1983ICRC...12....1N

RADIATION BACKGROUNDS AND THEIR COSMOLOGICAL IMPLICATIONS

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ABSTRACT

The information content of radiation backgrounds at wavelengths ranging from radio waves to gamma rays is reviewed, within the context of the standard big bang cosmology. It is shown that the various backgrounds provide useful inputs and constraints on the physical features of the universe such as the existence and growth of large scale inhomogeneities like galaxies, clusters and superclusters, the overall density of the universe, the photon to baryon ratio and the extent of antimatter in the universe, etc. It is argued that there are questions posed by the data which may require rethinking of some aspects of standard cosmology.

1. Introduction

Over the years the region of overlap between cosmic ray physics and astronomy has grown steadily. Nevertheless we may assume, in the first approximation, that the techniques of the two disciplines are mutually complementary : the astronomer bases his interpretations on the electromagnetic radiation from the different parts of the universe whereas the cosmic ray physicist is concerned with particles from outer space. My brief today is to don the astronomer's cap and review the information content of the radiation backgrounds with special reference to cosmology. Thanks to the inputs from space physics the astronomer now possesses information on radiation backgrounds over a wide range of wavelengths, from radio waves to gamma-rays. How does this information fit into our theoretical concept of the universe, a concept which was first formulated in the days when ground-based optical astronomy was the sole means of astronomical observations?

Cosmology was launched as a branch of science by Albert Einstein in his classic paper of 1917. Pioneering work on the theoretical side came from Alexander Friedmann in 1922 and on the observational side from Edwin Hubble in 1929. In fact the 'expanding universe' solutions of Friedmann anticipated Hubble's discovery of the nebular redshift and it is remarkable that today, some five to six decades later, cosmology still rests on the foundations laid by Friedmann and Hubble.

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It is also interesting that cosmology furnishes two classic examples of theory anticipating observations. The first example, I have just referred to above. The second example concerns the prediction and subsequent discovery of the microwave background radiation which I shall discuss in detail in §3.

Emboldened by these successes theoretical cosmologists have pushed the frontiers of their extrapolations of the past history of the universe to epochs very close to that of the big bang origin of the universe. The canonical early universe scenario is outlined in Table I below.

Table I : Cosmythology

Time t	What happened
$t=0$	Big bang (?)
$0 < t \lesssim 10^{-43}$s	Quantum cosmology
10^{-43}s $\lesssim t \lesssim 10^{-37}$s	Grand Unified Theory (GUT)
10^{-37}s $\lesssim t \lesssim 10^{-33}$s	GUT symmetry broken and baryon excess created
10^{-11}s $\lesssim t < 10^{-8}$s	Electroweak symmetry broken
10^{-8}s $\lesssim t \lesssim 10^{-4}$s	Hadron era
10^{-2}s $\lesssim t \lesssim$ 1s	Neutrinos decouple
1s $\lesssim t \lesssim$ 10s	Electron-positron pairs annihilate
10s $\lesssim t \lesssim$ 3m	Nucleosynthesis of light nuclei
$t \sim 10^5 - 10^6$ yr	Decoupling of radiation from matter
? ? ?	Galaxies form

The post-World War II developments in astronomy and theoretical physics are responsible for making cosmology so exciting, and the cosmologists so daring. While compressing the highlights of these thirty eight years into a survey of thirty eight minutes' duration I have to be necessarily very brief. I hope the lack of detail in places will be compensated by the references cited during the talk.

2. The Contents of the Universe

Leaving aside the speculations of Table I let us consider the present information about the state of the universe summarized in Table II. The matter contents of the universe are divided into two categories, 'seen' and 'unseen.' Arguments based on the flat rotation curves of galaxies (Faber and Gallagher, 1979) and the high velocity dispersion of clusters of galaxies (Zwicky, 1933, Bahcall

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1983ICRC...12....1N

1977) suggest that a substantial part of the universe may still be unseen. The objects mentioned in the third column of the matter part of Table II are some of the conjectures advanced for the form of unseen matter.

Table II: Present Contents of the Universe: Hard Facts + Conjecture

	Form	Type	Estimated Mass Density in $g\ cm^{-3}$
MATTER	Seen	Galaxies, Radio sources, Quasars, BL Lacs etc	$\sim 3 \times 10^{-31}$
	Unseen	Intergalactic medium, black holes, low mass stars, massive neutrinos, other 'ino's, monopoles	? ?
	Form	Wavelength Range in centimetres	Estimated Energy Density in $erg\ cm^{-3}$
RADIATION	Radiowaves	$\lambda \gtrsim 7.3$	$\lesssim 10^{-18}$
	Microwaves	0.1 - 80	$\sim 6 \times 10^{-13}$
	Infrared	$10^{-4} - 10^{-3}$	$\sim 4 \times 10^{-13}$ (?)
	Optical	$4 \times 10^{-5} - 8 \times 10^{-5}$	$\sim 3.5 \times 10^{-15}$
	Ultraviolet	$2 \times 10^{-6} - 2 \times 10^{-5}$	$\sim 10^{-16} - 10^{-15}$ (?)
	X-rays	$3 \times 10^{-9} - 1.2 \times 10^{-7}$	$\sim 10^{-16}$
	gamma rays	$\lambda \lesssim 1.2\ 10^{-13}$	$\lesssim 2 \times 10^{-17}$

