and $L_\nu \approx 3 \times 10^{29}$ erg s^{-1} Hz^{-1} ($L \approx 10^{45}$ erg s^{-1}), we see that such sources could lead to ionisations of the intergalactic gas at any redshift

$$z \leqslant 27\, \Omega^{-2/3} h^{-4/3}$$

In this case the optical depth of the gas to Thomson scattering must be less than $\tau \leqslant 4\, \Omega^{-1/2} h^{-1/2}$

We note that the total number of quasars which were active at any time in the Universe is of the order of the total number of galaxies such as our own (Lynden-Bell 1969, Komberg and Sunyaev 1971). If the models of Doroshkevich et al (1971) are correct, in which it is proposed thatthe cosmological evolution of quasars and radio galaxies are more or less simultaneous, both in their birth-rate an subsequent decline in activity, then quasars can be responsible for the secondary ionisation of the gas. This was noted by Arons and Wingert (1971). Another natural sources of ionising photons are young galaxies because, just as in the case of quasars, they are anomalously bright at ultraviolet wavelengths (Weymann 1966). Therefore the secondary ionisation of intergalactic gas can lead to effective washing-out of fluctuations in the MWBR if observed galaxies and quasars formed at $z \approx 20$ to 30 and went through a bright phase at that time.

It should be noted that the early formation of galaxies contradicts the adiabatic model of primaeval fluctuations in which first clusters of galaxies form at a redshift of 4 - 10 and then later fragment into separate galaxies (Sunyaev and Zeldovich 1973, Doroshkevich et al, 1974). On the other hand in models of entropy fluctuations (Rees and Gott, 1976) and of whirl perturbations (Ozernoi and Chernin, 1968), early formation of galaxies is completely natural.

It should be noted that at that period the velocities of matter on scales $10^{13-16} M_\odot$ were very large which must inevitably give rise to fluctuations in the MWBR because of Doppler scatterings. However, at that time the optical depth to scattering for a single object in this mass range was many times (10^{2-3}) smaller than the optical depth of the Universe. Naturally, for a completely random distribution of velocities, the effect corresponds to

$$\frac{\Delta T}{T} \approx \frac{1}{\sqrt{n}}\, \sigma_T N_e \lambda\, \frac{v}{c} \langle \cos^2\theta \rangle^{1/2}$$

and the region within which such an effect is expected corresponds to $c\tau \approx 1$.

Literature

Anile A.M., Danese L., De Zotti G. and Motta S., 1976. Astrophys. J, 205, L59.

Arons J. and Wingert D., 1972. Astrophys. J., 177, 1.

Carpenter R.L., Gulkis S. and Sato H., 1973. Astrophys. J., 182, L61.

Chibisov G.V., 1972. Astron. Zh., 49, 286.

Chibisov G.V. and Ozernoi L.M., 1969. Astrophys. Letters, 3, 189.

Conklin E.K. and Bracewell R.N., 1967. Phys. Rev. Letters, 18, 614.

Doroshkevich A.G., Longair M.S. and Zeldovich Ya.B., 1970. Mon. Not. R. astr. Soc., 147, 139.

Gull S.F. and Northover K.J.E., 1976. Nature (in press).

Komberg B.V. and Sunyaev R.A., 1971. Astron. Zh., 48, 235.

Longair M.S. and Sunyaev R.A., 1969. Nature, 223, 719.

Parijskij Yu.N., 1972. Astron. Zh., 49, 1322.

Parijskij Yu.N., 1973. Astron. Zh., 50, 453.

Peebles P.J.E., 1968. Astrophys. J., 162, 815.

Peebles P.J.E. and Yu, I.T., 1970. Astrophys. J., 162, 815.

Silk J., 1968. Astrophys. J., 151, 459.

Stankevich K.S., 1974. Astron. Zh., 51, 216.

Sunyaev R.A. and Zeldovich Ya.B., 1970. Astrophys. and Space Science, 7, 20.

Sunyaev R.A. and Zeldovich Ya.B., 1972. Comments Astrophys. and Sp. Phys., 4, 173.

Weinberg S., 1972. "Gravitation and Cosmology", Wiley, New York.

Zeldovich Ya.B., Kurt V.G. and Sunyaev R.A., 1968. ZhETP., 55, 278.

DISCUSSION

Bonometto: I would like to comment on the possibility that isothermal fluctuations may cause fluctuations of BB radiation over scales $\sim 10^{12} M_\odot$ or so.

We must remember that the surface of last scattering for BB photons is at $z \sim 1000$, while any significant dragging effect between matter and radiation on those scales has stopped at $z \sim 1300$ to 1200. During the Δz interval between 1200 and 1000, radiation density fluctuations will be completely damped because of the residual ionisation. All that is, however, strongly dependent on the rate of residual ionisation in the late recombination period. Previous statements implied no extra energy input. If such inputs took place, fluctuations would be even more strongly damped.

Longair: I have concentrated mainly upon scales $M \sim 10^{15} M_\odot$ where fluctuations $\Delta T/T \sim 10^{-4}$ are expected, taking into account the effects you mention.

Lynden-Bell: Is there any evidence for reheating?

Longair: Sunyaev has adopted the conventional view that there must be some intergalactic gas because the process of galaxy formation cannot have been 100 per cent efficient in mopping up intergalactic gas and there is no evidence for depression of the continuum in the spectra of quasars beyond redshift Ly-α. The cooling rate of the intergalactic gas at redshifts $z \sim 30 - 100$ is less than cosmological timescales and therefore ionisation and consequent reheating seem inevitable.