THE ANGULAR DISTRIBUTION OF THE COSMIC BACKGROUND RADIATION

NELSON JORGE SCHUCH
CNPq - Observatório Nacional - Departamento de Astrofísica

Three are the reasons which make the astronomers to accept the concept that the cosmic background radiation, CBR, has a primordial origin at microwaves:

I - The observations suggest that the shape of the CBR intensity spectrum, at microwaves,has a Planckian nature, which can be described by only one parameter, the temperature.

II - The CBR energy density at microwaves, is very high: 0.25 eV . cm^{-3} or 400 $fotons/cm^{-3}$.

III- The CBR angular distribution, at microwaves, is highly isotropic.

In the review "The electromagnetic spectrum of the Cosmic Background Radiation", topics I and II were discussed in detail. In this present review, a summary of the observations related to item III above and their cosmological implications, i.e., the CBR isotropy at microwaves, is presented.

One of the most convincing evidences that the CBR has a cosmological nature due to very distant sources or to a primordial explosion is its isotropy, i.e., the fact that the CBR do not show the same anisotropy associated to the local sources.

If the CBR is really the residual of an epoch when the matter and radiation were in thermic equilibrium, then it should be expected that the flux of this radiation would be isotropic. However, there could exist small scale anisotropies due to inhomogeneities in the primordial plasma, possibly associated to the presence of photo-galaxies (Partridge and Peebles (1)). There could also exist large scale anisotropies due to the expansion of the Universe as a whole, or due to the deviation of our local gravitational field from the perfect isotropy.

However, there must exist a small anisotropy on a 360° angular scale (24^h) or dipole due to the solar system motion in relation to the CBR. If the CBR does not have a primordial origin, than the study of its angular distribution on the celestial sphere could give information about its origin, if the radiation is emitted by a large number of discrete sources. In this case it would be possible to observe large anisotropies with very small scales.

1 - THE CBR DETERMINATION OF THE ANGULAR DISTRIBUTION OF ITS INTENSITY

The experiments to determine the isotropy of CBR do not have the same characteristics as the ones used to determine its spectrum. The principal difference is due to the fact that the experiments to determine the isotropy do not need to be of absolute nature. The measured quantity is the intensity difference observed at different directions; therefore, absolute calibrations are not essential.

Inconsistences of the experiments could be tested by using the differential results, since one is observing fixed structures on the celestial sphere. The apparatus and the medium criate by themselves anisotropies which could be removed, in principle, by observing the same region of the sky on different experimental conditions.

The principal sources of sistematic errors in low sensitivity surveys of the sky are the local sources, in particular those associated to extense objects or low brightness surface regions.

All the observations with positive results where made above the most emmiting layers of the atmosphere using balloons or jet-planes. The observations made by Henry (2), Corey and Wilknson (3), Muehlner and Weiss (4) and Cheng et al. (5) using balloons are all simmilar in principle. See Figure 1.

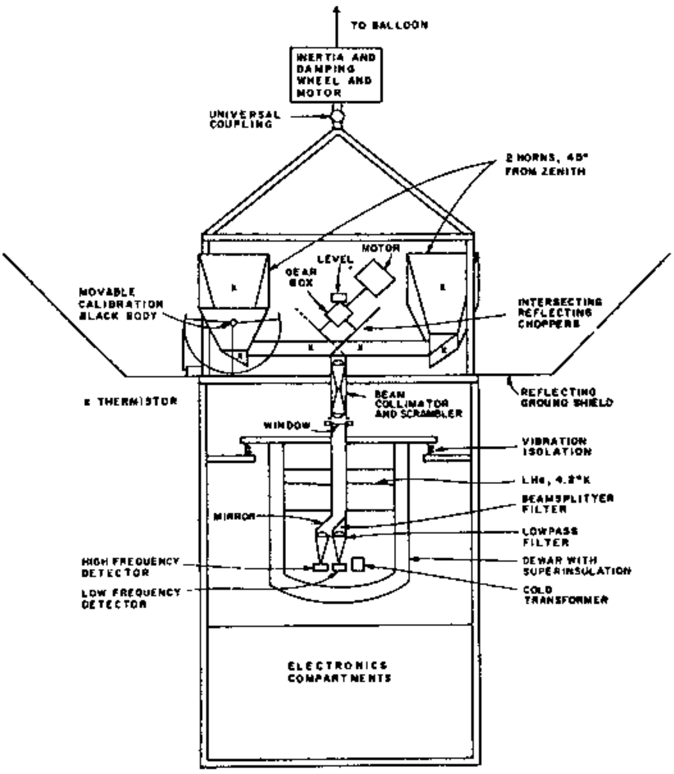

FIGURE 1 - The M.I.T. instrument for balloon-borne large angular scale isotropy experiment. The Princeton instrument is similar in concept (Weiss(6), Figure 11, pag. 525).

The intensity in two beams 90° apart, dissected by the zenith and separated by 180° in azimuth, is differenced at a rapid rate (10 - 200 Hz). The beams are formed with low side-lobe horns and further protected from the radiation of the ground and the lower atmosphere with a large ground shield that reflects the sky. With the given beam configuration, about 1/4 of the sky can be covered in a single flight. The entire instrument is set into rotation about the zenith at about 1 revolution per minute. The rotation serves both to scan the sky and to allow the measurement of the intrinsic anisotropy of the apparatus. The azimuth is determined with magnetometers using the earth's field as a reference. Provision is made to measure or eliminate the systematic noise terms that might be synchronous with the rotation such as magnetic interactions in the ferrite components of the microwave receivers (Henry (2)).

