(NASA-TM-84974) ACTIVE GALAXIES AND THE DIFFUSE GAMMA-RAY BACKGROUND (NASA) 14 p HC A02/MF A01 CSCL 03B

N83-22088

Unclas
G3/93 09544

NASA

Technical Memorandum 84974

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JANUARY 1983

National Aeronautics and
Space Administration

Goddard Space Flight Center
Greenbelt, Maryland 20771

ACTIVE GALAXIES AND THE DIFFUSE GAMMA-RAY BACKGROUND

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A new model[1] for the origin of relativistic particles and gamma-rays in active galactic nuclei and quasars, together with recent HEAO-1 observations[2] of the spectra of active galaxies from 2 to 165 keV, provide the basis for a re-examination of the nature of the extragalactic gamma-ray background[3,4]. We find that active galaxies could account for the observed background if their X-ray spectra steepen to $E^{-2.1}$ above ~100 keV, as has been observed in Cen-A[5], together with a further steepening to $E^{-2.7}$ as a result of absorption of gamma-rays by photon-photon pair production interactions with X-ray photons. The compactness of active galaxies required to give this steepening is consistent with current estimates of their typical luminosity and radius.

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The observed spectrum, as reviewed by Ramaty and Lingenfelter[6], is shown in Fig. 1. These recent observations are consistent with earlier results[7,8,9]. In particular the feature at MeV energies observed in balloon experiments (e.g. Shönfelder et. al.[8]) is also apparent in the more recent data. The X-ray spectrum from 3 keV to 50 keV is consistent with thermal bremsstrahlung from a plasma at ~40 keV and may result from a hot intergalactic medium[10], while at the highest energies (30 - 150 MeV) the γ--ray photon spectrum is consistent with a power law of index 2.7. Several other possibilities have been proposed to account for the observed diffuse gamma-radiation (see reviews by Silk[11,12] and Horstman et al.[7]). Stecker[13], for example, has suggested that it may result from matter antimatter-annihilation in a baryon symmetric universe, the annihilation occuring at the boundaries between domains of matter and antimatter. Emission from unresolved active galaxies has also been proposed to account for the diffuse gamma-ray flux[14,15,16,17]. To date, only one extragalactic object, the quasar 3C273, has been detected at 100 MeV energies[18]. The contribution of quasars to the gamma-ray background is however quite uncertain since the volume density of gamma-ray emitting quasars is unknown. Seyfert 1 galaxies show flat power law energy spectra at X-ray energies[19] and could contribute significantly to the diffuse gamma-ray flux. We shall consider the latter possibility in this letter.

Recent HEAO-1 observations by Rothschild et al.[2] of 12 active galaxies (the sample is dominated by Seyfert 1 galaxies) show that the X-ray photon spectra of all these objects from 2 keV to 165 keV are consistent with a single power law with exponent ~1.6. Upper limits exist above 30 MeV from

SAS-2 observations of 7 of these objects[19] and indicate that their spectra must steepen between hard X-ray and gamma-ray energies.

Rothschild et al.[2] also showed, using the luminosity function of active galaxies from the HEAO-1 flux limited X-ray survey[20], that active galaxies could account for all of the diffuse X-ray emission above ~150 keV with no evolution. It has also been suggested[21] that active galaxies might account for the observed flattening in the hard X-ray background from 500 keV to 2 MeV. We propose that the gamma-ray background may also be due to these unresolved active galaxies and will show how the observed spectral shape could arise naturally in the model for relativistic particles and gamma-rays in active galaxies and quasars described in our earlier work[1].

The model[1] we use for the X-ray and gamma-ray spectra of active galaxies has already been applied to the observed spectrum of 3C273. The salient features of this model are: a) protons are accelerated by the first order Fermi mechanism at a shock in a spherical accretion flow onto a massive black hole; b) relativistic protons have a spectrum which is a power law in energy $E^{-(2+\epsilon)}$, where $\epsilon \ll 1$ for strong shocks; c) nuclear interactions result in production of gamma-rays from π^0 decay and electrons from π-μ-e decay, both being produced with spectra $E^{-(2+\epsilon)}$ above several hundred MeV; d) synchrotron and inverse Compton losses steepen the ambient electron spectrum to $E^{-(3+\epsilon)}$; e) gamma-ray photons from inverse Compton interactions then have a photon spectrum $E^{-(2+\epsilon/2)}$, very similar to that of π^0 gamma-rays; f) the high energy gamma-ray spectrum is steepened by photon-photon pair production interactions with X-rays.

