CAN THE COSMIC X-RAY AND GAMMA-RAY BACKGROUND BE DUE TO REFLECTION OF A STEEP POWER LAW SPECTRUM AND COMPTON SCATTERING BY RELATIVISTIC ELECTRONS?

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ABSTRACT

We reconsider the recent model for the origin of the cosmic X-ray and γ-ray background by Rogers and Field. The background in the model is due to an unresolved population of by AGNs. An individual AGN spectrum contains three components: a power law with the energy index of $\alpha = 1.1$, an enhanced reflection component, and a component from Compton scattering by relativistic electrons with a low energy cutoff at some minimum Lorentz factor, $\gamma_{\rm min} \gg 1$. The MeV bump seen in the γ-ray background is then explained by inverse Compton emission by the electrons. We show that the model does not reproduce the shape of the observed X-ray and γ-ray background below 10 MeV and that it overproduces the background at larger energies. Furthermore, we find the assumptions made for the Compton component to be physically inconsistent. Relaxing the inconsistent assumptions leads to model spectra even more different from that of the observed cosmic background. Thus, we can reject the hypothesis that the high-energy cosmic background is due to the described model.

I. INTRODUCTION

Recently, two *Letters* by Rogers & Field (1991a, and 1991b, hereafter RF91) presented a model for the cosmic X-ray and γ-ray background as being due to an unresolved population of AGNs. The X-ray and γ-ray emission of individual AGNs contributing to the background were modelled as a superposition of (i) a power law component with the energy index of $\alpha = 1.1$, (ii) a component due to strongly enhanced reflection of the power law from cold matter, and (iii) a component from Compton scattering by power law relativistic electrons with a low-energy cutoff at $\gamma_{\rm min}$. RF91 claimed they obtained an excellent spectral fit, with the deviations less than a few percent from the cosmic X-ray and γ-ray background data.

According to our calculations, the model spectrum of RF91 does not reproduce the shape of the observed X-ray and γ-ray background spectrum, with the discrepancies between the model and the data being as large as a factor of 5 (§II). Furthermore, we find the assumptions of that model made for the Compton-scattering component to be physically inconsistent. Relaxing the inconsistent assumptions further increases the discrepancies between the model and the data (§III).

Thus, we can conclusively reject the model of RF91 by both comparing its predictions with the data and by studying its physical self-consistency.

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II. COMPARISON OF THE MODEL TO THE DATA

The model of RF91 assumes that a population of AGNs providing the major contribution to the background radiate X-ray and γ-ray spectra consisting of three components. The first component is a power law with an energy index of $\alpha = 1.1$, which is assumed to be due to both synchrotron emission and inverse Compton scattering of some soft photons (e.g., from a cold accretion disk) by a distribution of relativistic electrons. The second component is due to Compton reflection and reprocessing of the power law emission by cold, neutral matter in the disk (Guilbert & Rees 1988; White, Lightman & Zdziarski 1988; Lightman & White 1988). In their best-fit model, 89% of the power law radiation is directed towards the disk and reflected, and 11% is directly radiated away. The large reflected fraction can be due to either geometry (Fabian et al. 1990) or anisotropic Compton scattering by relativistic electrons above the surface of the disk (Ghisellini et al. 1990; Rogers 1991). The two spectral components are identical to those proposed by Fabian et al. (1990) except for the power law spectral index, which equaled $\alpha = 0.7$ in the original model.

The third component in the model of RF91 is due to Compton scattering by a population of relativistic electrons. The electrons have a steady-state power law distribution, $N(\gamma) \propto \gamma^{-p}$ with an index $p = 3.2$ and a low energy cutoff at $\gamma_{\rm min} = 28$. The electrons are implicitly assumed to Compton scatter only photons with energies > 1 keV (R. D. Rogers, private communication). The resulting photons provide the third component of the model, which is claimed to explain the data for the γ-ray background.

Figure 1 shows a comparison between the predictions of the model of RF91 (solid curve) and the data points (Marshall et al. 1980; Trombka et al. 1977; Rothschild et al. 1983; Fichtel, Simpson & Thomson 1978). RF91 do not give their assumed value of the volume emissivity at $z = 0$. We have chosen it to be 3×10^{38} erg s^{-1} Mpc^{-1} in order to obtain the best possible fit. The volume emissivity is assumed by RF91 to evolve with z as $(1+z)^{2.8}$ up to $z_{\rm max} = 4.6$. We see that the overall fit is very poor. The model spectrum deviates from the observed data points by up to 50% in the range from 3 keV to 10 MeV and it overproduces the observed background by a factor of up to 5 in the 30–100 MeV range.