The resulting signal is the difference in the intensities measured in the two beams as a function of the azimuth. The averages of these signals, over a set of rotations occurring during the time it takes the celestial sphere to move about 1/2 a beam width are then expanded in an harmonic series, in multiples of the rotation frequency. The fundamental component includes information on all multipole moments of the intensity distribution; higher odd harmonics exclude the lower order anisotropy moments and are a diagnostic for discriminating discrete sources.

A dipole anisotropy (24 hours or 360°) of amplitude T_d, pointing along α_d(RA) and δ_d (dec), would produce a fundamental component with polar and equatorial projections (Weiss (6)) given by:

$$\Delta T_{N-S} = 2T_d \text{ sen EA} \left[\text{sen } \delta_d \cos \delta - \cos \delta_d \text{ sen } \delta \cos (\alpha - \alpha_d)\right] \qquad (1)$$

$$\Delta T_{W-E} = 2T_d \text{ sen EA} \left[\cos \delta_d \text{ sen } (\alpha - \alpha_d)\right] \qquad (2)$$

where α and δ are the right ascension and declination of the zenith, respectively, and EA is the elevation angle of the beams (45^o).

The best fit of equations (1) and (2) to the data of Cheng et al. (5) shows a maximum and a minimum of approximately 2.5 mK for ΔT_{N-S} near to 13^h and 23^h, respectively, and a maximum of the order of 3.7 mK for ΔT_{W-E} near to 18^h.

The Berkeley group (Smoot et al. (7)) measured the large scale anisotropy using the U2 airplane as a platform (Figure 2).

The U2 radiometer is similar to the balloon-borne differential radiometers. It operates at 33 GHz and includes a 54 GHz radiometer to monitor the tilt of the airplane in the atmosphere. The radiometer beams are separated by 60^o and are switched at 100 Hz. The entire apparatus is turned periodically within the airplane housing to measure intrinsic instrument anisotropies. The observing and data analysis strategy (Gorenstein and Smoot (8)) is different than that used in the balloon experiments. Observation points in the sky are selected and the difference in intensity between the two beams is fitted to a dipole distribution in a celestial coordinate system. A recent compilation of these results is presented in Table 1.

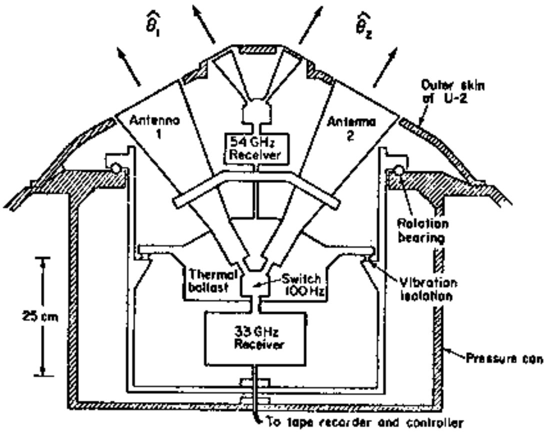

FIGURE 2 - The U2 differential radiometer (Smoot et al. (7)).

REFERENCE	λ	f	ALTITUDE	BEAM WIDTH	ANISOTROPY ΔT mK		MAXIMUM	
	(cm)	(GHz)	(km)	(°)	24h - 360° Dipole	12h - 180° Quadrupole	RA (h)	δ (°)
Boughn et al. (19)	0.86	35	0	4	7.5 ± 11.6	5.5 ± 6.6	Circle, δ= 0°±2.1h RA beam switched	
	1.21	24.8	27	8				
Cheng et al. (5)					2.99 ± 0.34	<2	12.3 ± 0.4	- 1 ± 6
	0.955	31.4	27	6				
Conklin (10)	3.75	8.0	3.8	12	1.6 ± 0.8	-	$13^{+1.9}_{-2.3}$	-
Corey & Wilkinson (3)	1.58	19	25	-10	2.9 ± 0.7	-	12.3 ± 1.4	-21 ± 21
Henry (2)	2.96	10.0	24	15	3.2 ± 0.8	-	10.5 ± 4	-30 ± 25
Partridge & Wilkinson (11)	3.2	9.4	0	10	1 ± 2.2	4.9 ± 2.0	Circle, = -8°, Celestial pole.	
Smoot et al. (7)	0.9	33	20	7	3.5 ± 0.6	<1	11.0 ± 0.5	6 ± 10
Smoot & Lubin (12)	0.9	33	20	7	3.1 ± 0.4	<1	11.4 ± 0.4	9.6 ± 6
Weiss (6)	ν=3-10(cm^{-1})		-	18	2.8 ± 0.8	-	9.6 ± 1.5	- 9 ± 20

TABLE 1 - Results of large scale anisotropy experiments.

