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A model for the γ-ray background—further results

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Abstract. A theory for the γ-ray background involving cosmic-ray interactions at high redshifts has been re-examined using improved computational techniques and more realistic radiation fields. Comparison with observations shows good overall agreement but a possible discrepancy in the 10–100 MeV range.

1. Introduction

The presence of an isotropic flux of cosmic γ-rays—presumably of extragalactic origin—is an established experimental fact. A number of explanations have been put forward, e.g. $p\bar{p}$ or pp interactions at early epochs (see Stecker 1975, for a recent summary).

In two previous papers (Strong *et al* 1973, 1974) attention was drawn to the possibility of linking the γ-ray background with the cosmic-ray primary spectrum, if the latter is of cosmological origin. Hillas (1968) appears to have been the first to point out that the shape of the primary proton spectrum can be interpreted as the result of interactions of a power-law production spectrum with the black-body radiation at early epochs ($z\sim15$), the shape being reproduced by the assumption of strong evolution ($\sim(1+z)^4$) of the cosmic-ray sources. Strong *et al* used this model and examined the consequent γ-ray production. The details of the model have been described previously and will only be summarized here.

The intergalactic gas density n_0 is assumed to be low enough for γ-ray production via proton–gas inelastic interactions to be unimportant. If we wish the model to account for the whole cosmic-ray spectrum down to energies of 1 GeV, this places severe limits on n_0, namely $n_0<3\times10^{-9}\ \mathrm{cm}^{-3}$ (Strong *et al* 1974), which does not however conflict with any observations at present. Alternatively, we can avoid the problem altogether by assuming extragalactic origin of CR only above say 10^{11} eV (as has in fact been suggested by Elliot 1974).

The important interaction is electron pair production on the black-body photons, i.e. $p+\gamma_{bb}\rightarrow p+e^++e^-$, which has a threshold at about $10^{18}/(1+z)$ eV at redshift z. This interaction can clearly steepen the presently observed cosmic-ray spectrum above $10^{18}/(1+z_m)^2$ eV, where z_m is the epoch at which cosmic-ray sources were 'switched on'. Identification of this steepening with that observed at around 3×10^{15} eV gives a value for z_m of about 14, and the actual magnitude of the change in slope determines the rate of evolution required. The first-generation γ-ray spectrum is formed by interactions of the electrons, produced in the (p, γ_{bb}) interaction, with the black-body radiation field. An inverse Compton (IC)–pair production (PP, via $\gamma+\gamma\rightarrow e^++e^-$) cascade is initiated, and this cascade continues until the γ-ray energies are too low for PP on the starlight radiation, at around $E_\gamma = 10^{11}/(1+z)$ eV. Since the main contribution is from cascades occurring at $z \sim z_m$, the maximum γ-ray energy expected to be present in the spectrum is about $10^{11}/(1+z_m)^2 \sim 5 \times 10^9$ eV.

The absolute magnitude of the γ-ray spectrum from this process can be determined by reference to the observed primary cosmic-ray spectrum, since the difference in energy content between a power-law extrapolation above 3×10^{15} eV and the spectrum actually observed is entirely resident in γ-rays (the energy content in electrons is negligible owing to the rapidity of the IC interaction). Using recent data on the primary cosmic-ray spectrum, the energy flux removed in the form of γ-rays is found to be $2^{+2}_{-1} \times 10^5$ eV cm^{-2} s^{-1} sr^{-1}.

The calculation of the present day γ-ray spectrum on the model is complicated because it involves electron–photon cascades in an expanding universe. The previous papers reported the results of various quasi-analytical approximations which strongly suggested that the γ-ray spectrum on this model was similar to that observed. However, since some doubt remained as to the accuracy of the analytical techniques used, it was decided to attempt a numerical solution which followed the cascading explicitly as a function of redshift. This also allowed the inclusion of a more realistic form for the starlight radiation field and its variation with epoch. The results of the calculations are the subject of this paper.