? : Tentative estimate. ?? Anybody's guess

The radiation part of Table II gives the approximate energy densities in the various wavelength ranges of the electromagnetic radiation. Not all wavelength ranges have been fully explored and so the figures presented here should not be regarded as final. Before we proceed further the following points may be noted.

a) The standard Friedmann models tell us that the universe is closed if the present mass density (of matter + radiation) exceeds the value

$$\rho_c = \frac{3H_o^2}{8\pi G} \simeq 2 \times 10^{-29}\ h_o^2\ \ g\ cm^{-3} \qquad (1)$$

where the Hubble constant is given by

$$H_o = 100\ h_o\ km\ s^{-1}\ Mpc^{-1}. \qquad (2)$$

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1983ICRC...12....1N

It is customary to denote by Ω_0 the ratio of the actual mass density to ρ_c. If we assume that the unseen part of the matter makes an insignificant contribution to the overall matter density compared to the seen part (i.e., ?? $\simeq$ 0 in Table 1) then the universe is open.

b) Even though the seen part of matter is not sufficient to close the universe, it far exceeds the energy density of radiation. However, according to the standard Friedmann models the matter energy density ε_m and the radiation energy density ε_r vary with the scale factor S of the expanding universe according to the rule

$$\varepsilon_m \propto \frac{1}{S^3} , \qquad \varepsilon_r \propto \frac{1}{S^4} . \qquad (3)$$

Therefore, if S has been increasing from the big bang value S = 0 , its small values in the early epochs imply that in sufficiently remote past $\varepsilon_r >> \varepsilon_m$. From Table II and relations (3) it follows that the universe was 'radiation dominated' prior to the epoch when S was about a thousandth of its present value. It is usual to indicate a past epoch by its redshift z. Thus 1 + z is the ratio of the scale factor S at the present epoch to the scale factor S at the past epoch.

c) Looking at the radiation part of Table II it is clear that at present bulk of the energy density resides in the microwaves (and possibly in the infrared if the question-mark is confirmed). Although in this talk I will cover most of the wavelengths listed in Table 1, the microwave background (MBR in brief) will occupy the major part of the discussion. For, the information content of the MBR is widely believed to have the most far reaching implications for cosmology.

Table III below summarizes the different aspects of cosmology on which the various radiation backgrounds throw some light. The entries are listed in the order in which they are to be discussed here and a glance at them is sufficient to explode the myth "Only sources carry information, the background is mere noise."

Table III: Cosmological Issues Raised by the Observations of Radiation Backgrounds

Form of Radiation Background	Issues of cosmological Relevance
Microwave	The cause of spectral distortion Galaxy formation Horizon effect Motion of the Galaxy Rotation of the universe Universality of MBR The photon to baryon ratio

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1983ICRC...12....1N

Table III continued ...

Form of Radiation Background	Issues of Cosmological Relevance
Infrared	Population III objects Nonrelic MBR
Optical	Estimate of ρ_m
Radio	Limits on source counts Limits on measurability of small scale fluctuations of MBR
Ultraviolet	Decay of massive neutrinos
X-rays	Discrete sources and the intergalactic medium Can quasars be local? Large scale anisotropy
Gamma rays	Antimatter in the universe

3. The Microwave Background

(i) The spectrum of microwave background. The existence of a microwave background was predicted by Gamow (1953) and his coworkers Alpher and Hermann (1949) on the basis of their work on primordial nucleosynthesis. According to the standard big bang model matter and radiation were in thermodynamic equilibrium until the so called recombination epoch when radiation decoupled from matter. This is believed to have happened when the scale factor of the universe was about 10^{-3} of its present value that is, around a redshift of $\sim$1000. The radiation since then cooled down but retained its black body spectrum. The Planckian spectrum was therefore predicted for the MBR, as a signature of its primordial origin.

Observations of MBR spectrum are now available from frequencies ranging from 0.014 cm^{-1} to 22.89 cm^{-1} [see Weiss (1980) for a review.] The most recent measurements at high frequencies (2.38cm^{-1} to 22.89cm^{-1}) were reported by Woody and Richards (1981) who, while finding the expected turnover of the black body spectrum at high frequencies reported a more than 3 σ discrepancy between their data and the best fit black body temperature of 2.96 $\pm$ 0.08K. Gush (1981) had also reported observations which showed significant departure from the black body curve, but his curve also differed from that of Woody and Richards. Woody and

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1983ICRC...12....1N

Richards (private communication) have argued that instrumental malfunction in Gush's experiment makes the error limits of his data wider than were published.