With the enhanced precision and more extended sky coverage of both the U2 (Smoot and Lubin, 1979) and balloon experiments (Change et al., 1979), limits have been set on the five independent terms of the quadrupole moment of the CBR intensity distribution. The fittings to the dipole and quadrupole distributions determined by the Princeton and Berkeley groups are given by the following equations:

Princeton:

$$T = T.n + \sum_{m=-2}^{2} (a_{2m} + ib_{2m}) Y_{2m} \tag{3}$$

Berkeley:

$$T(\alpha,\delta) = T_o + T_x \cos\delta \cos\alpha + T_y \cos\delta \,\mathrm{sen}\,\alpha + T_z \,\mathrm{sen}\,\delta + Q_1(3/2\,\mathrm{sen}^2\delta - 1/2) + \\ + Q_2 \,\mathrm{sen}\,2\delta \cos\alpha + Q_3 \,\mathrm{sen}\,2\delta \,\mathrm{sen}\,\alpha + Q_4 \cos^2\delta \cos 2\alpha + Q_5 \cos^2\delta \,\mathrm{sen}\,2\alpha, \tag{4}$$

α = RA and δ = DEC,

where the correspondences between the two equations (Princeton and Berkeley) are:

$$Q_1 = \sqrt{\frac{5}{4}\pi}\,a_{20} \;;\quad Q_2 = -\sqrt{\frac{15}{8}\pi}\,a_{21} \;;\quad Q_3 = \sqrt{\frac{15}{8}\pi}\,b_{21} \;;\quad Q_4 = \sqrt{\frac{15}{8}\pi}\,a_{22} \quad \text{e} \quad Q_5 = -\sqrt{\frac{15}{8}\pi}\,b_{22} \tag{5}$$

The Berkeley and Princeton results for the dipole and quadrupole moments are given in table 2.

	BERKELEY	PRINCETON
DIPOLE		
Tx	-3.01 ± 0.24	-2.98 ± 0.30
Ty	+0.39 ± 0.25	-0.24 ± 0.30
Tz	+0.52 ± 0.23	-0.06 ± 0.31
T mK	3.1 ± 0.4	2.99 ± 0.34
α(h)	11.4 ± 0.4	12.3 ± 0.4
δ(^{o})	9.6 ± 6	-1 ± 6
v(2.7 K) km s^{-1}	344 ± 44	332 ± 38
f(GHz)	33	19. 24.8, 31.4
QUADRUPOLE		
Tx (mK)	-2.78 ± 0.28	-3.27 ± 0.57
Ty	+0.66 ± 0.29	-0.17 ± 0.73
Tz	-0.18 ± 0.39	-0.10 ± 0.72
Q_1	+0.38 ± 0.26	-
Q_2	+0.34 ± 0.29	+0.22 ± 0.50
Q_3	+0.02 ± 0.24	+0.26 ± 0.67
Q_4	-0.11 ± 0.16	-0.05 ± 0.36
Q_5	+0.06 ± 0.20	-0.22 ± 0.38

TABLE 2 - Multipole fits for the distributions of the data of CBR intensity. (Lubin and Smoot (13)) and Princeton group (Cheng et al. (13)).

One may conclude that at large scales there is evidence for anisotropy only at the level of the order of $\frac{\Delta T}{T} \sim 10^{-3}$. At this scale it is expected an anisotropy of $\theta \sim 360^o$ because of the observer motion, with a velocity v, in relation to the reference system where the CBR has perfect isotropy. The velocity v is the resulting vector from the following movements:

- Earth in relation to the Sun;
- Sun in relation to the Galactic centre;
- Galaxy in relation to the Local Group;
- Local Group in relation to the Local Supercluster;
- Local Supercluster in relation to the reference system where the CBR is 100% isotropic.

All these contributions to the observer motion, with the exception of the last one, can be inferred with increasing uncertainty from the kinematics of the Sun in the Galaxy and the radial velocities of the galaxies in the Local Supercluster. According to Smoot et al. (7) the CBR anisotropy, observed at large angular scales, can be represented by

$$T = T_o + T_1 \cos \theta \tag{6}$$

where T_o is the observed temperature in a rest frame in relation to the emitting sources, θ is the angle between the direction of observation and the velocity of the observer v, and

$$T_1 \simeq \frac{v}{c} T_o \quad \text{for} \quad \frac{v}{c} << 1 , \tag{7}$$

or more precisely, according to Weiss (6),

$$T(\theta) = \frac{T_o \cdot \left[1 - \frac{v^2}{c^2}\right]^{1/2}}{1 - \frac{v}{c} \cdot \cos(\theta)} \tag{8}$$

where

$$T_1 = 3.5 \pm 0.6 \times 10^{-3} \,{}^oK \tag{9}$$

to the direction

$$\begin{matrix} \text{R.A.} = 11.0 \pm 0.6 \text{ h} & \ell = 248^o \\ \delta = 6^0 \pm 10^o & b = 56^o \end{matrix} \tag{10}$$

This result is consistent to all the previous estimates for the dipole anisotropy, i.e., the 24^h or 360^o. If this component is subtracted from the observed intensities there is no evidence for quadrupolar anisotropies, i.e., the 12^h or 180^o at the level of $\frac{\Delta T}{T} \sim 3 \times 10^4$. This anisotropy corresponds to a velocity of

$$390 \pm 60 \text{ km} \cdot \text{s}^{-1} \tag{11}$$

in the Solar reference system to the direction given by (10).

