ON THE ORIGIN OF THE MeV GAMMA-RAY BACKGROUND

F. W. Stecker
Laboratory for High Energy Astrophysics, NASA Goddard Space Flight Center, Greenbelt, MD 20771, U.S.A.

M. H. Salamon
Physics Department, University of Utah, Salt Lake City, UT 84112, U.S.A.

C. Done
Physics Department, University of Durham, Durham, UK

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ABSTRACT

In this paper, we suggest a new hypothesis for explaining the spectrum of the extragalactic MeV $\gamma$-ray background as observed by COMPTEL and SMM. We propose that both the flux level and spectrum can be accounted for as a superposition of non-thermal MeV tails in the spectra of Seyfert galaxies and other AGN. Although present detectors are not sensitive enough to obtain MeV data from individual extragalactic sources, indirect evidence in support of our hypothesis is found in OSSE and COMPTEL observations of the galactic black hole candidate Cygnus X-1.

Subject headings: gamma-rays:theory –
1. Introduction

There has been much recent progress over the last 10 years in understanding the origins of the high energy cosmic background radiation. It now seems almost certain that the bulk of the hard X–ray background from 2–200 keV is made from obscured radio–quiet AGN (Madau, Ghisellini & Fabian 1994; Comastri et al. 1995; Gilli, Risalti & Salvati 1999), while at high energies (30 MeV – 100 GeV) the beamed radio–loud AGN (blazars) dominate (Stecker & Salamon 1996; Zdziarski 1996; Sreekumar et al. 1998). However, between the radio–quiet AGN rollover at \( \sim 100 \) keV, and the low energy break in the spectrum of radio–loud AGN at \( \sim 10 \) MeV, there is a substantial background component detected by COMPTEL and SMM in the 200 keV – 3 MeV range which is not accounted for in these models. Some of this is produced by type Ia supernovae (Zdziarski 1996), but the latest calculations show that there is still a marked discrepancy (by about a factor 2) between the observed background and current best estimates of the supernovae contribution (Watanabe et al 1999). It also appears that blazars will not account for the MeV background because their spectra generally have a break at an energy of about 10 MeV (McNaron-Brown et al. 1995). The small population of possible “MeV blazars” will also not account for the MeV background. In fact, even if we accept that unresolved blazars account for the extragalactic background radiation at energies above 30 MeV (Stecker & Salamon 1996), essentially all of these blazars would have to be “MeV blazars” as well in order to account for the background flux level at MeV energies, contrary to the observational evidence (McNaron-Brown et al. 1995).

In this paper we propose a new hypothesis to account for the extragalactic background in the MeV region as derived from two independent analyses of the COMPTEL data from the Compton Gamma Ray Observatory satellite (Kappadath, et al. 1996; Sreekumar, Stecker and Kappadath 1997; Weidenspointner 1999). Our hypothesis is based on an
analogy between the galactic black hole candidate Cyg X–1 and active galactic nuclei (AGN), which are generally believed to be powered by supermassive black holes. We use this analogy to extend the observation of a nonthermal MeV “tail” in the Cyg X–1 spectrum to hypothesize that such nonthermal tails exist in extragalactic AGN spectra, even though past and present gamma-ray detectors could not observe such tails at the flux levels expected. We will then argue that a superposition of unresolved AGN with Cyg X–1 type spectra, such as has been shown to reasonably account for the X-ray background (e.g. Gilli, Risaliti, and Salvati 1999) can also account for the shape and flux level of the MeV background deduced from the COMPTEL data.

In this regard, it is relevant to note very recent observations of Seyfert galaxies with flat spectrum radio nuclei using the VLBA have shown that these sources are emitting non-thermal radiation from central core regions with sizes $\sim 0.05$ to $0.2$ pc (Mundell, Wilson, Ulvestad & Roy 1999). Such cores may also be the source of non-thermal MeV emission.

