LIMITS ON A MICROWAVE BACKGROUND WITHOUT THE BIG BANG

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Abstract The possibility of explaining the cosmic microwave background in terms of thermalisation of radiation from such sources as galaxies by dust grains is explored further. Relevant calculations of the optical cross-sections of graphite whiskers are given and it is shown that a smeared out dust density of $\sim 10^{-33}$ g cm^{-3} is required. Limits are set on the large-angle anisotropy of the background which is to be expected on the basis of this model. The relative merits of the conventional explanation and the present theory are discussed and a few discriminatory observational tests proposed. Some cosmological implications of whisker grains in the intergalactic space are examined.

1. Introduction

A universal background radiation existing as a relic from the big bang was predicted by Gamow and his collaborators[1] in the 1940's, on the basis of their work on nucleosynthesis in the very early stages of the universe. Subsequently Dicke and his colleagues[2] at Princeton reaffirmed a similar prediction. Whilst the thermal nature of the background was clearly expected in these predictions, its temperature could be specified only crudely. The original measurement of background radiation by Penzias and Wilson[3] indicated a temperature slightly in excess of 3 K, although subsequent measurements by other observers at different wavelengths set the best value of the temperature at 2.7 K. These observations are to the long wavelength side of the expected black body peak. Measurements at the peak of the curve are as yet tentative, and there are no undisputed published observations at shorter wavelengths. Nevertheless, the fit of the observed spectrum is sufficiently good to generate a confidence

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among most astronomers that the background has a blackbody distribution peaking at the microwave wavelength of ~ 1 mm.

The success of the big bang explanation has tended to overshadow other possible candidates for this background. Attempts to account for the background in terms of sources[4,5] or other processes taking place at more recent epochs[6] have encountered serious objections, particularly with regard to the observed fine scale isotropy[7,8]. To avoid any patchiness the sources of radiation have to be far more numerous than galaxies, although they need not individually be exceptionally bright. An entirely new approach has been suggested recently by Hoyle[9] in which he has related the microwave background to the history of the universe prior to the big bang, by working in the framework of the Hoyle-Narlikar theory of gravitation[10].

In this paper we explore further the dust grain model proposed recently by Wickramasinghe et. al[11]. In this model needle shaped grains such as the graphite whiskers act as the thermalisers of radiation in the intergalactic space. If the whiskers could grow to lengths in the range $100\mu m$ - 1 mm, they would have large absorption cross sections for photons peaking over a range of wavelengths $\lambda \gtrsim 0.3$ mm. Such grains could serve to thermalise the incident radiation from galaxies, QSO's etc., and the resulting blackbody curve could peak at a wavelength $\lambda \sim 1$ mm. This model gets round the objections raised on the grounds of small scale anisotropy at mm wavelengths. It may, however, be vulnerable to other observational or theoretical points of criticism. We discuss some of these below.

2. Thermalising Mechanism

The inadequacy of spherical or nearly spherical grains to serve as thermalisers for the microwave background has already been discussed[12]. The main difficulty arises from the fact that the ratio of the absorption cross section at optical wavelengths to that at infrared and millimetre wavelengths exceeds unity by a large factor for grain radii $\leq \sim 10^{-4}$ cm. This is not necessarily true for grains in the shape of long whiskers, which could occur in typical galactic and intergalactic conditions.

We confine our discussion here to graphite whiskers. There is substantial documentation of whisker growth for this material (see Wickramasinghe et. al[11] and references therein) and we also have a fairly extensive set of optical data. Graphite whiskers may condense in the expansion phases following explosions of supermassive stars in galactic nuclei, as well as in the atmospheres of normal carbon stars. Their ejection into the intergalactic medium might be accomplished by the action of stellar radiation pressure, or by gravitational encounters of the type discussed earlier[11]. Alternatively, a pregalactic population of stars could provide carbon stars[13].