A weighted average of the available observational data prior to 1980 permitted White (15) to determine the motion of the Sun with respect to the CBR, i.e.,

$$360 \pm 40 \text{ km} \cdot \text{s}^{-1} \tag{12}$$

towards

$$\alpha = 11^h.7 \pm 0^h.4 \quad \text{and} \quad \delta = + 15^o \pm 6^o \ (1950.0) \tag{13}$$

Assuming a Galactic rotation velocity of 275 km · s^{-1}, this implies in a peculiar velocity for the Milky Way of

$$520 \pm 40 \text{ km s}^{-1} \tag{14}$$

towards

$$\alpha = 10^h.8 \pm 0^h.4 \quad \text{and} \quad \delta = - 12^o \pm 6^o \tag{15}$$

or

$$\ell = 262^o \pm 8^o \quad \text{and} \quad b = + 41^o \pm 6^o \tag{16}$$

or

$$\text{SGL} = 122^o \pm 7^o \quad \text{and} \quad \text{SGB} = - 33^o \pm 6^o \tag{17}$$

where the two coordinates in (17) are the supergalactic longitude and the latitude of de Vaucouleurs et al. (16) respectively, that is, approximately 40° towards the Virgo cluster of galaxies ($\alpha = 12^{h}\ 30^{m}$ e $\delta = +\ 12^{\circ}$).

If one defines, in the supergalactic system (SGL, SGB), the equivalent supergalactic cylindrical coordinates with axes towards:

$$\begin{array}{lcc} & \mathrm{SGL} & \mathrm{SGB} \\ \vec{\mu}_r & 104^{\circ} & 0^{\circ} \\ \vec{\mu}_{\theta} & 194^{\circ} & 0^{\circ} \\ \vec{\mu}_z & 0^{\circ} & 90^{\circ} \end{array} \qquad (18)$$

one obtains the peculiar velocity of the Local Group, the movement component of the Galaxy towards the Virgo cluster:

$$\vec{v}_p \equiv (v_r, v_{\theta}, v_z) = (420 \pm 40,\ 130 \pm 40,\ 280 \pm 40)\ \mathrm{km} \cdot \mathrm{s}^{-1} \qquad (19)$$

This result shows the peculiar velocity of our Galaxy is directed mainly towards the centre of the Virgo cluster with a substantial component perpendicular to the supergalactic plane.

The degree of anisotropy in the local velocity field in conjuction with the observed overdensity, can place direct limits on the scale of the inhomogeneity responsible for our motion through the CBR.

The observational evidence for or against this anisotropy is still a matter of dispute. Sandage and Tammann (17), Sandage et al. (18), Sandage (19), Sandage and Tammann (20) and Tammann et al. (21) found no evidence for this anisotropy. In favor one can mention the work by de Vaucouleurs (22), Peebles (23) and de Vaucouleurs and Bollinger (24).

White (15) shows that if Sandage and his collaborators are right that is the Hubble flow is almost perfectly linear both within and without the Local Supercluster, then Ω, the density parameter, must be small and our motion through the CBR must result from perturbations on a very large scale. If de Vaucouleurs is correct then Ω cannot be very much less than unity and our peculiar motion reflects the gravitational influence of the Local Supercluster. The principal reason for the confused observational situation is almost certainly the lack of precision of absolute luminosity indicators for galaxies-errors in distance determinations.

The Tully-Fisher relation (25) between the luminosity of a spiral galaxy and its maximum rotation velocity may provide a greatly improved method for determining absolute luminosities, particularly if infrared rather than blue magnitudes are used. Aaronson et al. (26) have applied this technique very successfully to distance determinations for the Virgo and Ursa Major clusters. Their preliminary results show the Hubble constant within the Local Supercluster (as inferred from Virgo and Ursa Major) to be 30% smaller than the value found for more distant galaxies.

These results, if confirmed, will provide strong support for the de Vaucouleurs' general picture of the local velocity field and for the hypothesis that our motion through the CBR is a result of the collapse of the Local Supercluster in a universe with $\Omega \sim 0.2 - 0.7$(White (15)).

One can say that there are convincing observational evidences that at large angular scales the CBR permeates the Universe in an isotropic way. Remembering that the cosmological principle requires that all observers see the same universal characteristics at large scales,one may conclude that the Robertson (27, 28) - Walker (29) models for the Universe should be used. It is important to point out that it is not necessary to understand the origin of the CBR; what is important is to know that the CBR is highly isotropic.

2 - SMALL SCALES ANISOTROPIES OF THE CBR

The origin of galaxies, according to Sunyaev and Zeldovich (30), is related to the growth of small fluctuations in the rigorous homogeneity which existed during the distant past, before the recombination of the primordial plasma, an epoch corresponding to $z \sim 1000$.

One can consider,as a first approximation, that after the recombination of protons and electrons the "matter" (neutral atoms) did not interact with the radiation; as a consequence the CBR can readily provide informations about the conditions during $z \sim 1000$.

The temperature variation dependence, as a function of the direction of observation, characterises the dependence of physical values, i.e., the density deviations, at a distant past and in spacial coordinates. However, because of the gravitational instabilities these deviations grow with time, after recombination.

It is reasonable to consider that the initial density at the regions of formation of distinct objects was of the order of at least two times the average density, i.e., $\frac{\delta\rho}{\rho} \sim 1$.It is also considered that this separation of objects ocurred at a relatively recent period of time, i.e., $z \sim 2 - 10$. Therefore, in this case the variation of the density perturbation at the epoch of recombination is

$$\frac{\delta\rho}{\rho} \sim 10^{-2} \quad \text{to} \quad 10^{-3} \quad \text{for} \quad z \sim 1000 \tag{20}$$

which permit us to speak about small scale perturbations.

Sunyaev and Zeldovich (30) show that other than the perturbations which lead to the formation of galaxies there is a spectrum of perturbations which is of interest for the determination of the characteristics of the initial inhomogeneity. They point out the nature of these perturbations which may be qualitatively defined by:

(i) Density perturbations of matter (nuclei and electrons), "ρ_m", on a background of a constant density of quanta, "ρ_r" (so-called entropy perturbations).