The departure from the Planckian curve, if taken seriously, implies a deficit of photons in the Rayleigh Jeans part of the spectrum and an excess in the high frequency Wien part. More recently Smoot et al (1983, Preprint) have measured the low frequency part of the MBR spectrum (at frequencies .083 cm^{-1} to 3 cm^{-1}) and found the effective temperature to be 2.79 ± 0.10K. They argue that if the Woody-Richards calibration is correct and the peak of the MBR is narrower than the black body curve then one could fit the distorted spectrum by a Bose-Einstein distribution with a chemical potential $\mu = (5 \pm 3) \times 10^{-3}$ for $\Omega_o = 0.1$ and $\mu = (1.4 \pm 0.9) \times 10^{-2}$ for $\Omega_o = 1$.

Such a distortion and a fit with the Bose-Einstein spectrum could be accounted for qualitatively by multiple Compton scattering of the radiation by fast electrons at early epochs when the scale factor was less than 10^{-4} of its present value (Illarinov and Sunyaev 1972, Sunyaev and Zeldovich 1982). The value of $\mu = 1.4 \times 10^{-2}$ is however, too high to allow turbulence to play a major role in the formation of galaxies (Jones 1976).

Is the distortion of the MBR spectrum significant enough to warrant a non-primordial interpretation? I will briefly discuss non-primordial ideas later. Keeping within the primordial interpretation but departing from the standard Friedmann cosmology it is possible to get a better agreement with the Woody-Richards type curve. In the framework of the Hoyle-Narlikar cosmology with variable gravitational constant (Hoyle and Narlikar, 1972) Rana and I (1980, 1983 preprint) find that the Woody-Richards data can be fitted well within 1σ while all data at low as well as high frequencies can be fitted within 2σ.

(ii) Galaxy formation. Although the cosmologists have been struggling hard for several decades they do not yet have a satisfactory theory of galaxy formation. Most ideas, however, centre round the notion that there were some inhomogeneities in the cosmological substratum which subsequently grew in the post recombination era to form galaxies or clusters. If, as mentioned before, the present MBR is a relic of the epoch when radiation decoupled from matter and if the inhomogeneities mentioned above were present at that time then we ought to see their imprint in the form of small angle ($\lesssim$ 10 arc min) anisotropies of temperature. The early models of Silk (1968) and of Sunyaev and Zeldovich (1970) predicted temperature fluctuations of the order $\Delta T/T \sim 10^{-4}$.

Table IV shows the results of several searches for these

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1983ICRC...12....1N

fluctuations; none of them have yielded positive result. Partridge (1979) has discussed the difficulties of galaxy formation theories when confronted with these data.

Table IV : Small-angle Anisotropy of the Microwave Background

Frequency (cm^{-1})	Angular scale (in arc minutes)	$\Delta T/T$	Observers and year*
0.090	10 - 20	$< 1.5\times10^{-4}$	Stankevich (1974)
0.278	>2	$< 7\times10^{-4}$	Carpenter et al (1974)
0.0357	10	$< 1.8\times10^{-3}$	Conklin and Bracewell (1967)
0.357	>5	$<8.0\times10^{-5}$	Parijskij (1978)
0.500	>1.25	$< 7\times10^{-4}$	Pigg (1978)
1.03	7	$< 8.0\times10^{-5}$	Partridge (1980)
2.857	2	$< 6\times10^{-3}$	Penzias et al (1969)
2.857	1.5	$< 1.9\times10^{-3}$	Boynton and Partridge (1973)
7.692	30	$< 1.2\times10^{-4}$	Caderni et al (1977)

* For detailed references see Narlikar (1983).

These measurements are such as to eliminate certain models like the vortex or whirl models. Similarly models of galaxy formation through adiabatic growth of density fluctuations appear to be in difficulty. Some theoreticians are therefore putting their money on isothermal models which predict smaller $\Delta T/T$. However, by and large it is not an exaggeration to say that the accuracy achieved by the observers has got the theoreticians on the run.

If one is looking for signature on MBR of units bigger than galaxies, e.g. clusters or superclusters then this should be found in $\Delta T/T$ over angular scales of a few degrees. Fabbri et al (1980) find $\Delta T/T < 3 \times 10^{-4}$ at 1σ at the scale of 2° while Melchiorri et al (1981) give an upper limit of 4×10^{-5}K on the MBR fluctuations at 2σ level over 6° scale. Thus MBR fails to reveal unambiguous evidence of development of substructures in the universe.