2. The Cyg X–1 Epitome

Cyg X–1 in its low/hard state has a spectrum dominated by a power law component which rolls over at $\sim 200$ keV. This is well fit by a model involving a thermal population of hot electrons which Compton upscatter soft seed photons from the accretion disk (e.g. Gierlinski et al 1997). However, recent COMPTEL observations show a small hard tail of emission, extending out to MeV energies (McConnell et al. 1997). An explanation that has been suggested to account for this hard tail would be that the electron distribution is not completely thermalized (Poutanen & Coppi 1998). This is physically reasonable since the thermalization timescales for the electrons can be rather slower than the other timescales in these systems (e.g. Coppi 1999). The overall $2$ keV – $5$ MeV spectrum of Cyg X–1 can then
be modelled if 90 per cent of the power goes into a $\sim 100$ keV thermal electron distribution, while the remaining $\sim 10$ per cent is in the form of a non–thermal tail (Poutanen & Coppi 1998).

It is well known that the low/hard state spectrum of Cyg X–1 and other galactic black hole candidates bear a remarkable similarity to that from radio–quiet AGN (see e.g. the review by Poutanen 1998), plausibly because both involve the same physical processes of disk accretion onto a black hole. Thus we expect a similar hard tail to be present in Seyfert galaxies (both type 1 and type 2). In Cyg X–1 this tail begins roughly an order of magnitude below the peak in the hard X–ray spectrum. Such a tail could not be detected in an individual AGN using current instrumentation, but we will show that a superposition of such tails in the spectra of AGN would account for the reported MeV background spectrum and flux.

3. A Further Component to the MeV background from Seyferts?

Galactic black hole candidate sources are known to make spectral transitions to a high/soft state at accretion rates of greater than 10 per cent of the Eddington mass accretion rate. In this state the spectrum is dominated by a thermal component at $\sim 1$ keV (presumably corresponding to emission from the accretion disk), but also shows a steep non–thermal hard X–ray tail which extends past 511 keV (Grove et al 1998; Gierlinski et al 1999). It is not yet known where this power law breaks (Grove et al 1998), but it is plausible that this also extends to MeV energies, as seems to be indicated by COMPTEL data from Cyg X–1 (Poutanen & Coppi 1998; Gierlinski et al 1999). There is a class of Seyfert galaxies, the Narrow Line Seyfert 1’s Osterbrock & Pogge 1985; Boroson & Green 1992), which are thought to be the AGN analogue of these high mass accretion rate systems (Pounds, Done & Osborne 1995). These comprise about 10 per cent of Seyferts (Boroson &
Green 1992), so would also contribute to an extragalactic MeV background if these truly are comparable to the soft/high state galactic black holes in having a steep unbroken power law spectrum extending beyond 511 keV.

4. An Illustrative Spectrum

We will now estimate contributions that AGN power-law MeV tails would make to the X-ray/MeV background were these to be universal components in AGN spectra. Because our main concern is with the MeV component of the diffuse background, we restrict our calculation of the extragalactic background spectrum to energies in the range 100 keV - 10 MeV. Our calculation of the X-ray background (XRB) follows that of Pompilio, La Franca & Matt (1999) (PLM), to which we refer the reader for details. Briefly, the XRB is assumed to be comprised of the summed emission of unresolved AGN, which fall into two types: AGN1 and AGN2. In the standard unification scheme, the spectral differences between the two are due to the orientation of the AGN molecular torus relative to our line of sight. For AGN1, there is no obscuration of the nucleus by the torus along our line of sight, while for AGN2 the nuclear spectrum is both attenuated and altered by photoelectric absorption and Compton scattering within the torus.

