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Diffuse Background X Rays and the Density of the Intergalactic Medium

David F. Crawford

School of Physics, University of Sydney,
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Abstract

Most of the 3–300 keV spectrum of the unresolved X-ray background can be explained as thermal bremsstrahlung from a hot intergalactic gas plus a small non-thermal component at higher energies. The model used assumes a static Universe with an exponential redshift with distance relationship that is due to photon interactions with curved space–time. The interglactic gas is found to have a temperature of $1\cdot3\times10^9$ K and a density of $2\cdot05\,C^{-2/3}$ hydrogen atoms m^{-3}, where C is an unknown factor that depends on the clumpiness of the intergalactic gas.

1. Introduction

The origin of the spatially unresolved X-ray background (XRB) is still a matter of controversy with two explanations receiving most attention. One is that the XRB comes from unresolved discrete objects that are similar to, but perhaps at an earlier stage of evolution than known X-ray emitters such as quasars and Seyfert galaxies. The other explanation is that most of the X rays are produced by thermal bremsstrahlung in a hot intergalactic plasma. Since unresolved sources exist and thermal bremsstrahlung cannot provide the highly energetic X-ray and γ-ray emission, the argument is whether there is any need for a thermal component. Using data from the highly sensitive X-ray imaging instruments of the Einstein Observatory, Giaccioni *et al.* (1979) estimated that $37\pm16\%$ of the XRB in the 1–3 keV region comes from discrete sources, with the rest possibly coming from thermal bremsstrahlung.

This paper shows that a major part of the XRB could be due to thermal bremsstrahlung from a static high temperature plasma, where the X rays are subject to a Hubble frequency shift and a geometric factor consistent with a static Einstein cosmology. There is no evolution of density or pressure. The motivation for this model is the suggestion of a new mechanism (Crawford 1987; this issue p. 449) that can explain the Hubble shift without requiring an expanding Universe.

2. X-ray Model

It is assumed that the thermal component comes from a hot, homogeneous and isotropic intergalactic plasma that does not evolve in time, and that the frequency of photons decreases as an exponential function of distance. Let $j(E_0, T)\,\mathrm{d}E_0$ be the power emitted as X-ray photons per unit volume of the plasma at temperature T,

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into an angle of one steradian and within the energy range E_0 to $E_0+\mathrm{d}E_0$. For X-ray energies (>2 keV) and plasma temperatures ($\approx 10^9$ K) considered here the effects of absorption can be neglected. If these photons travel for a time t before detection, they will be within the energy range from E to $E+\mathrm{d}E$ where (Crawford 1987) the energies are related by

$$E = E_0 \exp(-Ht), \tag{1}$$

and H is the (Hubble) parameter given by

$$H = (8\pi G\rho)^{\frac{1}{2}}, \tag{2}$$

with ρ being the density of the intergalactic plasma.

Then, the power received from all elements of the plasma along the line of sight is

$$J(E)\,\mathrm{d}E = \int_0^t j(E_0, T)\frac{E}{E_0}\frac{\mathrm{d}E_0}{\mathrm{d}E} f(t) c\,\mathrm{d}t\,\mathrm{d}E, \tag{3}$$

where $f(t)$ is a geometric factor to allow for the decreased volume in a static Einstein cosmology as a function of distance. This space has a radius of curvature of $8\pi G\rho/c^2$ and, using equation (2) to substitute for the density, the geometric factor (Rindler 1977, p. 109) is

$$f(t) = \sin(2Ht)/2Ht. \tag{4}$$

With the use of equation (1) and a change of independent variable to $u = \exp(Ht)$, we can change (3) to

$$J(E)\,\mathrm{d}E = \frac{c}{H}\int_1^\infty j(Eu, T) f(t)\frac{\mathrm{d}u}{u}. \tag{5}$$

Gould (1980) has given an accurate expression for $j(E, T)$, including modifications for (1) relativistic corrections to the thermal electron velocity distribution, (2) relativistic and spin corrections to the nonrelativistic electron–ion bremsstrahlung cross section, (3) electron–electron bremsstrahlung, and (4) first order Born approximation corrections to electron–ion bremsstrahlung. His equations (without his suggested approximations) have been used in calculating $j(E_0, T)$. It is convenient to measure the plasma density by a parameter n, which is the density in units of hydrogen atoms m^{-3}. With cosmic abundances given by Allen (1976), we find that the electron density $N_e = 0{\cdot}862n$, the emission measure $N_e \sum N_Z Z^2 = 0{\cdot}914n^2$, and $\sum N_Z Z^3 = 2{\cdot}358n$. Equation (2) becomes

$$H = 51{\cdot}68\, n^{\frac{1}{2}}\,\mathrm{km\,s^{-1}\,Mpc^{-1}}. \tag{6}$$

Since $j(E, T)$ is proportional to n^2 we can use equation (6) to eliminate H in (5) and get an expression that is proportional to $n^{2/3}$. Finally, a power law distribution in received energy is added to the thermal component to allow for discrete, unresolved sources; this has the form $A(E(\mathrm{MeV}))^{-\gamma}$. It will be found that this contribution is small and is only needed for the very high energy X rays. The complete model has four parameters to be found by a fit to the experimental data: n, the density; T, the plasma temperature; γ, the slope of a power law; and A, the coefficient of the power law.