In this model, one might initially expect the $E^{-(2+\frac{\epsilon}{2})}$ gamma-ray photon spectrum to continue without a break to X-ray energies, contrary to observation. A break in the electron spectrum from $E^{-(3+\epsilon)}$ at high energies to $\sim E^{-2}$ at low energies, may however manifest itself as a break in the photon spectrum from $E^{-(2+\frac{\epsilon}{2})}$ at γ-ray energies to $\sim E^{-1.5}$ at X-ray energies. Two possibilities may account for this. The first possibility is that relativistic particles might leak out of the central object on some timescale t(leak), perhaps producing the beams or jets associated with many active galaxies[22]. At energies below which the energy loss time is equal to the leakage time, i.e. $E/(dE/dt) > t(leak)$, the ambient electron spectrum would have the same power law index as that at producton, i.e. $2+\epsilon$. The power law index of the photon spectrum of inverse Compton X-rays would then be $(3+\epsilon)/2$; the observed spectral index of 1.6 implying $\epsilon = 0.2$, consistent with shock acceleration. The second possibility is that the observed X-ray spectral index may result from the kinematical cut-off of secondary electrons, i.e. those resulting from π-μ-e decay. The production spectrum of secondary electrons[1] due to pion production cuts off steeply below ~100 MeV below which knock-on electrons become important. There is thus a change in the production spectrum which may manifest itself as a change in slope of the inverse Compton radiation. In the case of no leakage (energy losses balance production) and if the knock-on component were small, the ambient spectrum would be inversely proportional to the rate of energy loss below the cut-off energy; i.e. an E^{-2} spectrum if synchrotron and inverse Compton losses dominate. The resulting X-ray photon spectral index would be 1.5, just slightly flatter than the observed spectrum. The inclusion of a knock-on component will however steepen the spectrum slightly.

In active galaxies, we expect a further steepening in their gamma-ray spectra due to photon-photon pair production interactions with X-ray photons. For the photon spectrum which is observed at X-ray energies in most active galaxies, $E^{-1.6}$, the gamma-ray spectral index would be steepened by 0.6, relative to that at production, above the energy at which the optical depth to this process is unity. This break energy depends on the X-ray source compactness, the ratio of X-ray luminosity to the dimensions of the emitting region. The expected steepening in photon spectral index from $(2+\epsilon/2)=2.1$ to 2.7 is just what is required if the observed diffuse gamma-ray background is due to unresolved active galaxies.

The radio galaxy Cen-A has a very similar X-ray spectrum[5] to the active galaxies observed by Rothschild et al.[2]; indeed, the compact object responsible for the X-ray emission from Cen-A may be of the same class of object as the X-ray sources in Seyfert nuclei (the nucleus of Cen-A is obscured at optical to infra-red wavelengths by dust). In Cen A, the spectrum is seen to break from $E^{-1.6}$ below 140 keV to $\sim E^{-2}$ above 140 keV[5]. Such an E^{-2}, or slightly steeper, spectrum is expected if the relativistic particles result from shock acceleration and the emission is due to inverse Compton scattering of soft photons. A further steepening must then occur at some energy above a few MeV to be consistent with the SAS-2 upper limit[18]. This could then result from absorption of high energy gamma-rays by photon-photon pair production interactions with the X-ray photons. (The observation of a flux of gamma-rays above 100 GeV from Cen-A[23] which is above an $E^{-2.7}$ extrapolation from the SAS-2 upper limit merely implies, in this model, that the photon density at ~2.5 eV in the region of the compact gamma-ray source is low.)

