A DUST MODEL FOR THE COSMIC MICROWAVE BACKGROUND

(Letter to the Editor)

N. C. WICKRAMASINGHE and M. G. EDMUNDS
Dept. of Applied Mathematics and Astronomy, University College, Cardiff, Wales

and

S. M. CHITRE, J. V. NARLIKAR, and S. RAMADURAI
Tata Institute of Fundamental Research, Bombay, India

(Received 7 February, 1975)

Abstract. The cosmic microwave background may be explained on the basis of absorption and re-emission of the light from galaxies by graphite whiskers of lengths $l \simeq 0.1$–1 mm. The mass density of such particles required is of the order of 10^{-34} g cm^{-3}.

The 2.7 K cosmic microwave background is generally interpreted as representing relic radiation from an early phase of the Universe. Several attempts at explaining this phenomenon in terms of processes taking place in more recent epochs have not been considered successful (Narlikar and Wickramasinghe, 1968; Hoyle *et al.*, 1968). Explanations based on thermalization of starlight in galaxies by grains and on considering the integrated effect from such discrete sources of far infrared radiation may be criticized for a variety of reasons. Such models face difficulties with regard to explaining the black-body spectrum of the radiation as well as the high degree of isotropy observed (Hazard and Salpeter, 1969).

Direct thermalization of light from galaxies by intergalactic dust is not a viable model if dust particles are approximately spherical in shape and have dimensions typical of interstellar grains. For such grains the extinction cross-section at optical wavelengths is close to the geometrical cross-section whilst the maximum possible efficiency for absorption and emission in the infrared is $Q_{IR} \simeq 10\, a/\lambda$ (Hoyle and Wickramasinghe, 1969). To obtain the observed isotropy and Planckian nature of the 2.7 K background one requires an optical depth up to the Hubble radius at $\lambda \simeq 0.1$–1 mm exceeding unity by a significant factor. Such a high optical depth at mm wavelengths implies an untenably large optical depth at visual wavelengths.

An interesting case arises if dust particles exist in intergalactic space which are in the form of slender whiskers of fairly high electrical conductivity with lengths in the range 0.1–1 mm. The growth of whiskers of lengths less than 1 μ of $(CH_2O)_n$ has been discussed by one of us in the context of galactic dust clouds (Wickramasinghe, 1974, 1975). Particles composed of such strongly insulating material would not be important in the present context, even if such molecular solids were able to form in

Astrophysics and Space Science **35** (1975) L9–L13. *All Rights Reserved*

extragalactic conditions. The accretion of mantles composed of semi-conducting ices, which may occur under suitable conditions, could however enhance the emissivity of these grains. The role of such coated grains will be discussed elsewhere (Edmunds and Wickramasinghe, 1975), but in the present context we invoke the formation of graphite whiskers.

The condensation of graphite whiskers could occur wherever the C/O ratio exceeds unity. There is evidence to suggest that metals are more abundant in the nuclear regions of galaxies than in the outer parts (Burbidge, 1970). If expulsion of heavy elements into intergalactic space occurs mainly by violent events such as the explosion of super-massive stars in dense galactic nuclei a depletion of oxygen with respect to carbon can take place in certain regions of the exploding star (Audouze and Fricke, 1973). The excess of carbon over oxygen may now be able to condense as graphite particles, the amount of graphite condensed depending upon which nucleosynthetic regions are expelled and on the dynamics of the explosion.

It has been recognized for many years that graphite particles condensing at relatively high temperatures from the gas phase could grow as slender whiskers which are endowed with considerable tensile strength (Bacon and Bowman, 1957; Bacon, 1958). Many crystalline solids grow as whiskers from the gas phase under suitable conditions (Nabarro and Jackson, 1958). Although the precise conditions under which graphite whisker growth occurs are uncertain, it seems probable that irradiation of grain nuclei by high energy photons could play an important role (Moto, 1968). Growth in the form of whiskers may then occur along dislocation axes (Hillig and Turnbull, 1956; Higashi *et al.*, 1968). The conditions of high energy X- or γ-irradiation necessary for such a process may well be realized near the nuclei of active galaxies. Whisker grains condensing in inter-galactic space on suitable seed nuclei grow in length l at a rate

$$\frac{\mathrm{d}}{\mathrm{d}t}(\ln l) = \frac{2}{as} n_{\mathrm{C}} \langle v_{\mathrm{th}} \rangle m_{\mathrm{C}}, \tag{1}$$

where n_{C} is the ambient carbon density, a is the grain radius, s is the specific gravity of graphite, $\langle v_{\mathrm{th}} \rangle$ is the mean thermal speed of impinging C atoms and m_{C} is the mass of a C atom, assuming growth in the form of a right circular cylinder. This integrates to give

$$l = a \exp(t/\tau), \tag{2}$$

where

$$\tau = \frac{as}{(n_{\mathrm{C}}/n_{\mathrm{H}}) 2 n_{\mathrm{H}} \langle v_{\mathrm{th}} \rangle m_{\mathrm{C}}}. \tag{3}$$