In order to test our numerical code we compared its results with those of Lightman & White (1988) and Terasawa (1991) and found good agreement to within a few per cent with their results. We used the opacities for neutral matter at the standard cosmic abundances, as given in Morrison & McCammon (1983).

We choose to plot the intensity per logarithmic decade of photon energy, EI_E, as then the features of the background become more discernible. Analyzing Figure 1, we first see that the reflected spectrum (dotted curve) of the power law with $\alpha = 1.1$ (long dashes) peaks at about 15 keV, while the X-ray background has a broad peak between 25 and 40 keV (in EI_E). This discrepancy is serious and it is unlikely to be reduced by changing the opacities. We have artificially increased the bound-free opacities by a factor of two, in order to see if this can harden the reflected spectrum and move its peak to higher energies. However, this had a small effect on the spectrum and we were unable to improve the fit of the model. In fact, the opacities are likely to be smaller in a realistic situation due to photoionization, which would then move the peak in the reflected spectrum to even lower energies.

If we change the spectral index of of the underlying power law in the model of

RF91 to $\alpha = 0.7$, which spectrum contains many more hard photons, the peak in the reflected component moves to about 30 keV, in a better qualitative agreement with the background data. A similar model with $\alpha = 0.7$ was used by Fabian et al. (1990). Terasawa (1991) uses a steep power law (similar to that of RF91) in his fit to the X-ray background but his model includes additional hardening of the spectrum due to external absorption by cold matter.

Second, we see that the sum of the power law (long dashes) and the Compton component (short dashes) forms a peak at several MeV that is much broader than the characteristic MeV bump (cf. Bassani & Dean 1983) seen in the observed spectrum. The data points in the 1–10 MeV range lie on a rather smooth curve with low dispersion in that curve from one point to another. It is statistically highly unlikely that the errors on the individual measurements are such that this characteristic hump is smoothed out to conform to the model fit, even though the fit marginally goes through the error bars of individual measurements in the 1–10 MeV range.

Third, we see the model spectrum in the 30-100 MeV range overproduces the background spectrum by a factor up to 5. This is definitely inconsistent with the error box of the measurements.

Thus, we are able to reject the model of RF91 for the background based on the comparison with the observational data only. In addition, in §III we show that some assumptions of the model are highly unphysical.

III. SELF-CONSISTENCY OF THE MODEL

Apart from the disagreement between the model and the data, there are severe problems with the physical self-consistency of the model of RF91. First, the assumed low energy cutoff at $\gamma_{\rm min} = 28$ in the steady state electron distribution is highly unphysical. Such a low energy cutoff can be obtained only if electrons with lower Lorentz factors can escape very efficiently from the source (e.g., Blumenthal & Gould 1970). This is not consistent with two other assumptions made in RF91. First, RF91 give $L \simeq 10^{44}$ erg s^{-1}, $R = 3 \times 10^{14}$ cm, and $B \gtrsim 500$ G (above equipartition) as characteristic parameters of the required AGN population. For those parameters, the energy loss length of a relativistic electron at $\gamma = \gamma_{\rm min}$ due to synchrotron and Compton losses is *two orders of magnitude* shorter than the source size, R. Thus, any injected electrons lose energy down to Lorentz factors of $\gamma \sim 1$ before they can escape. Second, RF91 assume that the electrons are confined by the magnetic field, thus excluding their escape regardless of the values of L and R. Without escape, the steady state electron distribution continues to $\gamma \sim 1$ with a power law index $p \geq 2$ (Blumenthal & Gould 1970).

The presence of electrons with $\gamma < \gamma_{\rm min}$ strongly broadens the shape of the Compton-scattered component, further increasing the discrepancy between the model and the MeV data, as seen in Figure 2. We assumed that the electron distribution below $\gamma_{\rm min}$ continues with a power law index of $p = 2$, which corresponds to no electron injection in this regime (this assumption gives the strongest possible peak in the spectrum). We see that the Compton scattered component (short dashes) is now much broader than the background MeV bump, and it peaks around 1 MeV, which is much below the peak in the data.

We note here that it is in general unphysical to *assume* a fixed electron distribution in a compact source. This unfortunate tradition, carried over from the studies of extended sources, does not apply to compact sources where the energy loss lengths are much smaller than the source size. The form of the electron (or pair) spectrum then follows from the balance of the production rate and energy loss rate (see, e.g., Blumenthal and Gould 1970) and cannot be freely adjusted. Self-consistent models of compact sources including the effects of electron energy loss and $e^{\pm}$ pair production have been done by, e.g., Svensson (1987), Lightman and Zdziarski (1987), Ghisellini (1989), and Zdziarski et al. (1991). If one does assume a fixed electron distribution, then one can obtain unlimited luminosities, depending only on the density of seed photons. This is clearly unphysical as the luminosity in the upscattered photons approximately equals the power supplied to the electrons.