A way out of this difficulty would be to argue that matter in the universe got reionized after the decoupling epoch and the universe again became optically thick and hence all early signatures of galaxy formation (such as $\Delta T/T$) were wiped out. Or, of course, the alternative (and non-canonical) explanation could be that the MBR is not primordial and may have formed in recent epochs.

(iii) The horizon effect. The fact that the MBR is so smooth poses another problem for standard cosmology. This is the

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1983ICRC...12....1N

problem of the small particle horizon. In the early universe a good approximation for S(t) is

$$S(t) \propto t^{1/2}. \tag{3}$$

General relativity then tells us that at the cosmic epoch t the past light cone of an observer with comoving coordinate r = 0 when extended back to t = 0 (the singular beginning of the big bang universe) encompasses other comoving observers upto a proper distance d/2 where

$$d \leq d_H(t) = 4ct. \tag{4}$$

At the epoch of decoupling $t \cong 2.2 \times 10^5\ h_o^{-1}$ yrs for the Einstein de Sitter model. Thus the characteristic size of a region over which homogeneity may be expected to be established by physical processes was $\sim 0.3\ h_o^{-1}$ Mpc. By now this region will have expanded to a size of diameter $\sim 3 \times 10^2\ h_o^{-1}$ Mpc. At a characteristic distance from us of $\sim 3000\ h_o^{-1}$ Mpc, a blob of the above radius is expected to subtend an angle of

$$\theta_H \sim \frac{3 \times 10^2 h_o^{-1}}{3000\ h_o^{-1}} \sim \frac{1}{10} \sim 6^\circ. \tag{5}$$

A rigorous calculation gives (cf Narlikar 1983) that in a Friedmann model of present density $\rho_c \Omega_o$,

$$\theta_H \sim 3.6^\circ \sqrt{\Omega_o}. \tag{6}$$

However, no patchiness is seen on this angular scale in the MBR. This observation implies that the observed smoothness of MBR is an outcome of special initial conditions at t = 0 rather than of physical processes which tend to produce a homogeneous background.

This difficulty disappears if the early universe scenario produce horizon-free cosmologies which tend to simulate the Friedmann model at large t. This has not been possible under classical general relativity but could be achieved with inflationary scenarios (Guth 1981) or in quantum cosmology (Narlikar and Padmanabhan 1983).

(iv) Motion of the galaxy. The MBR does display anisotropy on the large (180°) angular scale. Two groups of observers, one at Berkeley (Smoot et al 1977) and one at Princeton (Cheng et al 1979) using the different techniques of the U2 airplane and balloon respectively, arrived at the conclusion that the background temperature shows a dipole anisotropy, with a variation law of the form

$$T = T_o + T_1 \cos\theta, \qquad (T_1/T_o << 1) \tag{7}$$

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1983ICRC...12....1N

where θ measures the polar angle with the direction of the dipole.

The dipole anisotropy can be accounted for by the assumption that the observer has a proper motion relative to the cosmological substratum. Now it is not sufficient to say that the proper motion is due to the Earth going round the Sun which goes round the Galaxy. It is necessary to ascribe proper motion to the Galaxy also. This last motion is estimated at $\sim$ 540 km s^{-1} in the direction $\ell = 280°$ $b = 30°$ by the Princeton group and at $\sim$ 603 km s^{-1} in the direction $\ell = 261°$, $b = 33°$ by the Berkeley group.

These measurements broadly agree with each other and are also consistent with the velocity of the Galaxy against the cosmological rest frame measured by Hart and Davies (1982) who used the 21 cm observations of the anisotropy of Hubble flow of 81 nearby galaxies. However, the earlier and more extensive optical measurements of Rubin et al (1976) of the anisotropy of Hubble flow of another sample of nearby galaxies (the Rubin-Ford effect) gave results disagreeing from the above measurements. Recently Vishwanathan (private communication) found a similar discrepancy from another survey.

I may also mention that at this conference Issa et al (1983) report that within its somewhat large error bars, the direction of dipole anisotropy of the diffuse cosmic X-ray background is consistent with the polar direction of anisotropy of MBR.

(v) Is the universe rotating? About ten years ago Collins and Hawking (1973) calculated that if the universe is spinning then the microwave background measurements should show a quadrupole anisotropy. Although the two groups at Berkeley and Princeton originally reported very small quadrupole anisotropies in their measurements described above, the claims were later withdrawn on a more careful reduction of the data. Since rotating universes are anti-Machian such measurements have special significance for the validity of Mach's principle (Narlikar 1983).

(vi) Universality of MBR. Although the homogeneity and isotropy of MBR suggests that it could not be due to nearby sources, its far reaching implications for cosmology require us to test its universality as thoroughly as possible. Direct measurements of its existence are made from the Earth and its immediate environment. It would be worthwhile making measurements from spacecrafts in the Solar Systems - a feat not beyond human technology today.