2. Numerical methods used in computing the γ-ray spectrum

A numerical code was developed which allowed the electron and photon spectra to be followed through successive IC and PP interactions. Spectra were represented by assigning particles to bins of appropriate width (typically 10 per decade of energy). The differential reaction rates for IC and PP on a black body and starlight (assumed grey body, see § 3) were computed, using the exact forms for the differential cross sections (Jauch and Rohrlich 1955). From these, the IC and PP processes were represented by matrices giving the resultant transfer of particles between the energy bins of the photon and electron spectra. The spectra could then be developed by repeated application of these matrices to the spectra in the appropriate order.

Since the reaction rates vary with redshift, it was necessary to divide up the range 0–z_m into intervals (z_i, z_{i+1}) with $z_i - z_{i+1} = \Delta z$, over which the rates could be assumed to be sensibly constant. Propagation of the spectrum from z_i to z_{i+1} was then effected using the matrices appropriate to that redshift, and then the matrices were recalculated for the next z interval. Since IC converts all electron energy into photons in a negligible redshift interval (see Strong *et al* 1974), the extent of the IC–PP cycling is determined by the PP interaction length. In the PP part of each cycle, the number of particles in each bin interacting before the end of the interval (z_i, z_{i+1}) was computed, and the remainder stored until the next interval was encountered. This is a somewhat approximate technique for including the spatial development of the cascade, but it is sufficient here because of the rapid changeover as particles lose their energy from propagation essentially in energy space to propagation in the real space, with energy a slowly varying function of z.

The effect of redshift energy losses was included implicitly by defining the energies bracketing energy bins as $E_i(z) = E_i(0)(1+z)$, when $E_i(0)$ defines the bins at $z = 0$.

Injection of electrons by the (p, γ_{bb}) process occurs at all z, and the injection spectrum resulting from the proton spectrum at any z was computed using the differential cross sections given by Blumenthal (1970), applied to the case of black-body radiation. The proton spectrum injected at a rate proportional to $(1+z)^{\beta}$ and undergoing the (p, γ_{bb}) energy losses, was followed explicitly.

3. Results of numerical computations

The parameters z_m and β were taken from previous work (Strong *et al* 1974) to be $z_m = 14{\cdot}3$ and $\beta = 4{\cdot}3$, as determined from the primary spectrum. The other important parameter is the starlight spectrum. For comparison with the earlier calculations, the cases of a constant starlight intensity with $T_s = 6000$ K, and energy densities $W_s = 10^{-2}$ and 10^{-1} eV cm^{-3} were treated. However, a more realistic model is provided by Tinsley (1973), in which the effect of stellar evolution in galaxies is explicitly included. In her model, the epoch of formation of galaxies is taken as $1{-}2\times10^{8}$ yr, corresponding to $z\sim10{-}30$ depending on the cosmological model. The presence of bright young stars gives a very high initial luminosity in the UV ($T\sim3\times10^{4}$ K), which is subsequently redshifted to give an IR peak at $z=0$, which is quite well represented as a grey-body spectrum with $T_s = 1500$ K and $W_s = 4\times10^{-2}$ eV cm^{-3} in the case of Tinsley's model 1. In the present calculations, these values were used for $z=0$, and the change with redshift taken to follow $T_s(z) = T_s(0)(1+z)$ and $W_s(z) = W_s(0)(1+z)^4$. A constant UV intensity with $T_{uv} = 3\times10^{4}$ K and $W_{uv} = 5\times10^{-3}$ cm^{-3} was included to represent the effect of contemporary UV stars, and this is consistent with the OAO-2 upper limits on the UV background (Lillie *et al* 1972).

The resulting spectra are shown in figure 1 for the case $q_0 = \frac{1}{2}$ and $H_0 = 50$ km s^{-1} Mpc^{-1} (the effect of varying the cosmological parameters was found to be small). For comparison, figure 2 summarizes the analytical solutions obtained by Strong *et al* (1974). Treatment A of that work, in which all interactions were assumed to occur at the redshift of electron injection via the (p, γ_{bb}) process corresponds roughly