Setting $a \simeq 10^{-6}$ cm, $s \simeq 2.2$ g cm^{-3}, $n_{\mathrm{C}}/n_{\mathrm{H}} \simeq 10^{-3}$, $n_{\mathrm{H}} \simeq 10^4$ cm^{-3}, $\langle v_{\mathrm{th}} \rangle \simeq 10^6$ cm s^{-1} as may be appropriate in the region around a young massive star we have $\tau \simeq 2.2 \times 10^3$ yr so that $l \simeq 1$ mm in $t \simeq 2.5 \times 10^4$ yr. This is a time scale short compared with the lifetime of the Seyfert phenomenon and with the expansion time scales associated with the galactic nuclei. Exhaustion of gas phase C atoms (over and above those combined as CO) will in general take place very quickly in both galactic and extragalactic situations. The particle lengths resulting from this process will then be limited by the concentration relative to hydrogen of condensation nuclei, assuming a constant value for the radius of condensation nuclei. If a steady wind of grain-free carbon-rich gas is emitted from the central source, nucleation of graphite particles may be sufficiently slow to give rise to a value of n_g/n_{H} which is lower than the canonical interstellar value by a few orders of magnitude (cf. Nishida and Nakazawa, 1973). Final grain lengths of $l \simeq 0.1$–1 mm could then be easily achieved (Edmunds and Wickramasinghe, 1975). Such whisker grains may be expelled into intergalactic space along with gaseous material as a result of the explosions of massive objects in Seyfert nuclei (Hoyle and Wickramasinghe, 1968). It should also be noted that close collisions between galaxies in a cluster can lead to stars and gas being thrown out into the intergalactic medium. In 10^{10} yr about 10^{-3} to 10^{-2} part of cluster mass is thus thrown out (Gallagher and Ostriker, 1972). This will lead to some enrichment of the intergalactic medium by heavy elements and graphite whiskers from carbon stars.

The electromagnetic absorption properties of infinite right circular cylinders with arbitrary radius and lengths l may be calculated from rigorous formulae (Wickramasinghe, 1973) for given values of the bulk optical constants. The asymptotic form of the mean absorption cross-section in the limit $2\pi a/\lambda \ll 1$, $l \gg \lambda$ for cylinders of complex refractive index m assuming random orientation is

$$C_{\mathrm{ext}} = -\frac{2\pi^2 a^2 l}{3\lambda} \operatorname{Im}\left\{(m^2 - 1) + 4\left(\frac{m^2 - 1}{m^2 + 1}\right)\right\}. \tag{4}$$

Writing $m^2 = K - 2i\sigma\lambda/c$, where K is the dielectric constant and σ the conductivity, we obtain

$$C_{\mathrm{ext}}(\lambda) = \frac{4\pi^2 a^2 l \sigma(\lambda)}{3c}\left\{1 + \frac{8K}{(K+1)^2 + 4(\sigma\lambda/c)^2}\right\}. \tag{5}$$

With $a \simeq 10^{-6}$ cm, this expression is expected to be valid to a good approximation for wavelengths ranging from ~ 3000 Å to $\sim 2l$. Using optical data available for the case of bulk graphite for **E** parallel to the basal planes (Taft and Phillip, 1963) we obtain

$$\frac{C_{\mathrm{ext}}(3200\ \text{Å})}{C_{\mathrm{ext}}(\lambda > 300\ \mu)} \simeq \frac{\sigma(3000\ \text{Å})}{\sigma(\lambda > 300\ \mu)} \simeq 5. \tag{6}$$

No general theory is available for particles whose lengths are $l \lesssim \lambda$. Based on radar scattering data for thin wires we expect a peak in cross-section to occur at $\lambda \simeq 2l$ with a sharp decline for longer wavelengths (Barton, 1974). The absorption cross-section for graphite whiskers would thus peak at $\lambda = 1$ mm for particles of length $l \simeq 0.5$ mm.