There are indirect ways of checking its existence

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1983ICRC...12....1N

elsewhere in the universe. The measurements based on relative populations of excited and ground states of the CN-molecule indicate that the radiation is also present elsewhere in the Galaxy. Another probe, of special interest to this audience comes from the spectrum of high energy cosmic rays.

If the very high energy ($E \gtrsim 10^{19}$eV) cosmic rays are extragalactic then collisions with MBR photons would reduce the energy of the cosmic ray protons. Hence it was predicted (Greisen 1966, Zatsepin and Kuzmin 1966) that the cosmic ray spectrum should steepen at high energy end. At least seven air shower primaries have been assigned energies greater than 10^{20}eV (Cunningham et al 1980, Linsley 1980) and no evidence of a cut off has been seen. The Soviet investigators (Dyakonov et al 1979) reported rough agreement with these results but more recently with an exposure about one third as great as in the Volcano Ranch and Haverah Park, they find no events with $E > 4 \times 10^{19}$eV. Does this imply that a cut off in the cosmic ray spectrum has been seen? In a recent analysis of this result Bower et al (1983) have concluded that the cut off may be due to the failure of the experiment to detect some high energy events. In this conference Horton et al (1983) have found a flattening of the spectrum above 10^{19}eV from S.U.G.A.R. array data in the Southern Hemisphere. Thus the cut off cannot be considered established and further observations of CR spectrum at high energy end are needed to settle the issue.

If there is no definite cut off and the spectrum does not steepen for $E \gtrsim 10^{19}$eV then we have to draw the conclusion that the high energy cosmic rays would not have travelled a distance more than $\sim$10 Mpc before entering the Galaxy. Such a conclusion may put limitations on the hypothesis of extragalactic origin of cosmic rays. However, the alternative conclusion that MBR does not extend beyond the local supercluster may be even more unpalatable to the cosmological establishment.

Another effect known as Zeldovich-Sunyaev effect can in principle tell us of the existence of MBR in remote clusters of galaxies (Sunyaev and Zeldovich 1970). The clusters contain high energy electrons which by collision with microwave photons generate inverse Compton X-rays. Thus there is a small depletion ΔT in background temperature across a cluster in the Rayleigh-Jeans part of the spectrum:

$$\frac{\Delta T}{T} \simeq -2\tau \frac{kT_e}{m_e c^2} \qquad (8)$$

where τ = optical depth across the cluster, T_e = electron temperature and m_e = electron mass. This effect has been looked for not seen in the clusters studied so far (Meyer et al, 1983, Andernach et al, 1983).

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(vii) The photon to baryon ratio. A fundamental problem linked with the relic radiation interpretation of MBR is the ratio of the number densities of photons (N_γ) to baryons (N_B). The ratio is

$$\frac{N_\gamma}{N_B} = 4.57 \times 10^7 (\Omega_o h_o^2)^{-1} \left(\frac{T_o}{3}\right)^3 , \qquad (9)$$

where T_o is the present blackbody temperature of MBR in degrees Kelvin. This ratio was frozen in essentially from the very early epochs in the universe and it is a mystery to understand the significance of its magnitude.

The progress of grand unified theories (GUTs) over the last decade has prompted fresh attack on this problem. First we have to note that N_B has a meaning only if we agree that there is net excess of matter over antimatter. I will consider this problem again while discussing the gamma-ray background. The calculations based on (i) matter-antimatter symmetry and (ii) thermodynamic equilibrium (Steigman 1976) suggest that

$$\frac{N_B}{N_\gamma} = \frac{\bar{N}_B}{N_\gamma} = 10^{-19} \approx \left(\frac{Gm_B^2}{\hbar c}\right)^{1/2} . \qquad (10)$$

Here N_B and $\bar{N}_B$ are baryon and antibaryon number densities The smallness of this value indicates that the above assumptions may have to be given up. In the simple SU(5) framework it was then possible to have a consistent range of parameters to achieve a net N_B/N_γ lying close to (9). No doubt other GUTs also can be suitably adjusted to give the right answer.

The success of such a calculation might be taken by particle physicists as vindication of their particular brand of GUTs and by cosmologists as vindication of the big bang scenario. In reality the calculation at best describes a self-consistent approach which is not necessarily unique.

4. The Infrared Background : A Non-relic MBR?

The ratio N_γ/N_B may be something of a red herring if the MBR is non-primordial. Indeed, Table V (p.12) presents circumstantial evidence to generate suspicion that the canonical relic interpretation of MBR may not be correct.