Following Comastri et al. (1995), PLM adopt the following for the AGN1 source luminosity $l(E)$ in units of keV s$^{-1}$keV$^{-1}$

$$l(E) \propto \begin{cases} E^{-1.3} & E < 1.5 \\ E^{-0.9} e^{-E/400} + r(E) & E > 1.5 \end{cases}$$

(1)

where $E$ is in keV, and $r(E)$ is a Compton reflection component of nuclear emission off the surrounding gas and dust. The normalization coefficient is determined by requiring $\int l(E) dE = L$, where $L$ is the AGN luminosity in the energy band 0.3-3.5 keV at the source. To this we have added a non-thermal power-law component with a soft cutoff at
energies below the XRB peak of \( \sim 30 \) keV whose amplitude and spectral index are variable parameters. We neglect the reflection component, which is essentially compensated for in our energy region by normalizing the AGN1 spectrum to the AGN luminosity \( L \). Integration of

\[
l(E) = \kappa L \begin{cases} 
(E/1.5)^{-1.3} & E < 1.5 \\
(E/1.5)^{-0.9}e^{-E/400} + \eta(E/1.5)^{-\alpha}C(E) & E > 1.5 
\end{cases}
\] (2)

over \( 0.3 < E < 3.5 \) keV determines the normalization constant \( \kappa \). The power-law tail is assumed to be cut off below 30 keV by an arbitrary cutoff function \( C(E) \).

The spectra of AGN2 are modified by the intervening molecular tori. The ratio \( R(z) \) of AGN2 to AGN1 sources is taken from PLM, and is approximately 5 at redshift \( z = 0 \). The distribution of torus thicknesses through which the AGN2 emissions pass is taken from Risaliti, Maiolino & Salvati (1999) (their Table 3). Above 100 keV photoelectric absorption is negligible compared to Compton scattering (Morrison & McCammon, 1983), so we consider only the latter in calculating the mean transmission coefficient \( T(E) \) for AGN2 spectra.

The AGN1 X-ray luminosity function (XLF) \( \Phi(L, z) \), following PLM, is taken to be separable, \( \Phi(L, z) = \Phi_0(L)f(z) \), where \( f(z) \) is the evolution factor, and \( \Phi_0(L) \) is the current XLF. Integrating over the XLF gives the intensity of the diffuse background \( I(E) \) in units of keV cm\(^{-2}\)s\(^{-1}\)sr\(^{-1}\)keV\(^{-1}\)

\[
I(E) = \frac{c}{4\pi H_0} \int_0^{z_{\text{max}}} dz \frac{f(z)I[E(1+z)]}{(1+z)^2(1+2q_0z)^{1/2}} \int_{L_{\text{min}}}^{L_{\text{max}}} dL L\Phi_0(L). \quad (3)
\]

Figure 1 shows the results of this calculation with two power-law tail spectral indices, \( \alpha = 1.2 \) and 1.4. The amplitude \( \eta \) for these two cases is chosen to best fit the set of diffuse background measurements; in both cases this results in the power-law tail component being roughly an order of magnitude below the 30 keV peak value of the XRB. This is consistent (within the considerable uncertainties) with the amplitude of the MeV tail of Cyg X–1
relative to its hard-state peak.

5. Conclusion

We have examined a new hypothesis for explaining the origin of the extragalactic background radiation at MeV energies. Based on data from the galactic black hole candidate Cygnus X-1, and assuming that radio quiet active galactic nuclei, *i.e.* the Seyfert galaxies, contain much more massive black holes at their cores, we assume that all such black hole sources exhibit a high energy tail of the same magnitude relative to the thermal emission as Cygnus X-1. We show that by making this assumption, we can account for the flux and spectrum of the extragalactic MeV background as a superposition of emission from Seyfert AGN.

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Fig. 1.— Calculated diffuse X-ray and MeV gamma-ray background from AGN1 and AGN2 sources to whose spectra a power-law tail has been added. The two solid lines correspond to power-law tails of energy indices $\alpha = 1.2$ and 1.4 at the source. These are slightly hardened after passage through the molecular tori due to the energy dependence of the Compton cross section. Also shown is data from the GCRO/COMPTEL instrument (filled squares: Weidenspointner 1999; open squares (slightly displaced in energy): Kappadath et al. 1996), the Solar Maximum Mission (central thin line, and two 1σ lines: Watanabe et al. 1997 and 1999), and HEAO-A4 (filled circles: Kinzer et al. 1997; open circles: Gruber et al. 1992).