Furthermore, the AGN model of RF91 implicitly assumes a low energy cutoff at in the photon spectrum at 1 keV. Such a cutoff is highly unlikely for AGNs, as they universally show UV bumps (containing perhaps most of the bolometric luminosity) as well as soft X-ray excesses above the extrapolation of the hard X-ray power laws to lower energies (e.g., Turner et al. 1991). Furthermore, no radiation below 1 keV is inconsistent with the assumption of the model that the underlying power law is partly due to synchrotron radiation.

We find that even if we keep the electron distribution with a cutoff at $\gamma_{\rm min} = 28$ but decrease the cutoff energy in the photon spectrum to below 1 keV, the fit provided by the model becomes much worse. Figure 3 compares the model spectrum with the data for the case with the cutoff at 100 eV (down to which photon energy the X-ray spectra of AGNs are observed not to exhibit any cutoff). Again, we see that the shape of the scattered component has become much broader than the shape of the MeV bump. If we, furthermore, included a component in the electron distribution at $\gamma < \gamma_{\rm min}$, the discrepancies between the model and the data would become even larger.

SUMMARY

We find that the cosmic X-ray and γ-ray background model of RF91 disagrees with the data. The X-ray peak from reflection of a steep power law component (with $\alpha = 1.1$) peaks at an energy that is a factor two smaller than the peak energy in the data. The MeV bump seen in the data is not reproduced by the model. The model overproduces the background by large factors in the 30-100 MeV range.

We also find some of the assumptions of the model to be physically inconsistent. The assumed low-energy cutoff in the electron distribution occurs at $\gamma_{\rm min} = 28$ at which Lorentz factor the electron energy loss time is at least two orders of magnitude shorter than the electron residence time in the source. Thus, the distribution is very likely to continue to $\gamma \sim 1$. If this effect is included, the fit of the model to the MeV data becomes much worse than that of the original model.

RF91 also require that no photons with energies < 1 keV are present in the source. This is both unlikely to be the case for AGNs and it is inconsistent with the assumption that the photon power law is in part due to the synchrotron process.

Thus, we can conclusively reject the hypothesis that the cosmic X-ray and γ-ray background is due to compact sources emitting the three-component spectra described by RF91.

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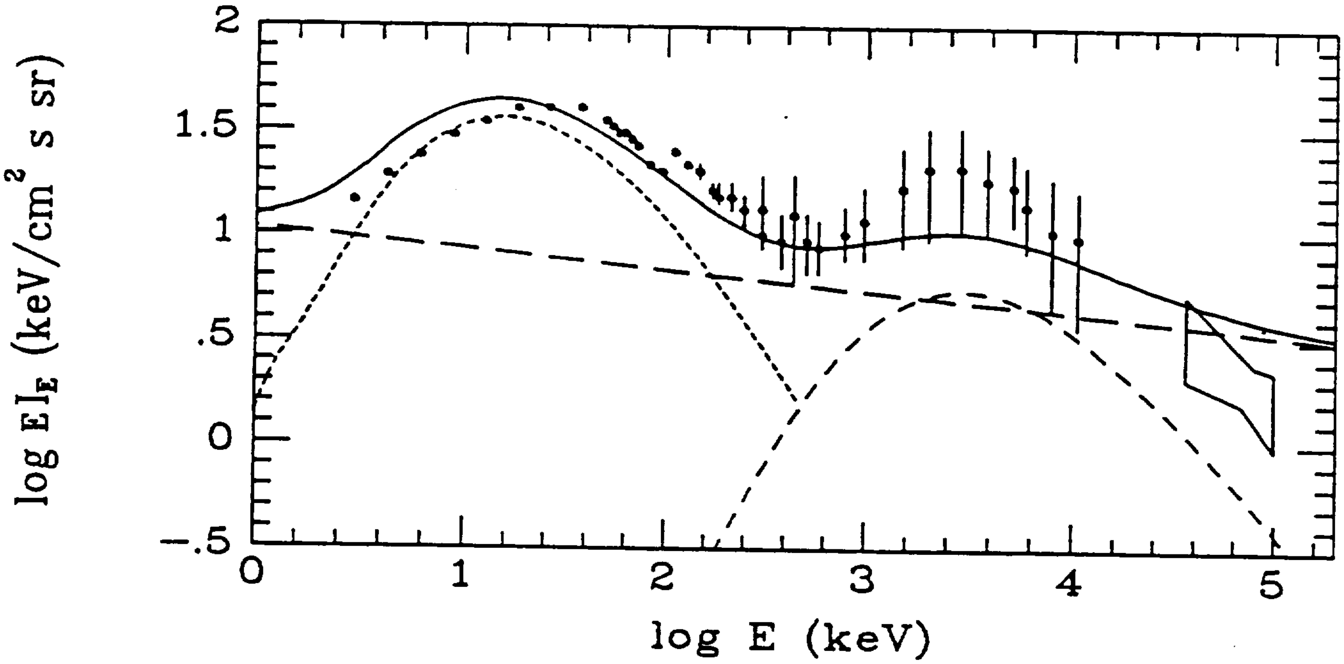
Figure Captions