Consider graphite particles in the form of cylindrical needles of cross-sectional radius a and length $\ell >> a$. The basal planes of graphite are parallel to the cylinder axis (Bacon[14]) and the complex refractive index data for electric vector along the cylinder axis are essentially those given by Taft and Phillipp[15]. The complex refractive index data for electric vector perpendicular to the basal planes are given by Tossatti and Bassani[16].

Cylinder cross sections are taken to have radii $a \simeq 10^{-6} - 10^{-5}$ cm, similar to the radii of interstellar grains. Whisker growth may allow particle lengths ℓ to become as long as several hundred microns (cf ref. 11). For optical and ultraviolet wavelengths we now have $2\pi a/\lambda \gtrsim 1$, and the rigorous formulae for cylinders must be used for computing optical cross sections at these wavelengths. The only condition necessary for the applicability of these formulae is $\lambda << \ell$, and this will be satisfied at optical wavelengths for cylinders of lengths $\gtrsim 1$ μm. For cylinders in random orientation, the mean efficiency factor for absorption, computed from the rigorous formulae for infinite cylinders, is

$$Q_{abs}(\lambda, a) = \frac{C_{abs}(\lambda)}{2\ a\ \ell} = \frac{1}{3}\left|Q^{\parallel}_{abs}(a, \lambda) + 2Q^{\perp}_{abs}(a, \lambda)\right| \qquad (1)$$

Here $Q^{\parallel}$ refers to absorption efficiency calculated from the data of Taft and Phillipp[15] and $Q^{\perp}$ that from data of Tossatti and Bassani[16]. The values of $Q_{abs}(3200\ \text{Å}, a)$ are given for various grain radii in the second column of Table I.

The asymptotic form of the mean absorption cross section in the limit of $2\pi a/\lambda << 1$ for a randomly oriented set of graphite cylinders is

$$C^{IR}_{abs}(\lambda) = -\frac{2\pi^2 a^2 \ell}{3\lambda} \mathrm{Im}\{(m^2_{11} - 1) + 4\left|\frac{m^2_\perp - 1}{m^2_\perp + 1}\right|\} , \quad (2)$$

provided $\lambda \lesssim \ell$. Writing $m^2_{11,\perp} = K_{11,\perp} - 2i\sigma_{11,\perp}\lambda/c$ with the usual notation (K = dielectric constant, σ = optical conductivity) we obtain

$$C^{IR}_{abs}(\lambda > 300\mu) = \frac{4\pi^2 a^2 \ell\sigma_{11}}{3c} \quad (3)$$

with $\sigma = 10^{15}\ s^{-1}$ (ref 11). For far infrared and millimetre wavelengths (3) is valid to a good approximation for graphite cylinders of radii $a \simeq 10^{-5}$ cm, lengths $\ell \sim 100\mu m - 1$ mm. The third column of Table I sets out the ratio $C_{abs}(\lambda > 300\mu)/C_{abs}(3200\ \mathring{A})$ as a function of the cross-sectional radius a.

TABLE I

a/μ	$Q_{abs}(3200\ \mathring{A}) = C_{abs}(3200\ \mathring{A})/2a\ell$	$C_{abs}(\lambda > 300\mu)/C_{abs}(3200\ \mathring{A})$
0.01	0.58	0.37
0.03	0.46	1.40
0.05	0.51	2.17
0.07	0.56	2.72
0.10	0.64	3.39
0.15	0.75	4.33
0.20	0.82	5.33
0.25	0.88	6.19

For grains of radii $> 0.10\mu m$ we note that the optical depth of the universe up to the Hubble radius at far infrared and millimetric wavelengths can be greater than that at ultraviolet wavelengths by a factor $\gtrsim 3.4$. Thus the universe could be marginally optically thick in the UV but much more opaque at the far IR and millimetre wavelengths. This is therefore a feasible mechanism for thermalising optical and shorter wavelength radiation from galaxies, QSO's and other sources. On account of the multiple scatterings and reabsorptions of far IR photons an approach to an isotropic thermalised background is expected.