(ii) Compression and rarefraction waves of the plasma as a whole with simultaneous changes of "ρ_m" and "ρ_r" (adiabatic perturbations).

(iii) Turbulent motions of the plasma.

(iv) Chaotic magnetic fields and perhaps other types of perturbations.

Different types of perturbations evolve differently at plasma periods ($z > 1400$) and give different predictions concerning the formation of galaxies and fluctuations of relic radiation. Silk (31, 32, 33) made quantitative predictions concerning adiabatic perturbations. His results were obtained on the assumption that recombination of the initial plasma occurs quite suddenly for a definite z_r. Earlier in time, for $z > z_r$, perfect adiabaticity is assumed, so that

$$\frac{\delta\rho_m}{\rho_m} = 3\,\frac{\delta T}{T} \quad ; \quad \frac{\delta\rho_r}{\rho_r} = 4\,\frac{\delta T}{T} \,. \tag{21}$$

Later, the recombination ($z < z_r$) of matter is completely transparent and any observer measures of $\frac{\delta T}{T}$ reach the moment $z = z_r$ directly. On the other hand, due to gravitational instability, $\frac{\delta\rho}{\rho}$ subsequently grows proportionally to $(1 + z)^{-1}$, so that

$$\left[\frac{\delta\rho}{\rho}\right]_{z_r} = \frac{1 + z_o}{z_r}\left[\frac{\delta\rho}{\rho}\right]_o = \frac{1 + z_o}{z_r} \tag{22}$$

for a definite z_o, at the moment $\frac{\delta\rho}{\rho} = 1$.

Measurements of the fluctuations of the CBR allow a judgement of the conditions of the Universe, at the time of galaxy formation, only if radiation does not interact with matter after recombination. However, it is important to point out that recombination may not occur instantaneously. Detailed calculations by Zeldovich et al. (34), Peebles (35) and Sunyaev and Zeldovich (36), show the recombination of hydrogen does not occur according to the Saha equation of equilibrium but much more slowly. When a protogalaxy or proto-cluster of galaxies (a small perturbation of density, at the moment of recombination, enclosing a mass which later is converted into a presently existing object) becomes transparent to radiation, the optical depth for Thompson's scattering by matter between the proto-objects and the observer,

$$\tau_T = \int_0^{z_{max}} \sigma_T N_e(z)\ c\ \frac{dt}{dz}\ dz \quad , \tag{23}$$

is still very large, as a result of which temperature fluctuations of CBR are smoothed out.

There are several possible energy sources which could promote the interaction of radiation with matter after the recombination. At redshifts $z < 10$ there were explosions in the galactic and quasars nuclei, ionization losses of subcosmic rays in the intergalactic medium(Ginzburg and Ozernoy (37)) and shock waves formed during the contraction of protoclusters of galaxies (Sunyaev and Zeldovich (38, 39)). Other sources of energy include matter-antimatter annihilation, evaporation of primordial black holes and heavy unstable particle decay. The energy released by these processes increases the radiation energy density and distorts its spectrum.Gunn and Peterson (40) observing the Ly-α absorption band in the spectra of distant quasars showed the absence of neutral intergalactic hydrogen at redshifts $z \leq 3.5$. They concluded that the intergalactic gas was at some time heated and ionized. If the gas is hot enough, Compton scattering influences the spectrum of the CBR. Therefore,from the observation of the CBR's spectrum one can learn when secondary heating occurred and how it affects the intergalactic gas (Weymann (41), Sunyaev (42), Zeldovich and Sunyaev (43), Chan and Jones (14, 44, 45), Field and Perrenod (46), Sunyaev and Zeldovich (36)).

If the energy was released during the epoch $0 < z < 4 \times 10^4\ \omega^{-6/5}$ (where $\omega = \Omega \cdot h^2$, $H_o = 50h \cdot km \cdot s^{-1}$, Ω = density parameter) it raises the electron temperature, so that $T_e > T_r$. For a wide range of physical conditions a typical spectrum arises, that is, the number of photons is conserved but their average energy increases and the photons are redistributed over frequency. The Rayleigh-Jeans slope of the spectrum is maintained in the low-frequency region, but the intensity and brightness temperature decrease. Distortions of this type are shown in Figure 3.

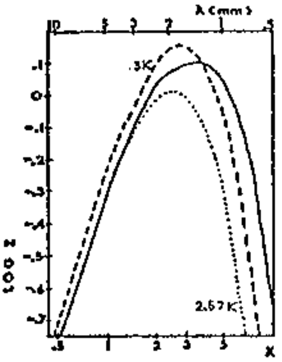

FIGURE 3 - The effect of Compton scattering on the spectrum of the microwave background in the case of late energy release. The broken line corresponds to the initial black-body spectrum, the solid line corresponds to the spectrum that results from Compton scattering, and the dotted line to a blackbody spectrum that mimics the spectrum produced by Compton scattering at long wavelengths:

$x = h\nu/kT_r$ and $y = 0.555$

(Sunyaev and Zeldovich (36), pag. 544).