In Table V all other processes except the MBR are non-primordial and are believed to be of recent origin. The similarity of energy densities of these processes is therefore not surprising. What is surprising is that the MBR also has comparable energy density. Since the energy density of MBR is epoch-dependent ($\propto S^{-4}$) the closeness of its present

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1983ICRC...12....1N

value to the other entries listed in Table V must therefore be something of a coincidence.

Table V: Energy Densities in Typical Astrophysical Processes and in MBR

Process	Energy density (erg cm^{-3})
MBR	6×10^{-13}
Starlight in the Galaxy	8×10^{-13}
H → He conversion*	6×10^{-13}
Galactic magnetic field	3×10^{-14}
Cosmic rays	3×10^{-12}
Radio sources (outer regions)	$10^{-11} - 10^{-12}$

*Energy released on the assumption that all observed helium is produced in stellar nucleosynthesis.

Or is it? The coincidence was noticed (cf Hoyle et al 1968) in the early days after the discovery of MBR and indeed, several nonrelic interpretations were tried, in which the MBR was shown as the thermalized radiation from astrophysical processes of recent origin (Sciama, 1966, Narlikar and Wickramasinghe 1967, Wolfe and Burbidge 1969, Wickramasinghe et al 1975, Narlikar et al 1976).

In 1978 Rees proposed the attractive idea that massive Population III stars of pregalactic origin evolved quickly to become supernovae and produced radiation as well as synthesized nuclei. These nuclei, e.g. C, Si , etc formed gas and dust particles which thermalized the stellar radiation from Population III objects. The Rees model has been investigated and modified subsequently by others (Rowan-Robinson et al 1979, Tarbet and Rowan Robinson 1982). While it may not be possible to produce the entire MBR in this way, its spectral distoritons could be explained by such a nonrelic component.

Rana (1981) has, however shown that it is possible to generate MBR at epochs more recent than when Population III stars formed. Rana's model presupposes a greater stellar activity in the past at epochs of redshifts 10-12 (as opposed to 100-200 for Population III stars) and hence larger production of helium than suggested by the present stellar activity. Indeed it may be possible to argue that all observed helium was produced in stars and the stellar radiation so produced was thermalized to infrared and then redshifted to microwaves. Following the model of Narlikar et al (1975) Rana discussed thermalization by dust grains in the form of long whiskers of graphite.

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1983ICRC...12....1N

Recently Hayakawa has discussed similar ideas involving Population III stars. In his preprint (1983) Hayakawa has referred to recent measurements by Matsumoto et al (1983) which indicate that there is a considerable flux of background radiation in the 2-4μm range, of the order of (2-6) × 10^{-4} erg cm^{-2} s^{-1} Sr^{-1}. The indications are that the flux of cosmic light rises from the visible to the infrared 2-4μm range and then slowly declines at longer wavelengths. The total energy content in this part of the background may be as high as $\sim 4 \times 10^{-13}$ erg cm^{-3} , i.e., comparable to MBR.

Clearly the measurements in the infrared, of the background as well as of strong sources will in future throw considerable light on cosmological ideas and will provide clues to whether the canonical relic interpretation of MBR is correct or whether the radiation backgrounds in the infrared and microwaves are of more recent origin, from Population III stars or from more luminous stars at redshifts of ~ 10. After all, backgrounds at other wavelengths listed in Table II are mostly due to discrete sources. The non-primordial interpretations will, I feel, be severely tested by the isotropy constraints. In Rana's model, for example, the limit on small angle anisotropy is predicted to be $\sim 10^{-4}$ for $\Delta T/T$ at long wavelengths, decreasing to $\sim 10^{-3}$ at $\lambda < 1$mm.

5. Optical and Radio Backgrounds

The two ground based background measurements, in the optical and the radio, give information about the source populations in the universe.

The optical background is believed to be largely due to galaxies and this has been used to set limits on the density of luminous matter in the universe. The luminosity density of galaxies is estimated to be of the order

$$\ell_G \gtrsim 2.2 \times 10^8 L_\odot \, h_o (\mathrm{Mpc})^{-3}. \qquad (10)$$

Denoting by $\langle \eta \rangle$ the mass to light ratio averaged out for all galaxies, we get the matter density residing in galaxies as

$$\rho_G \gtrsim \ell_G \langle \eta \rangle \frac{M_\odot}{L_\odot} \gtrsim 1.5 \times 10^{-32} \langle \eta \rangle \, h_o \ \mathrm{g\ cm^{-3}}. \qquad (11)$$

Observations of ηh_o^{-1} for various types of galaxies and clusters as well as the local supercluster range from ~ 10 to ~ 500 (Faber and Gallagher 1979). From these the density parameter $\Omega_G = \rho_G/\rho_c$ is estimated to lie in the range

$$0.003 < \Omega_G \lesssim 0.53 , \qquad (12)$$

depending on how the average is taken. This estimate does not depend on the uncertain Hubble parameter h_o.