The mass density of whisker grains necessary to produce $\tau_{UV} \simeq 1$ at the Hubble radius $R \sim 2 \times 10^{28}$ cm can now be estimated. The mass absorption coefficient of whisker grains is

$$K(3200\ \mathring{A}) = \frac{C_{abs}}{\pi a^2 \ell s} = \frac{2\ Q_{abs}}{\pi\ as}\ \mathrm{cm}^2\ \mathrm{g}^{-1} \qquad (4)$$

For $s = 2\mathrm{g\ cm}^{-3}$ and $a = 10^{-5}$ cm, equation (4) gives

$$K(3200\ \mathring{A}) \cong 2 \times 10^4\ \mathrm{cm}^2\ \mathrm{g}^{-1}\ , \qquad (5)$$

using Q_{abs} from Table I. The smeared out mass density of such grains required to produce $\tau(3200\ \mathring{A}) = 1$ at the Hubble radius is therefore

$$\rho_{grains} = \frac{1}{KR} \cong 2.45 \times 10^{-33}\ \mathrm{g\ cm}^{-3} \qquad (6)$$

This is consistent with the limits on the intergalactic dust density which are determined from other criteria[17,18]. Also, this is two orders of magnitude lower than the smeared out density of matter in the form of galaxies, QSO's etc, and four orders of magnitude lower than the cosmological closure density.

3. Cosmological Considerations

Although this model is free at $\lambda \lesssim 3$ mm of the objections which can be raised on the grounds of small angle anisotropy[7,8] the question remains whether there could result an observable large angle anisotropy of the theramalised background. In particular, if the thermalisation is more effective for galaxies within a cluster (or a super-cluster) than for the field galaxies, would a nearby large cluster (or a super-cluster) produce a detectable fluctuation over large angles of the order of a few degrees? The expected fluctuation may be crudely estimated by the following simple calculation.

Suppose we are dealing with radiating units of linear size a and number density n. We shall later identify these units with clusters or super-clusters. Let each unit produce an energy output at the rate L per unit time, this being the energy available for thermalisation. To calculate the total background energy flux at a typical point it is necessary to specify the cosmological model. We shall consider two models: (a) the steady state model (SS in brief) and (b) the empty Friedmann model (EF in brief) to illustrate the results. The background flux density is given by

$$B = n \left(\frac{c}{H}\right) L\, f(z) \tag{7}$$

where c = velocity of light, H = Hubble's constant, and

$$f(z) = \begin{cases} \text{(a)} \;\; \frac{1}{4}\left\{1 - \frac{1}{(1+z)^4}\right\} & \text{(SS)}, \\ \text{(b)} \;\; \frac{1}{2}\left\{1 - \frac{1}{(1+z)^2}\right\} & \text{(EF)} \end{cases} \tag{8}$$

For SS, $f(1) = 15/64$ while for EF $f(1) = 3/8$. If thermalisation takes place for $z \sim 1$, the two models do not differ from each other significantly.

Suppose we have a nearby unit at a redshift $z_0 \ll 1$, contributing the radiation flux

$$b = \eta \frac{L}{4\pi(\frac{c}{H})^2 z_o^2} \tag{9}$$

where η represents a fraction of the total radiation which has actually thermalised. It must be remembered that as opposed to distant units the light from a nearby unit may not completely thermalise (since thermalisation involves long passage through the intergalactic medium). Thus the fluctuation from the nearby unit is measured by the ratio

$$\frac{b}{B} = \frac{\eta}{4\pi(\frac{c}{H})^3 n f z_o^2} \tag{10}$$

Notice that both η and f are less than unity in all cases. Although η may be considerably smaller than f we will assume $\eta/f \sim 1$ and estimate an upper limit to the fluctuation.