These distortions are described by equations derived by Zeldovich and Sunyaev (43).

$$\frac{\Delta I_\nu}{I_\nu} = \frac{\Delta n}{n} = y \frac{xe^x}{(e^x-1)} \cdot \{x \left[\frac{e^x+1}{e^x-1}\right] - 4\} \qquad (24)$$

$$\frac{\Delta T_r}{T_r} = \frac{d\ell n\ I_\nu}{d\ell n\ T_r} \quad \frac{\Delta I_\nu}{I_\nu} = y\ \{x \left[\frac{e^x+1}{e^x-1}\right] - 4\} \qquad (25)$$

and

$$n(x,y) = \frac{1}{\sqrt{4\ \pi y}} \int_0^\infty n_o(w) \exp\ \{- \frac{(\ell nx-\ell nw+3y)^2}{4y}\} \frac{dw}{w} \qquad (26)$$

where

$$x = h\nu/kT_r \quad , \quad y = \sigma_T N_e ct \quad ,$$

and

$$n_o = (e^x - 1)^{-1} \quad ,$$

which is the initial arbitrary radiation spectrum (black-body).

Sunyaev (42) and Zeldovich and Sunyaev (43) showed that neutral hydrogen remained neutral during some time after recombination at z_r. Otherwise, distortions of the blackbody spectrum would be observable.

Sunyaev and Zeldovich (36) showed that spectral distortions, as shown in figure 3 and discribed by equations (24), (25) and (26), are predicted under very different conditions, such as:

(i) The temperature of electrons exceeds that of the radiation. Plasma heating by shock waves during the formation of clusters of galaxies, explosions in quasars and in galactic nuclei.

(ii) The energy released is stored in chaotic motions of optically thick plasma clouds together with their components, i.e., matter and radiation. Kinematic energy is transformed into thermal energy and photon diffusion smoothes the radiation field.

(iii) A small fraction of the photons, 5% for example, is scattered by very hot electrons ($T_e \sim 10^8\ ^oK$) and the other 95% are not. This might occur if the background photons interact with hot gas clouds in clusters of galaxies.

Data obtained by X-ray satellites show that the rich clusters of galaxies contain a large amount of hot ($T_e \sim 10^8\ ^oK$), rarefied ($N_e \sim 10^{-2} - 10^{-3}\ cm^{-3}$) intergalactic gas. Therefore, clusters are high-temperature plasma clouds with noticeable optical depth for Thompson scattering

$$\tau_T = \int_{-\infty}^{+\infty} \sigma_T N_e(\ell) d\ell \qquad 0 < \tau_T << 1 \qquad (27)$$

Bremsstrahlung radiation produced by this gas is observed at X-ray frequencies. Compton scattering of microwave photons on free electrons leads to many important effects, but from the observational view point the thermal effect is the most important.

The thermal effect consists on the scattering, by hot electrons, of a fraction of the order of τ of the background photons observed in the direction of a cluster of galaxies. The remaining fraction $(1 - \tau)$ is not scattered. Scattering by electrons with $kT_e >> h\nu$ changes the photon frequency through the Doppler effect. With the scattering of CBR photons, with

$T_r \ll T_e$, by a Maxwellian distribution of electrons, the frequency of the photons is increased. In the Rayleigh-Jeans region ($h\nu \ll kT_r$) the intensity and the brightness tenperature decrease:

$$\frac{\Delta T}{T_r} = -\frac{2\ kT_e}{m_e\ c^2} \tag{28}$$

In the Wien region ($h\nu > 3.83\ kT_r$) the intensity increases; the effect is proportional to the fraction of photons that have undergone scattering in the cloud (Sunyaev and Zeldovich (36)). In the Rayleigh-Jeans region one has the thermal effect:

$$\frac{\Delta T}{T_r} = -\frac{2\ kT_e}{m_e\ c^2}\tau_T \tag{29}$$

The difference of the effective temperature of the CBR, when observed in the direction of a rich cluster of galaxies and compared with the observed temperature in other direction, is given by:

$$\frac{\Delta T}{T_r} = -\frac{4k\ T_e}{m_e\ c^2}\sigma_T\ N_e R \tag{30}$$

where R is the radius of the gas cloud in the cluster. In the Rayleigh-Jeans region the effect does not depend on the wavelength, and the brightness temperature decreases in the direction of the hot gas cloud. The amplitude of the effect does not depend on the redshift. Only the angular dimension of the cloud depends on z. Therefore, it may be possible to observe clusters and protoclusters of galaxies by satellittes, in the λ1-2mm band, where this effect is strongest, even if they are at cosmological distances (these observations are seriously perturbed by the atmosphere emission when made from the Earth's surface). The radio observations combined with X-ray data permit us to determine the gas density and temperature distribution inside clusters.

White and Silk (47), on their cluster of galaxies models, have shown that once a temperature structure of the gas, consistent with the spectral data, is adapted for a cluster of galaxies, where the intergalactic gas properties in any point are specified by the equation which define:

(i) the volume emissivity, L, of the gas in a particular band,

(ii) the bremsstrahlung, $\Lambda(t)$, for passbands measured in keV,

(iii) the emissivity profile, L(r), of a function of the observed central surface brightness, ℓ_o, and the X-ray, r_c, core radius,

the expected microwave decrement at the cluster center can be calculated in the Rayleigh-Jeans limit as

$$\frac{\Delta T_m}{T_m} = \frac{2k\sigma_T}{m_e c^2}(2r_c\ell_o)^{1/2}\int_0^\infty T(x).\{\Lambda\left[T(x)\right]\}^{-1/2}.(1+x^2)^{-3/4}\ dx \tag{31}$$

where m_e and σ_T are the electron mass and the Thompson cross section. This prediction can, in principle, be compared with the observed microwave decrement to determine the cluster distance by means of the dependence of $\Delta T_m/T_m$ on $(2r_c)^{1/2}$ or the cluster diameter, $d_A^{1/2}$ (see eq. 31). A comparison of $d_A^{1/2}$ with cluster radial velocity may give a direct measurement of the Hubble constant.