FIG. 1.—Comparison of the model of RF91 (*solid curve*) with the cosmic background data (see §II for references). The parameters used are the same as those for Fig. 2 of RF91, in particular the low energy cutoff of the photon spectrum equals 1 keV, and the Thomson scattering optical depth of the relativistic electrons is $\tau = 3 \times 10^{-4}$. The three components of the model, due to the underlying power law (*long dashes*), reflection (*dotted curve*), and Compton scattering (*short dashes*), are also shown. It is clearly seen that (i) the peak in the reflection component (*dotted curve*) is at a significantly lower energy than the peak in the X-ray data, (ii) the peak due to Compton scattering (*short dashes*) is too shallow to reproduce the MeV bump seen in the data, and (iii) the model spectrum overproduces the observed spectrum by a large factor in the 30-100 MeV range. Thus, the model spectrum (*solid curve*) does not reproduce the overall shape of the high-energy cosmic background.

FIG. 2.—The model spectrum compared to the data for the case when the electron distribution is continuously extended to $4 < \gamma < \gamma_{\rm min} = 28$ as a power law with the slope $p = 2$ (*solid curve*). As regards the electron density, this is the minimum possible continuation required by the very short electron energy loss time in the model of RF91. (A change of the assumed value of the minimum Lorentz factor, e.g., from 4 to 2, has very little effect on the resulting spectrum.) The Thomson scattering

optical depth of the electrons with $\gamma \geq 28$ has been reduced to $\tau = 2 \times 10^{-4}$ in order to achieve the best possible fit to the data. The three components of the model are displayed in the same way as in Fig. 1. One sees that the Compton scattering component (*short dashes*) is now much broader than for the case with an unphysical cutoff at $\gamma_{\rm min} = 28$, and the model can be rejected with a likelihood even larger than for the case shown in Fig. 1.

FIG. 3.—The model spectrum of RF91 (with a cutoff in the electron distribution at $\gamma_{\rm min} = 28$) compared to the data for the case where the low energy cutoff in the photon spectrum equals 100 eV (*solid curve*). The lower photon energy cutoff is more compatible with both the assumptions of the model and the observations of AGNs. The Thomson scattering optical depth of the electrons has been reduced to $\tau = 10^{-4}$ in order to achieve the best possible fit to the data. The three components of the model are displayed in the same way as in Fig. 1. One sees that the Compton scattering component (*short dashes*) is now much broader than for the case with the photon spectral cutoff at 1 keV, and the model can be rejected with a likelihood even larger than for the case shown in Fig. 1.