At the ultraviolet wavelength $\lambda \simeq 3200$ Å we have $K \simeq 2$, $\sigma \simeq 5 \times 10^{15}$ s^{-1} for graphite so that Equation (5) gives

$$C_{abs}(3200 \text{ Å}) = 3.1 \times 10^6 a^2 l \tag{7}$$

and

$$\kappa(3200 \text{ Å}) = \frac{C_{abs}}{\pi a^2 l s} \simeq 4.5 \times 10^5 \text{ cm}^2 \text{ g}^{-1}. \tag{8}$$

The mass density of such grains required to produce τ (3200 Å)$\simeq 1$ at $R = 2 \times 10^{28}$ cm is thus

$$\varrho_{dust} \simeq \frac{1}{\kappa R} \simeq 10^{-34} \text{ g cm}^{-3}.$$

This is less than the limits set for the intergalactic dust density by other criteria (Nickerson and Partridge, 1971; Karachentsev and Lipovetski, 1968). The associated H density of intergalactic space assuming $n(\text{C})/n(\text{H}) \simeq 10^{-3}$ is thus

$$\varrho_H \simeq 10^{-32} \text{ g cm}^{-3}.$$

This value may be compared with the density $\varrho \simeq 10^{-29}$ g cm^{-3} required to close the Universe. The density of matter in the form of galaxies is estimated at a few times 10^{-31} g cm^{-3}, if smeared out over the whole Universe. The above requirement of ϱ_H is therefore not excessive. If a dust density of 10^{-34} g cm^{-3} is considered plausible the Universe could be marginally optically thick at ultraviolet and visual wavelengths at the Hubble radius, and yet, by virtue of (6) totally optically thick at millimetric and submillimetric wavelengths. The consequence of this feature is that an isotropic or very nearly isotropic microwave background will be produced by the direct thermalization of the optical light emitted from galaxies. The energy density arising from galaxies due to the conversion of H to He (He/H$\simeq$0.28) is coincident with that of a 2.7 K microwave background (Fowler, 1968). The spectrum of the thermalized radiation will thus be close to the effective black sphere temperature of intergalactic space $\sim$2.7 K. Perturbations from isotropy in the microwave background to be expected on the basis of this model will be discussed elsewhere (Edmunds *et al.*, 1975).

N. C. Wickramasinghe is grateful to the Tata Institute of Fundamental Research for the award of a Visiting Professorship and to the British Council for providing travel funds which made this collaboration possible. J. V. Narlikar acknowledges the award of a Jawaharlal Nehru Fellowship.

References

Audouze, J. and Fricke, K. J.: 1973, *Astrophys. J.* **186**, 239.
Bacon, R. and Bowman, J. C.: 1957, *J. Appl. Phys.* **28**, 826.
Bacon, R.: 1958, Cambridge Conference on Strength of Whiskers and Thin Films.
Barton, D. K.: 1964, *Radar Systems Analysis*, Prentice Hall Inc.

Burbidge, G. R.: 1970, *Ann. Rev. Astron. Astrophys.* **7**, 369.
Fowler, W. A.: 1968, *Colloquium on Cosmic Ray Studies in Relation to Recent Developments in Astronomy and Astrophysics*, T.I.F.R., Bombay, p. 348.
Gallagher, III, J. S. and Ostriker, J. P.: 1972, *Astron. J.* **77**, 288.
Hazard, C. and Salpeter, E. E.: 1969, *Astrophys. J.* **157**, L89.
Higashi, A., Oguro, M., and Fukada, A.: 1968, *J. Crystal Growth* **3**, 728.
Hillig, W. B. and Turnbull, D.: 1956, *J. Chem. Phys.* **24**, 914.
Hoyle, F., Wickramasinghe, N. C., and Reddish, V. C.: 1968, *Nature* **218**, 1124.
Hoyle, F. and Wickramasinghe, N. C.: 1968, *Nature* **218**, 1126.
Hoyle, F. and Wickramasinghe, N. C.: 1969, *Nature* **223**, 459.
Karachentsev, I. D. and Lipovetski, V. A.: 1968, *Astron. Zh.* **45**, 1148.
Moto, C.: 1968, *J. Cryst. Growth* **3**, 733.
Nabaro, F. R. N. and Jackson, P. J.: 1958, in R. H. Doremus, B. W. Roberts, and D. Turnbull (eds.), *Growth and Perfection of Crystals*, J. Wiley, New York.
Narliker, J. V. and Wickramasinghe, N. C.: 1968, *Nature* **217**, 1235.
Nickerson, B. G. and Partridge, R. B.: 1971, *Astrophys. J.* **169**, 203.
Nishida, S. and Nakazawa, K.: 1973, *Prog. Theor. Phys.* **49**, 1152.
Taft, E. A. and Phillipp, H. R.: 1965, *Phys. Rev.* **138A**, 197.
Wickramasinghe, N. C.: 1963, *Light Scattering Functions for Small Particles with Applications in Astronomy*, Adam Hilger Press, London.
Wickramasinghe, N. C.: 1974, *Nature* **252**, 462.
Wickramasinghe, N. C.: 1975, *Monthly Notices Roy. Astron. Soc.* **170**, 11P.