The predictions for the magnitude of the thermal effect are found in the interval 3×10^{-5} to 10^{-3} °K (Gull and Northover (38), Sarazen and Bahcall (49), Gould and Raphaelli (50), Boynton (51), Martin and Beckman (52)).

In Table 3 are listed the present observational limits for the temperature fluctuations of the CBR at small scales.

OBSERVERS	ANGULAR SCALE	λ(cm)	$\Delta T/T^{\dagger}$
Concklin & Bracewell	10'	2.8	$<1.8 \times 10^{-3}$
Penzias et al.	2'	0.35	$<6.0 \times 10^{-3}$
Boynton & Partridge	1!5	0.35	$<1.9 \times 10^{-3}$
Carpenter et al.	> 2'	3.6	$<7.0 \times 10^{-4}$
Parijskij	> 5'	2.8	$<4.0 \times 10^{-4}$
Stankevich	10'-20'	11.1	$<1.5 \times 10^{-4}$
Caderni et al.	30'	0.13	$<1.2 \times 10^{-4}$
Partridge	4'	0.9	$<5.0 \times 10^{-4}$
Pigg	1!25	2.0	$<7.0 \times 10^{-4}$
Parijskij	> 5'	2.8	$<8.0 \times 10^{-5}$
White & Silk	∿10'	*	6.3×10^{-5}
Birkinshaw et al.	∿ 5'	2.8	$<3.8 \times 10^{-5}$

TABLE 3 - Upper limits on fine-scale fluctuations of the CBR. (Boynton (51), Table I plus data from White and Silk (47) and Birkinshaw et al. (53)).

† Generally quoted as 2σ or 95% limit.

* X-ray (band 1-3 keV).

Untill the present time, the consistent results indicating a temperature decrement of the CBR towards rich cluster of galaxies have proved ELUSIVE. Only two clusters, A2218 and A576, show significant decrements at the 2σ level, in the results of at least two independent groups of observers. Lacke and Partridge (54) have failed to confirm the CBR temperature decrement toward A2218. Only towards A576 was detected a CBR temperature decrement at the 10^{-3} °K level. This decrement is presently undisputed (Birkinshaw et al. (53), Lacke and Partridge (54)).

Boynton (51) shows that the critical region to test for primordial fluctuations on the CBR is in the interval of angular scales, from 1 to 2 arcminutes, and of temperature, from 10^{-5} to 6×10^{-4} °K ($\Omega_o = 0.1$ and 10^{15} $M_{\odot}$). He states that in an $\Omega_o = 0.1$ universe, any observational effort which penetrates this region should detect fluctuations. However, the integration time requirement, τ, to achieve $\Delta T/T \approx 10^{-5}$ for N independent pairs of sky elements is given by

$$\tau \approx 10^{10}\ NB^{-1}\ T_{rec}^{2}\ \text{(seconds)} \qquad (32)$$

where B is the receiver pre-detection bandwidth in Hz, and T_{rec} the receiver noise temperature (Boynton (51)).

It should be pointed out that the best maser receivers yield τ/N values of around 24 hours. It is possible that future improvements of the receivers might reduce that time to ∿12 hours. Therefore, a statistically meaningful sample (N > 100) of sky elements would recuire concurrent use of a state of the art receiver and one of the largest radio telescopes for a large fraction of a year and optimal observing conditions (Boynton (51)).

There are at least two main objections for far infrared observations of fine scale anisotropy: one is the spectral of atmospheric emission fluctuations The second objection concerns the determination of the contributions of discrete emission sources to fine-scale anisotropy (Longair and Sunyaev (55), Ade et al. (56), Hildebrand et al. (57)).

Davis and Boynton (58) derived lower limits for the CBR fluctuations. These fluctuations where expressed in a form which could be directly interpreted in terms of temperature differences, in a given angular scale. Their predictions for puraly isothermal fluctuations of matter are much lower than the detection spectations for the present observational programs. They conclude in order to be possible to perform a critical test for the hypothesis of gravitational instability, it will be necessary to improve, about one order of magnitude, the sensibility for the small scale anisotropy measurements published untill the present.

One may conclude, the CBR, at small scale, is remarkably isotropic. It is still early to make investigations of thermic events which occurred at primordial times of the Universe, from measurements of the deviations of a perfect Planck curve for the CBR spectrum. It is generally accepted that only observations made from space platforms, out of the atmosphere contributions, will produce solid informations about the isotropy and the shape of the spectrum of the CBR (Robson and Clegg (59), Boynton (51), Partridge (60), Davis and Boynton (58), White and Silk (47), Weiss (6)).