Table 1. Observations of X-ray background

Reference	Energy range (keV)		Error (%)	N	χ^2
Marshall *et al.* (1980)	3	50	10	17	4·3
Kinzer *et al.* (1978)	24	159	(10)	14	15·3
Dennis *et al.* (1973)	20	194	10	7	29·7
Mazets *et al.* (1975)	41	2870	(15)	23	19·0
Fukada *et al.* (1975)	370	1710	25	4	3·7
Mandrou *et al.* (1979)	307	2050	24	9	4·9
Trombka *et al.* (1977)	300	3000	20	9	3·6
Horstman-Moretti *et al.* (1974)	33	151	22	4	3·9

3. The Data

A search was made for all accurate observations of the XRB that have four or more points in the energy range 3 keV $\leqslant E \leqslant$ 3 MeV. The requirement of at least four data points was made to try and prevent systematic errors between observers having a large effect on the shape of the spectrum. The lower limit of 3 keV was chosen to minimise contamination by galactic sources and the upper limit of 3 MeV was chosen to give sufficient data points beyond the thermal component (it is negligible beyond 300 keV), but yet to keep the energy range small enough for a power law to be a reasonable representation of the non-thermal component. A list of the observations used is given in Table 1 where column 1 gives the literature reference, columns 2 and 3 give the energy range covered, column 4 gives the typical percentage error in the data points, column 5 the number of data points, and column 6 the value of χ^2 for the fitted model. Where a reference did not give error estimates, values were determined from comparison with other results. This was done for the observations of Kinzer *et al.* (1978) and Mazets *et al.* (1975). The data points from Marshall *et al.* (1980) were read from their Fig. 3 at energies of 3, 4, 5, 6, 7, 8, 9, 10, 12, 15, 20, 25, 30, 35, 40, 45 and 58 keV. Where necessary photon spectra were converted to energy spectra and energy ranges converted to spot values using a local power law. Because of the large (>10%) errors, this procedure does not seriously distort the data. The choice of using an energy spectrum or a photon spectrum was immaterial since the fit was done by weighted least squares. The only observations that met the above criteria and were not used were those of Schwartz and Peterson (1974), since their results appeared to have a large systematic error when compared with other observations.

4. Results

The four parameters n, T, γ and A were determined by a weighted least squares fit of the model to the 87 data points. If the error estimates are correct this is identical to a minimum χ^2 fit, hence the use of χ^2 to describe the weighted residual sum of squares. In fact all that is needed is that the errors are relatively correct. It was found that the parameters γ and A were poorly determined, but fortunately the estimates of n and T were insensitive to values of γ and A. The results for a fit for all four

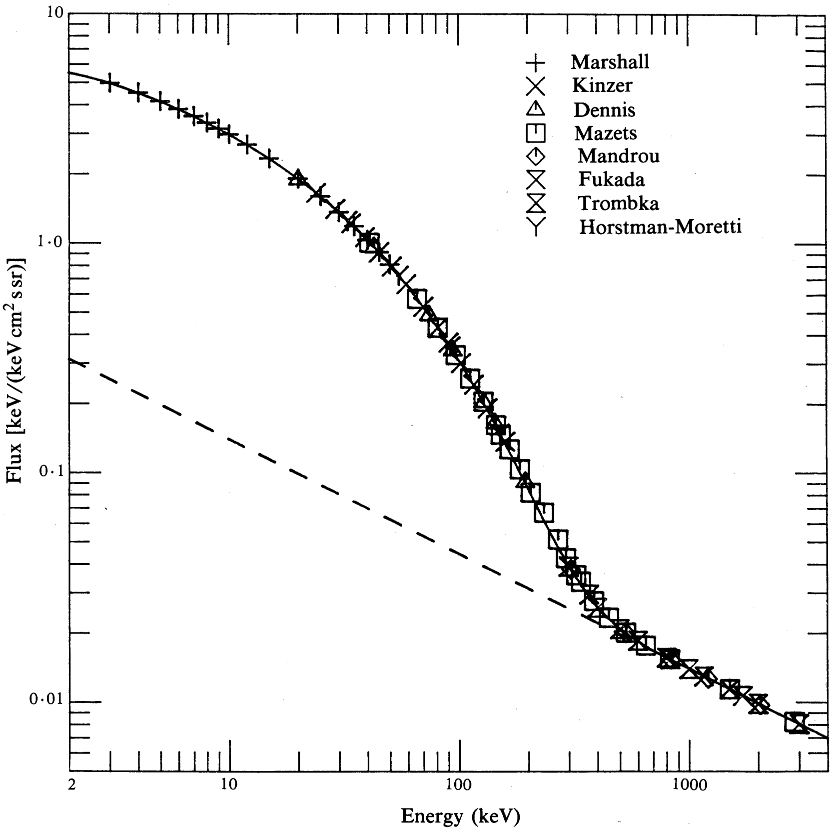

Fig. 1. Comparison of best-fit theoretical curve for the X-ray background with the experimental observations. The dashed line is an extrapolated power law fit to the high energy data (see Table 1 and text for references).