As mentioned before, hidden (unseen) matter could give a

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total Ω_o considerably in excess of Ω_c. For instance massive neutrinos of three species, each with a rest mass of 25eV would be sufficient to 'close' the universe for $h_o = 1$. I may mention in passing that a marginally closed universe for $h_o = 1$ has age only $\sim 6.6 \times 10^9$ yrs and it is hard to avoid a conflict between the age of the universe and the age of the galaxy estimated [at $\sim$ (10-15) $\times 10^9$ yrs] by nuclear cosmochronology and by stellar evolution.

The radio background has been used in the past to put limits on the number counts of extragalactic radio sources and to look for any possible conflict with local hypotheses of radio quasars (Rowan-Robinson 1973) I will refer to this latter point again in the context of the X-ray background.

Since the radio background merges with the long wavelength part of the MBR, an important issue is whether the detection of primordial anisotropy of the latter is inhibited by the graininess of the former. Calculations by Danese et al (Preprint: 1983) show that because the radio background at $\lambda \gtrsim 3$ cm is believed to be largely due to individual source contributions, there is a characteristic fluctuation $\Delta T/T \gtrsim 10^{-4}$ over angular scales 5' to 2° due to sources alone. As we saw earlier this would mask any primordial fluctuation due to galaxy formation etc.

6. The UV Background and Neutrino Lifetimes

Compared to other background radiations the UV background is not discussed so extensively. The possible existence of massive neutrinos mentioned earlier in this talk raises an interesting issue of relevance to the UV background. If neutrinos of different species exist with masses in the range of a few tens of electron volts, then the decay of the more massive neutrinos into lighter ones could release photons which would make a significant contribution to the UV background.

Sciama (Preprint: 1983) has reviewed the various handles one has on setting limits on masses, numbers, decay times etc. of massive neutrinos from astrophysical and cosmological observations. If neutrino decay produces photon of a unique frequency ν_o then such decays occurring all over the universe would generate a UV background of photons redshifted from ν_o according to their distance from us. The result is a continuum spectrum for $\nu \leq \nu_o$. The form of the spectrum computed by Kimble et al (1981) is

$$I(\nu \leq \nu_o) = \frac{cn_o}{4\pi H_o \tau} \left(\frac{\nu}{\nu_o}\right)^{5/2} [1 + (\Omega_o - 1)(1 - \frac{\nu}{\nu_o})]^{-1/2} \exp[-\frac{t}{\tau}] \qquad (13)$$

where t is the age of the universe at the time of decay, τ = lifetime of the neutrino and n_o = present number density of neutrinos (of the species in question).

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1983ICRC...12....1N

Stecker (1980) and Kimble et al (op cit) deduce from the observed background (which could also be partly due to other causes) that the decay time τ lies in the range 10^{22} - 10^{23}s for 10eV < $h\nu_o$ < 50eV. Shipman and Cowsik (1981) and Henry and Feldman (1981) have placed more stringent limits of $\tau > 10^{23}$ s over the photon energy range of 1 - 10 eV by using the optical and ultraviolet observations of Virgo and Coma clusters of galaxies.

7. The X-ray Background

A diffuse X-ray background is known to exist from the sub-keV region to hundreds of keV where it merges into the gamma ray background. Below 1 keV the background is due at least partially, to diffuse galactic sources while above 2keV an isotropic spectrum of (most likely) extragalactic origin dominates. The separation of galactic and extragalactic components seems difficult over 1-2 keV. Above 3keV, upto ∿50 keV the HEAO 1/A2 experiment (Marshall et al 1980) gives the X-ray background to an absolute accuracy of ∿10%.

The origin of the X-ray background holds clues to many cosmological issues, either directly or indirectly. First, it seems very likely that discrete sources contribute about 50% to the background in the 2-10 keV range. The estimates of contributions from various types of sources are ∿ 1% from normal galaxies, ∿ 6% from clusters of galaxies ∿ 18% from Seyfert galaxies and also a substantial (but quantitatively uncertain) contribution from quasars. I will discuss this last contribution shortly.

Hot intergalactic gas in clusters of galaxies can contribute to X-ray background through the process of thermal bremsstrahlung. A realistic model for this was provided by Field and Perenod (1977). In this model the gas is heated by explosive events with number density $\propto(1+z)^6$ for redshifts upto $z_c \simeq 3$. The heated gas is cooled because of the expansion of the universe. Best fit to the HEAO 1/A2 data is provided (for $z_c = 3$) by a present gas temperature of 26 keV and density close to ρ_c. Thus, provided models like these work, the X-ray background can be said to have furnished evidence for the existence of the intergalactic medium. The energy requirements for the active sources are, however, very severe in this model because of the inefficient way of generating the bremsstrahlung radiation. Moreover the model has some difficulty in fitting the residual background after the subtraction of the estimated contribution from discrete sources.