REFERENCES

1 - Partridge, R.B., Peebles, P.J.E., 1967, Ap.J., 148,377.
2 - Henry, P.S., 1971, Nature, 231, 516.
3 - Corey, B.E.,Wilkinson,D.T.,1976,Bull.Am.Astron.Soc.,8,351.
4 - Nuehlner,D.J.,Weiss,R.,1980.Mentioned by Weiss (06).
5 - Cheng,E.S.,Saulson,P.R.,Wilkinson,D.T.,Corey,B.E.,1979,Ap.J.Lett.,232,L139.
6 - Weiss,R.,1980,Ann.Rev.Astron.Astrophys.,18,489.
7 - Smoot,G.F.,Gorenstein,M.V.,Muller,R.A.,1977,Phys.Rev.Lett.,39,898.
8 - Gorenstein,M.V.,Smoot,G.F.,1980. Mentioned by Weiss (06).
9 - Boughn,S.P.,Fram.,D.M.,Partridge,R.B.,1971,Ap.J.,165,439.
10- Conklin,E.K.,1969,Nature,222,971.
11- Partridge,R.B.,Wilkinson,D.T.,1967,Phys.Rev.Lett.,18,557.
12- Smoot,G.F.,Lubin,P.M.,1979,Ap.J.Lett.,234,L83.
13- Lubin,P.M.,Smoot,G.F.,1979,Phys.Rev.Lett.,42,129.
14- Chan,K.L.,Jones,B.J.T.,1975,Ap.J.,200,461.
15- White,S.O.N.,1980,Phys.Scripta,21,640.
16- de Vaucouleurs,G.,de Vaucouleurs,A.e Corwin,H.G.,Second Reference Catalogue of Bright Galaxies,Univ.of Texas,Austin,1976.
17- Sandage,A.E.,Tammann,G.A.,1975,Ap.J.,196,313.
18- Sandage,A.,Tammann,G.A.,Hardy,E.,1972,Ap.J.,172,253.
19- Sandage,A.,1975,Ap.J.,202,563.
20- Sandage,A.,Tammann,G.A.,1972,Ap.J.,197,265.
21- Tammann,G.A.,Yahil,A.,Sandage,A.,1979,Ap.J.
22- de Vaucouleurs,G.,1976,Ap.J.,205,13.
23- Peebles,P.J.E.,1976,Ap.J.,205,318.
24- de Vaucouleurs,G.,Bollinger,G.,1979,Ap.J.,233,433.
25- Tully,R.B.,Fisher,J.R.,1977,Astron.Astrophys.,54,661.
26- Aaronson,M.,Huchra,J.,Mould,J.,1979,Ap.J.,229,1.
27- Robertson,H.P.,1935,Ap.J.,82,284.
28- Robertson,H.P.,1936,Ap.J.,83,187.
29- Walker,A.G.,1936,Proc.Lond.Math.Soc.,(2),42,90.
30- Sunyaev,R.A.,Zeldovich,Ya.A.B.,1970,Astrophys.Space Sci.,7,3.
31- Silk,J.,1967a,Astrophys.J.,151,459.
32- Silk,J.,1967b,Nature,215,1155.
33- Silk, J.,1968,Nature,218,453.
34- Zeldovich,Ya.B.,Kurt,V.G.,Sunyaev,R.A.,1968,Zh.E.T.F.,55,278.
35- Peebles,P.J.E.,1968,Ap.J.,153,1.
36- Sunyaev,R.A.,Zeldovich,Ya.B.,1980,Ann.Rev.Astron.Astrophys.,18,537.
37- Ginzburg,V.L.,Ozernoy,L.M.,1965,Sov.Astron.,42,943.
38- Sunyaev,R.A.,1972,in "Radio Astronomy and Cosmology",Ed.D.L.Jancey,IAU Symp.,74,327.
39- Sunyaev,R.A.,Zeldovich,Ya.B.,1972,Astron.Astrophys.,20,189.
40- Gunn,J.E.,Peterson,B.A.,1965,Ap.J.,142,1633.
41- Weymann,R.,1965,Ap.J.,147,887.

42- Sunyaev,R.A.,1968,Sov.Phys.Dokl.,13,183.

43- Zeldovich,Ya.B.,Sunyaev,R.A.,1968,Astrophys.Space Sci.,4,301.

44- Chan,K.L.,Jones,B.J.T.,1975,Ap.J.,195,1.

45- Chan,K.L.,Jones,B.J.T.,1975,Ap.J.,200,454.

46- Field,G.,Perrenod,S.C.,1977,Ap.J.,215,717.

47- White,S.O.M.,Silk,J.,1980,Ap.J.,241,864.

48- Gull,S.F.,Northover,K.J.E.,1975,MNRAS,173,535.

49- Sarazin,C.L.,Bahcall,J.N.,1977,Ap.J.Suppl.,34,451.

50- Gould,R.J.,Raphaelli,Y.,1978,Ap.J.,219,12.

51- Bounton,P.E.,1978, in "The Large Scale Structure of the Universe",ed.M.S.Longair and J. Einasto, IAU Symp. 79,317.

52- Martin,D.H.,Beckman,J.E.,1979,preprint of the European Space Agency.

53- Birkinshaw,M.,Gull,S.F.,Northover,K.J.E.,1981,Mon.Not.R.Astr.Soc.,197,571.

54- Lake,G.,Partridge,R.B.,1980,Ap.J.,237,378.

55- Longair,N.S.,Sunyaev,R.A.,1969,Nature,223,719.

56- Ade,P.A.R.,Rowan-Robinson,M.,Clegg,P.E.,1976,Astron.Astrophys.,53,403.

57- Hildebrand,R.H.,Harper,D.A.,Whitcomb,S.E.,Winston,R.,Stiening,R.F.,Moseley,S.H.,1977,Ap. J.,216,698.

58- Davis,M.,Boynton,P.,1980,Ap.J.,237,365.

59- Robson,E.I.,Clegg,P.E.,1977, in"Radioastronomy and Cosmology",ed.D.L.Jauncey,IAU Symp., 74,319.

60- Partridge,R.B.,1980,Ap.J.,235,681.