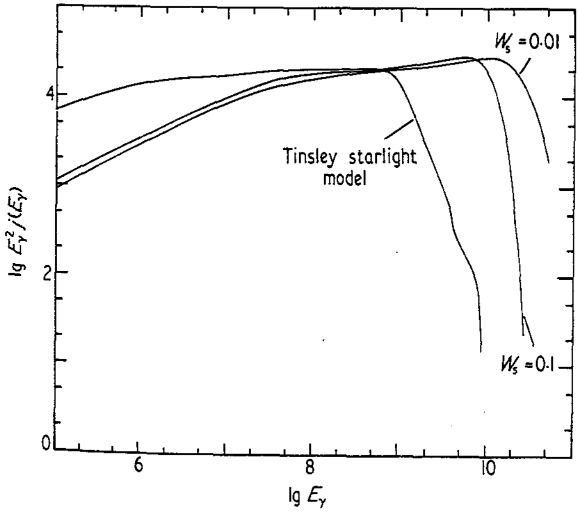

Figure 1. The γ-ray spectra obtained by the numerical techniques described in this paper. The curves with $T_s = 6000$ K, $W_s = 0{\cdot}1$, $0{\cdot}01$ eV cm^{-3} correspond roughly to approximate treatments A and B of figure 2 respectively. E_γ is in eV and $E_\gamma^2 j(E_\gamma)$ is in cm^{-2} s^{-1} sr^{-1} eV.

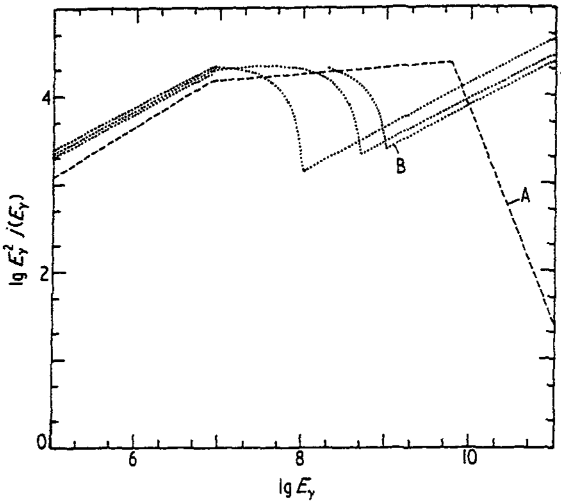

Figure 2. Semi-analytical approximations to the γ-ray spectrum on the model as obtained by Strong *et al* (1974). In approximation A all the interactions are assumed to occur at the redshift of initial electron injection via $(p+\gamma_{bb}\rightarrow p+e^{+}+e^{-})$; in approximation B the interactions are assumed to occur at the present epoch. E_γ is in eV and $E_\gamma^2 j(E_\gamma)$ is in $cm^{-2}\,s^{-1}\,sr^{-1}\,eV$.

to the case $T_s = 6000$ K, $W_s = 0{\cdot}1$ eV cm^{-3} of figure 1; it can be seen that agreement within a factor 2 is obtained for $E_\gamma < 10^{10}$ eV, which is satisfactory in view of the approximations made in treatment A. Treatment B, which assumed all energy injected at z_m with no γ–γ interactions occurring before $z \sim 0$, corresponds roughly to the $T_s = 6000$ K, $W_s = 10^{-2}$ eV cm^{-3} case. Agreement is satisfactory below 10^8 eV, but the rather sharp dip in the analytical results, which is caused by the δ-function treatment of the various processes, is removed in the numerical treatment which takes account of their wide energy distributions.

A rather different spectrum is produced when the time-dependent starlight field described above is included. The effect of the high UV densities at early epochs is to transfer much of the energy above 10^9 eV to the lower energy photons, so that at 1 MeV the spectrum is a factor 5 above that for the constant starlight cases. However, the difference in the 10^7–10^9 eV region is less than a factor 2, so this region appears to be fairly independent of the assumptions made about the starlight spectrum, and is thus a good region to compare with the observations in order to test the theory.