Suppose now that the units are clusters of $\sim 10^3$ galaxies and that on an average the number of such clusters per $(\mathrm{Mpc})^3$ is $\sim 10^{-4}$. (This corresponds to a smeared out average of 1 galaxy per 10 $(\mathrm{Mpc})^3$. If an average galaxy has a mass $\sim 10^{44}$g the matter density in the form of galaxies works out at $\sim 4.10^{-31}$g cm^{-3}.) With $c/H \simeq 6.10^3$ Mpc. we get

$$\frac{b}{B} \sim 5 \times 10^{-9} z_o^{-2} \tag{11}$$

For the Virgo cluster we use $z_o \sim 4 \times 10^{-3}$ to obtain b/B as low as $\sim 3 \times 10^{-4}$. For a super-cluster n is lower and z_o higher such that the effect may be to raise b/B by an order of magnitude above this value. Such a fluctuation is probably too small to be detected by presently available techniques.

A futher question arises with regard to the ability of the units to cover the entire sky effectively. This is essential if all radiation is to be trapped and thermalised. For the units mentioned above the total solid angle subtended out to the redshift z is given by

$$\Omega = 4\pi^2 a^2 \left(\frac{c}{H}\right) n g(z) \tag{12}$$

where

$$g(z) = \begin{cases} \text{(a)} \quad \ln(1+z) \quad \text{(SS)} \\ \text{(b)} \quad z(1+\frac{1}{2}z) \quad \text{(EF)} \end{cases} \tag{13}$$

For clusters comprised of ~ 1000 galaxies, we may take $a \sim 5$ Mpc and get $\Omega \sim 180$ g. At $z = 1$, $g \sim .7$ for SS and ~ 1.5 for EF. Thus $\Omega >> 4$ and the entire sky is expected to be covered. For superclusters Ω may be smaller but still much larger than 4π.

Finally, we come to the question of ascribing a temperature and spectrum to the thermalised radiation. If the spectrum were a blackbody spectrum the temperature is determined by equating aT^4 to the energy density of thermalised radiation (where a is the radiation constant). Using $L \sim 10^{47}$ erg s^{-1} and the other cluster parameters we get

$$aT^4 \sim 2 \times 10^{-13} \text{ f erg cm}^{-3} \tag{14}$$

The expression on the right hand side is a little lower than the energy density for a blackbody of temperature $T = 2.7$, which is $\sim 4 \times 10^{-13}$ erg cm^{-3}. On the other hand it is somewhat higher than the energy density of starlight in the intergalactic space, which is usually quoted around a few times

10^{-14} erg cm^{-3}. This, however, is not a serious discrepancy. The mechanism discussed above uses not only starlight but other wavelengths of electromagnetic radiation like X-rays in thermalisation. The observations of extragalactic astronomy are still by no means complete in their discoveries of other sources of radiation than the optical emission from galaxies. The right hand side of (14) could therefore be an under-estimate.

Another check on this calculation is provided by the He/H ratio in the universe. If all the helium were synthesised in stellar interiors, the amount of starlight would be comparable to the microwave background[6]. As suggested by Wagoner, Fowler and Hoyle[19], the helium synthesis might well have to take place in supermassive stars.

4. Restrictions of the Theory

As thermalisation is taking place in an expanding space, the redshift effect will modify the shape of the thermalised spectrum. The spectrum observed at earth will be a superposition of contributions from different redshifts, and the spectrum will deviate somewhat from a single-temperature blackbody. We propose to investigate the spectrum in a future paper, but note here that the shape of the spectrum is likely to be a strong observational test of the theory.

Perhaps the most unsatisfactory aspect of the explanation is its inability to account for the background at wavelengths longer than a few millimetres as the absorption cross-section of the whiskers is likely to fall off as λ^{-2} for $\lambda > \ell$, giving only small optical depths out to the Hubble radius at radio frequencies. Three possible (although very ad hoc) modifications are:- (i) the whiskers grow to lengths > 10 cm. This would allow high optical depths at the typical wavelengths of isotropy measurements[20], but the fragility and growth times of such long whiskers makes their existence highly unlikely. (ii) A large enough density of dust and radiation at high redshifts so that a spectrum thermalised to $\sim$ mm blackbody spectrum has redshifted to provide the centimetre wavelength "tail" now. The present-day observed spectrum is again unlikely to be an exact blackbody. (iii) The conventional hot big-bang provides the centimetre tail, and the whisker thermalisation provides a contribution at wavelength $\lesssim 3$ mm.