parameters are

$$n = 2\cdot05 \pm 0\cdot06 \ \mathrm{m}^{-3}, \qquad T = 96 \pm 4 \ \mathrm{keV} \ (1\cdot30 \times 10^9 \ \mathrm{K}),$$

$$\gamma = -0\cdot38, \qquad A = 0\cdot014 \ \mathrm{keV/(keV\,cm^2\,s\,sr)}.$$

With 83 degrees of freedom the best fit value of χ^2 was $84\cdot5$. The quoted errors in n and T are the 90% confidence limits obtained by treating γ and A as dummy variables and seeing what values of n and T increase χ^2 by $2\cdot71$ (Cash 1976). Only one degree of freedom was used for both dummy variables (γ and A) because of their high correlation. The excellent fit suggests that this method gives good estimates for the limits with the usual caveat that there may be unknown systematic errors common to all observations. To see if the weights used had a significant effect on the results, a new fit was done with the errors adjusted to reflect more closely the residual χ^2 for each set of data. There was a negligible change in the values of n and T.

One reason why the non-thermal power law was poorly determined is that there is a strong correlation between the estimates of γ and A. This correlation can be summarised by the requirement that any power law that fits the data must pass through the point with flux density $0 \cdot 016$ keV/(keV cm^2 s sr) at $E = 1$ MeV. If the points with $E > 300$ keV have the thermal component subtracted and then are fitted with a power law, the values obtained are $\gamma = -0 \cdot 42$ and $A = 0 \cdot 016$ keV/(keV cm^2 s sr). With the limited data used this is the best estimate of the non-thermal component. This power law and its sum with the best-fit thermal spectrum are compared with the observations in Fig. 1.

The most serious omission in the model is the neglect of density fluctuations. It is certainly true that there are density enhancements in clusters of galaxies, but what is happening in the intergalactic medium is unknown. Clumping is important because the XRB is proportional to $\langle n^2 \rangle$, while the redshift is proportional to $\langle n^{\frac{1}{2}} \rangle$. Following the approach by Field (1972), we introduce a clumping parameter C defined by

$$C = \frac{\langle n^2 \rangle}{\langle n \rangle^2} \Big/ \frac{\langle n^{\frac{1}{2}} \rangle}{\langle n \rangle^{\frac{1}{2}}},$$

which is greater than or equal to one for all density distributions. With allowance for clumping the density now is $n = 2 \cdot 05\, C^{-2/3}\,\mathrm{m}^{-3}$, showing that in ignorance of C all we can do is put an upper limit on the density. Consideration of simple gravitationally bound gas clouds shows that values of C in the range of one to two are easily possible. Another consideration is that the assumption of constant temperature is almost certainly inconsistent with a clumpy medium.

5. Discussion

The model of a homogeneous, constant temperature, intergalactic gas, with photon energy decay given by equation (5), gives an excellent fit to the XRB observations in the energy range 3 keV $< E <$ 3 MeV. The gas has a best-fit density of $n = 2 \cdot 05 \pm 0 \cdot 06\,\mathrm{m}^{-3}$ and temperature of $T = 96 \pm 4$ keV. Added to this thermal component is the energy from unresolved discrete sources. This is only important for $E > 300$ keV and in the limited range used can be fitted with a power law with slope $\gamma = -0 \cdot 42$ and coefficient $A = 0 \cdot 016$ keV/(keV cm^2 s sr). Marshall *et al.* (1980) found a best-fit temperature of 40 keV and a density of 36% of the closure density $(3H^2/8\pi G)$. Using earlier results, Field and Perrenod (1977) and Cowsik and Kobetich (1972) found $T = 26$ keV. Because they used a standard cosmological model their results cannot be directly compared with the results obtained above. In particular they had to make assumptions about the deceleration parameter and temperature evolution. As shown in a previous paper (Crawford 1979), the photon tidal interaction theory predicts that the density should be one-third the closure density. The close agreement of one-third with the observed value of 36% shows that the density estimate, as distinct from the temperature, is not very sensitive to the cosmological model. Using equation (5) and allowing for a clumping factor C (defined above), the parameter H is calculated to be 74 $C^{-1/3}$ km s^{-1} Mpc^{-1}, a value in good agreement with accepted values. Since C must be greater than one, the value of 74 km s^{-1} Mpc^{-1} is an upper limit to the predicted value for the Hubble constant.

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