How much do quasars contribute to the background? Estimates vary, ranging from 100% to a few per cent of the total background. Kembhavi and Fabian (1982) estimate from the

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1983ICRC...12....1N

radio source counts and the distribution of L_X/L_R (L_X = X-ray luminosity, L_R = radio luminosity) of EINSTEIN quasars that radio loud quasars contribute about 10% of the background at 2keV. Whether the overall quasar contribution to the background is large or small therefore depends on how bright the radio quiet quasars are. The ratio L_X/L_{opt} (L_{opt} = optical luminosity) is poorly known above the 18th magnitude and hence precise estimates cannot be made. Taking into account the flattening of optical counts of quasars at high magnitudes it may be estimated that quasars do not contribute more than $\sim$50% of the background.

Early estimates (Setti and Woltjer 1979) based on a few X-ray radio loud quasars, had placed severe limits on the local hypothesis of quasars. It has been shown recently (Narlikar and Burbidge 1983) that in view of the above uncertainties a theory which places most observed quasars at 30-100 Mpc cannot be ruled out by the present data.

Fabian (1982) has discussed the implications of anisotropies in the X-ray background. Whatever the nature of the sources of the background it is plausible to argue that any large scale inhomogeneity in the distribution of gravitating matter would be reflected in the inhomogeneities of the density of these sources. It is estimated that that 1% fluctuations in the X-ray background provide the best available limits on the spectrum of inhomogeneities on scales between $\sim$100 Mpc and $\sim$1000 Mpc. These scales correspond to superclusters or larger systems, if any. On scales exceeding this, the MBR fluctuations provide more sensitive limits.

8. Antimatter and the Gamma-ray Background

One of the fundamental questions of cosmology is "What is the relative proportion of matter and antimatter in the universe?" It is clear that matter and antimatter cannot be homogeneously mixed since they would annihilate and produce too many gamma ray photons. They could, however, be separated by vast regions of vacuum or very tenuous distributions of matter or antimatter, and survive in isolation. Indeed in many theories invoking matter-antimatter symmetry in the universe separation mechanisms are also proposed.

There are many who have convinced themselves that the entire universe is matter dominated and have tried to account for this matter excess through the operation of GUTs in the early universe (cf §3). The inherent matter-antimatter symmetry is destroyed if the CP invariance of the so called fundamental interactions is broken. This is done in most approaches by hand, by putting complex Yukawa couplings between fermions and scalar fields. Stecker (1982) has argued instead in favour of a theory wherein there is a spontaneous breakdown of CP. He calls it 'soft' CP violation

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1983ICRC...12....1N

in contrast to the 'hard' CP violation in the usual approaches. Because of spontaneous rather than contrived breakdown of symmetry the basic theory is baryon-antibaryon symmetric.

In Stecker's model the soft CP-violation gives rise to a domain structure in the universe with domains of matter excess separate from domains of antimatter excess. The so called inflationary scenarios which are invoked to solve the monopole and horizon problem (cf §3) can also be used to discuss the growth and separation of domains. The domains could be as large as superclusters.

One of the observational checks on the theory is provided by the gamma ray background generated in this case by the decay of π°s produced in the matter antimatter annihilation. Stecker (1982) claims that his baryon symmetric domain cosmology gives a good fit to the γ-ray background data from Apollo 15 and SAS-2, as well as from balloon experiments at high altitudes.

The detection of antiprotons (and antinuclei) in cosmic ray primaries would be relevant to Stecker's cosmology, since in his case the p would come from an antimatter galaxy as part of the extragalactic component of cosmic rays. Stecker has given calculations to show how the expected flux ratio $\bar{p}/p$ is $\sim 5 \times 10^{-4}$, quite close to the measured data. It is not clear, however, to what extent the predicted values are 'unique' rather than 'just consistent' with a range of model parameters.

9. Conclusion

This somewhat superficial survey highlights the wealth of information of relevance to cosmology that lies burried in the radiation backgrounds at various wavelengths. I have used the standard big bang model to interpret the data since this is the most developed and popularly favoured model available today. However, I would be less than fair to myself if I did not voice my personal reservations.

Often it is the case that the raw data alone do not reveal a signal; they have to be interpreted with the help of a model. It may well happen that despite an incorrect theory we are able to fit the data with the parameters of the model and delude ourselves into thinking that we are on the right track : as the Greeks did with their epicycles two thousand years ago.

So far the MBR is the strongest evidence for the big bang. But, as discussed here, not all is well with the canonical interpretation. If a nonrelic interpretation emerges and survives the primary motivation for the big bang is gone. In case these remarks sound in the present climate

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1983ICRC...12....1N

like coming from the devil's advocate, let me end by quoting Landau's comment :

" Cosmology is often wrong but never in doubt."

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