5. Conclusion

The big bang undoubtedly provides the simplest explanation of the cosmic microwave background. However, because of the profound implications of this result for cosmology, it is desirable, as a part of normal scientific practice, to consider alternatives to this explanation and discuss their relative merits. The present model has been proposed from this point of view.

The big bang explanation is not free from defects. For example, the present temperature (and energy density) of the radiation cannot be related to any other astrophysical property of the universe. The present temperature of 2.7 K and the coincidence of energy densities mentioned earlier must be regarded as accidental. An astrophysical explanation of the type considered here at least has the merit of relating the present temperature of the background to the processes taking place now or in the not too remote a past in the universe.

The second difficulty relates to the observed high degree of isotropy of the microwave background. The small particle horizons appropriate in the early stages after the big bang make it impossible to exchange information between remote parts of the universe. The present day isotropy cannot therefore be explained except by postulating it at the big bang. In the present approach the isotropy of the microwave background is related to the isotropy of the universe in the relatively recent past, irrespective of its isotropy (or lack of it) at very early epochs.

We realise that the grains required for our model are somewhat exotic and suffer from the constraints of a particular range of sizes. We have stated an extreme case in requiring the complete explanation of the microwave background by such grains, but an important consequence of these grains for the standard hot big bang models should also be noted. If the dust grain density were lowered by a factor ~ 10 compared to that given in equation (6), the optical depths in millimetre and infrared would extend to redshifts $z \sim 2, 3$. This could still interfere with the isotropy of the original big bang radiation.

For example, the small scale fluctuations expected to lead to galaxy formation (at much earlier epochs than $z \sim 2, 3$) could be smoothed out by the intervening dust. We await with interest any results from observations attempting to detect such fluctuations at mm wavelengths.

Finally, we enumerate briefly some possible consequences of this model for extragalactic observations other than those of the microwave background. The absorption produced by the dust in the optical and UV may affect the measurement of the deceleration parameter (q_0) of the expansion of the universe. The result will be to give a q_0 which is lower than the true value. The whisker grains will not have a high differential reddening effect in the optical or ultraviolet. If the QSO's are at the cosmological distances indicated by their redshifts their spectra are expected to show a serious modification in the millimetre range at large redshifts when compared to those at $z \ll 1$.

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DISCUSSION

Greenberg Did you use a Rayleigh type approximation for the millimetre emission from the long particles? If so did you take into account the length limitation on the applicability of this approximation especially when m is large. I tried to find the absorption efficiency magnification for metallic particles and a factor of 10 or so was the most I could find.

Wickramasinghe Yes, we did use a Rayleigh approximation. Our results remain valid for $\lambda > \ell/2$, say.

Greenberg The second point I would like to question is the use of 10^{-13} ergs cm^{-3} for the visible-uv radiation density in intergalactic space. This would be comparable with the visible-uv energy density in the Milky Way and therefore rather on the high side, I think.

Narlikar The value usually quoted is a few times 10^{-14} erg cm^{-3} which is lower than I have used. I feel, however, that there is sufficient uncertainty in the measurements of extragalactic astronomy to permit the higher value. Also it is consistent with the amount of starlight generated if all the observed helium were generated in stellar nucleosynthesis, e.g. in Hoyle-Fowler supermassive stars.

Hillas This model differs from the conventional one by filling space with absorbers, and with an optical depth to the Hubble radius of 3 or 4 it seems that the optical depth would be about 1 at redshifts of 0.25 say, so one should expect to see a large bite out of the spectrum of quasars in the millimetre region. I wonder what is the most distant quasar which has been studied at millimetre wavelengths?

Narlikar Some such effect should show up in QSO's with large cosmological redshifts ($z \gtrsim 0.5$, say). I am not aware of any observational results of this type at present.