4. Comparison with observations

Figure 3 compares the spectra with a compilation of recent data. Notice that a fairly good overall fit is obtained down to about 10^5 eV when the time-dependent starlight spectrum is used. The theory cannot account for the x-ray part of the spectrum below this energy. Above 50 MeV the recent data from SAS-II (Fichtel *et al* 1975) suggest a steep slope (about $E^{-2{\cdot}4}$), whereas the theory predicts roughly E^{-2} for the case of a time-dependent starlight spectrum, and a slightly flatter spectrum in the constant T_s cases. If the results of SAS-II are confirmed, this discrepancy will provide a disproof of the model which cannot be removed except by postulating very high UV fluxes at the

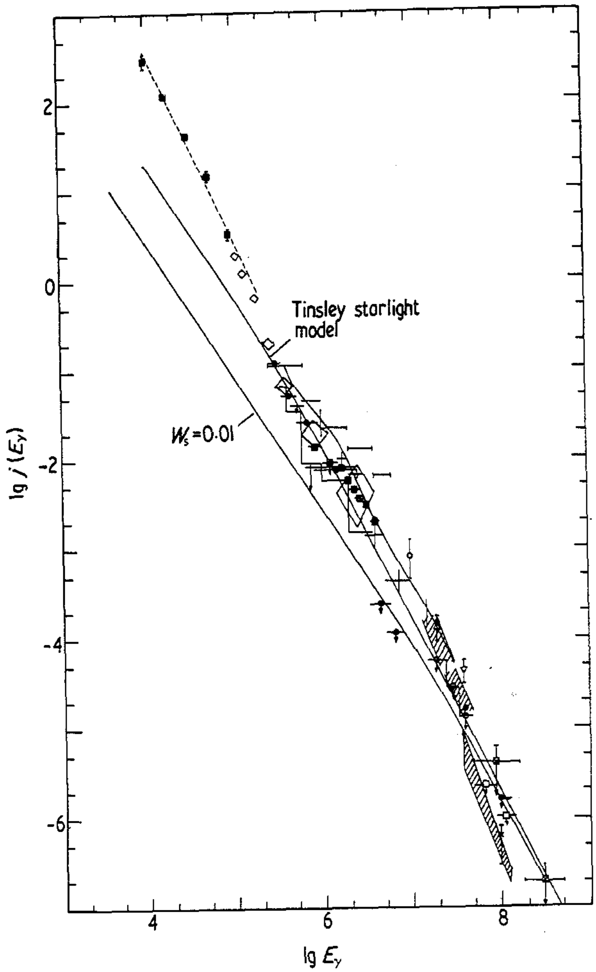

Figure 3. Comparison of the theoretical spectra of figure 1 with a compilation of recent data on the γ-ray spectrum. E_γ is in eV and $j(E_\gamma)$ is in $cm^{-2}\,s^{-1}\,sr^{-1}\,MeV^{-1}$. ⧋, Agrinier *et al* (1973); ⊢□⊣, ⊢⊠⊣, Bratolubova-Tsulukidze *et al* (1970); –●–, Daniel *et al* (1972); – – – – –, Dennis *et al* (1973); ▨, Fichtel *et al* (1974); ◇, Fukada *et al* (1975); ⌈, Galper *et al* (1973); ⊔, ⊤, Golenetskii *et al* (1971); ⊽, Herterich *et al* (1973); ⫯, Hopper *et al* (1973); ⫲, Kraushaar *et al* (1972); ◊, Kuo *et al* (1973); ◈, Mayer-Hasselwander *et al* (1972); +, Schönfelder and Lichti (1974); ▮, Schwarz and Gursky (1973); ⊢○⊣, Share *et al* (1974); ⧹, Trombka *et al* (1973); –■–, Vedrenne *et al* (1971); ⊢⊣, Vette *et al* (1970).

present epoch, which would be inconsistent with the OAO-2 results (Lillie *et al* 1972). Data on the background at around 1 GeV will provide an even better test of the model since an E^{-2} spectrum up to at least this energy is predicted.

5. Conclusions

We have calculated the spectrum of the γ-ray background to be expected in a model which relates it to the steepening of the primary cosmic-ray spectrum above 10^{15} eV.

Although the model is attractive in giving a good overall fit to the data and a rather surprising coincidence in absolute intensities, it appears that the predicted spectrum is too flat in the energy range above 50 MeV for consistency with the SAS-II data. However, it would be wise to await confirmation of these data by further experiments before dismissing the present theory as a contender for the γ-ray background.

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