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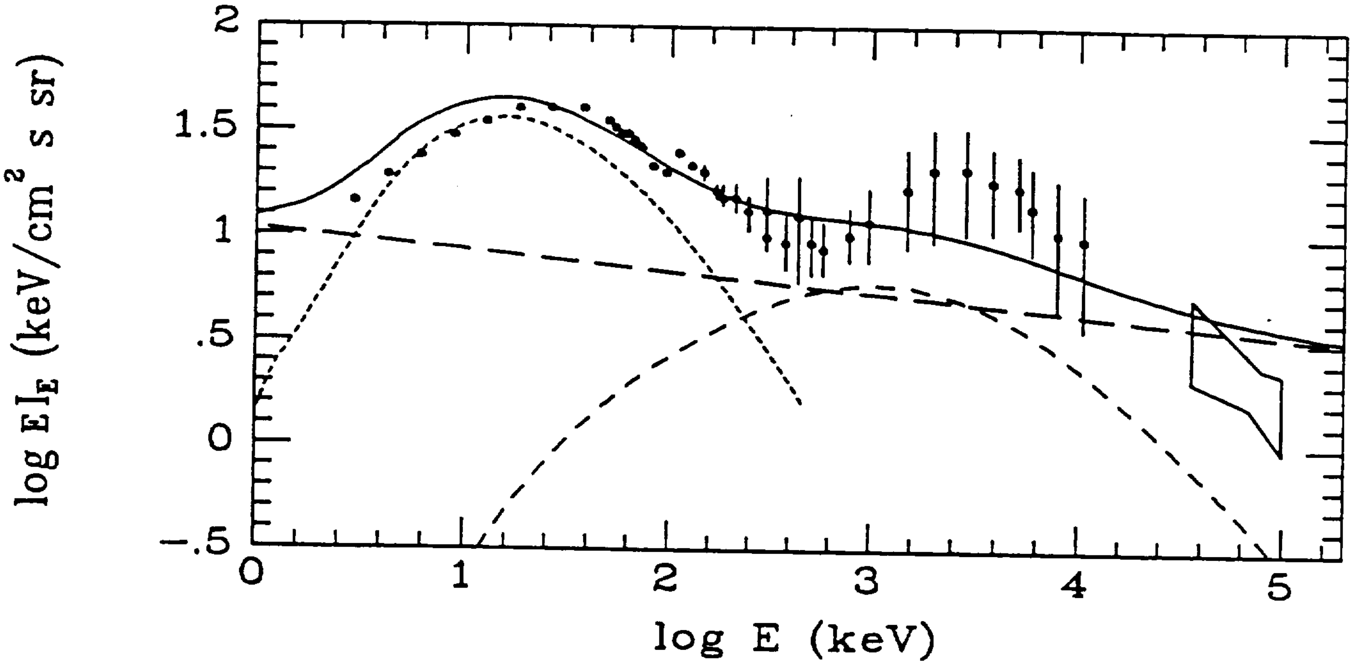

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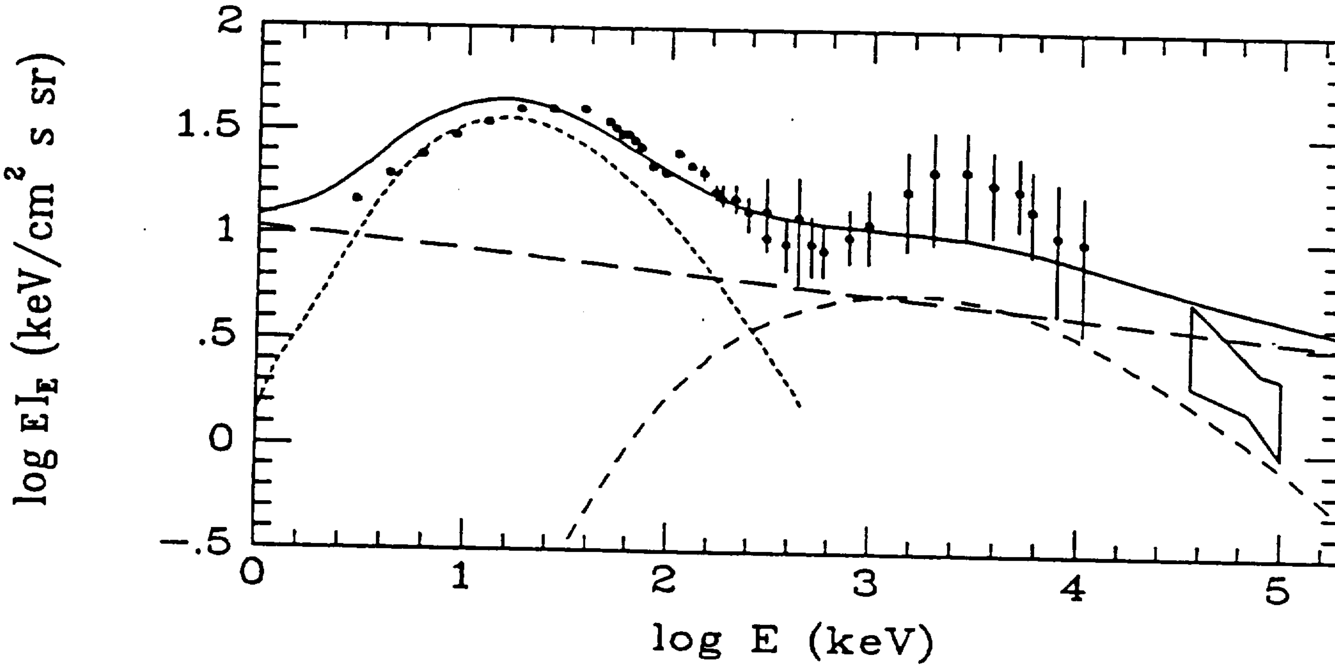
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