In Figure 1, we show (solid line) the expected contribution of active galaxies to the X-ray background calculated, assuming no evolution, by Rothschild et al.[2] from the X-ray luminosity function of active galaxies obtained by Piccinotti et al.[20] and taking a low luminosity cut-off at 3.5×10^{42} erg/s. We have extrapolated this spectrum to 140 keV where we have assumed that the X-ray spectrum of average active galaxies smoothly breaks from $E^{-1.6}$ to $E^{-2.1}$, in a way similar to that observed in Cen-A. A further break is then required at ~5 MeV (to $E^{-2.7}$) to account for the observed gamma-ray background from 30 - 100 MeV (see Fig. 1).

We shall now calculate the X-ray source compactness required to account for the gamma-ray background with unresolved active galaxies. We do not present here results of a full cosmological integration which would take into account the red shifting of energy spectra of distant active galaxies which contribute to the background. We have found, however, that the effect on the spectral shape is small in the present case; the greatest contribution to the gamma-ray flux being due to relatively nearby active galaxies. The optical depth of gamma-rays of energy E_γ to photon-photon pair production is given by:

$$\tau(E_\gamma) = s \int n_x(E_x)\,\sigma(E_\gamma,E_x)\,dE_x$$

where: $s = 1.33 R$ is the average distance through the source, of radius R; $n_x(E_x)$ is the average density of X-ray photons at energy E_x and is given by

$$n_x(E_x) = L_x(E_x)\ E_x^{-2}\ /\ (\pi R^2 c)$$

where $L_x(E_x)$ is the X-ray luminosity at energy E_x (energy /unit time /ln[energy]); $\sigma(E_\gamma, E_x)$ is the cross section[24] for a gamma-ray photon of energy E_γ producing a pair on interacting with an X-ray photon of energy E_x. For $n_x(E_x) \propto E^{-1.6}$, and an optical depth of unity at the required break energy, i.e. τ(5 MeV)=1, we find for the X-ray source compactness, L_x(2-10 keV)/R = 6×10^{27} erg/s/cm. For a luminosity function[20] proportional to (luminosity)$^{-2.75}$, the mean luminosity is 2.4 times the low luminosity cut-off, L_1. Then, for L_1(2-10 keV) = 3.5×10^{42} erg/s (solid line in Fig. 1), the mean luminosity is 8.4×10^{42} erg/s and we obtain a typical source radius of 1.4×10^{15} cm. The low luminosity cut-off in the X-ray luminosity function of active galaxies is however somewhat uncertain. If L_1 were 10^{43} erg/s, then the contribution to the X-ray background[2] would be as shown by the dashed line in Fig. 1. The gamma-ray observations would then permit a single spectral break from $E^{-1.6}$ to $E^{-2.7}$ at about 2.5 MeV (i.e. energy at break from spectral index of 1.6 to 2.1 coincident with that from 2.1 to 2.7), producing the observed flattening in the energy spectrum at MeV energies. On this assumption, the X-ray compactness would be 9×10^{27} erg/s/cm for a typical active galaxy, corresponding to a source radius of 2.7×10^{15} cm. Values of the radii of Seyfert 1 galaxies obtained from their X-ray time variability[25] range from 6×10^{14} to 8×10^{16} cm and bracket the values we obtain here.

If the bulk of the diffuse γ-ray background is due to active galaxies, one might expect considerable fluctuations in the diffuse flux to arise from the few nearest sources. Unfortunately , the magnitude of the fluctuations we expect, after appropriately scaling the corresponding fraction of the X-ray fluctuations due to active galaxies[26] , is well below the upper limits of the SAS-2 data[4] . Even the Gamma Ray Observatory (GRO)[27] , with its large area and long exposure time, may still be limited by photon statistics.

If, however, the model proposed (ref. 1) for the γ-ray spectra of active galaxies is correct, GRO should be able to detect several of these objects. It will then be possible to infer the active galaxy contribution to the diffuse gamma-ray background and thus provide a test for the present hypothesis.

In conclusion, we have shown that the observed spectrum of the diffuse gamma-ray background could be accounted for by unresolved active galaxies, even with no evolution, if their spectra are described by a spherical accretion/shock acceleration model (ref. 1) and are steepened by photon-photon pair production interactions at high energies.

We are indebted to R. Mushotzky, R. Shafer and D. Thomson for their helpful discussions on the fluctuations.

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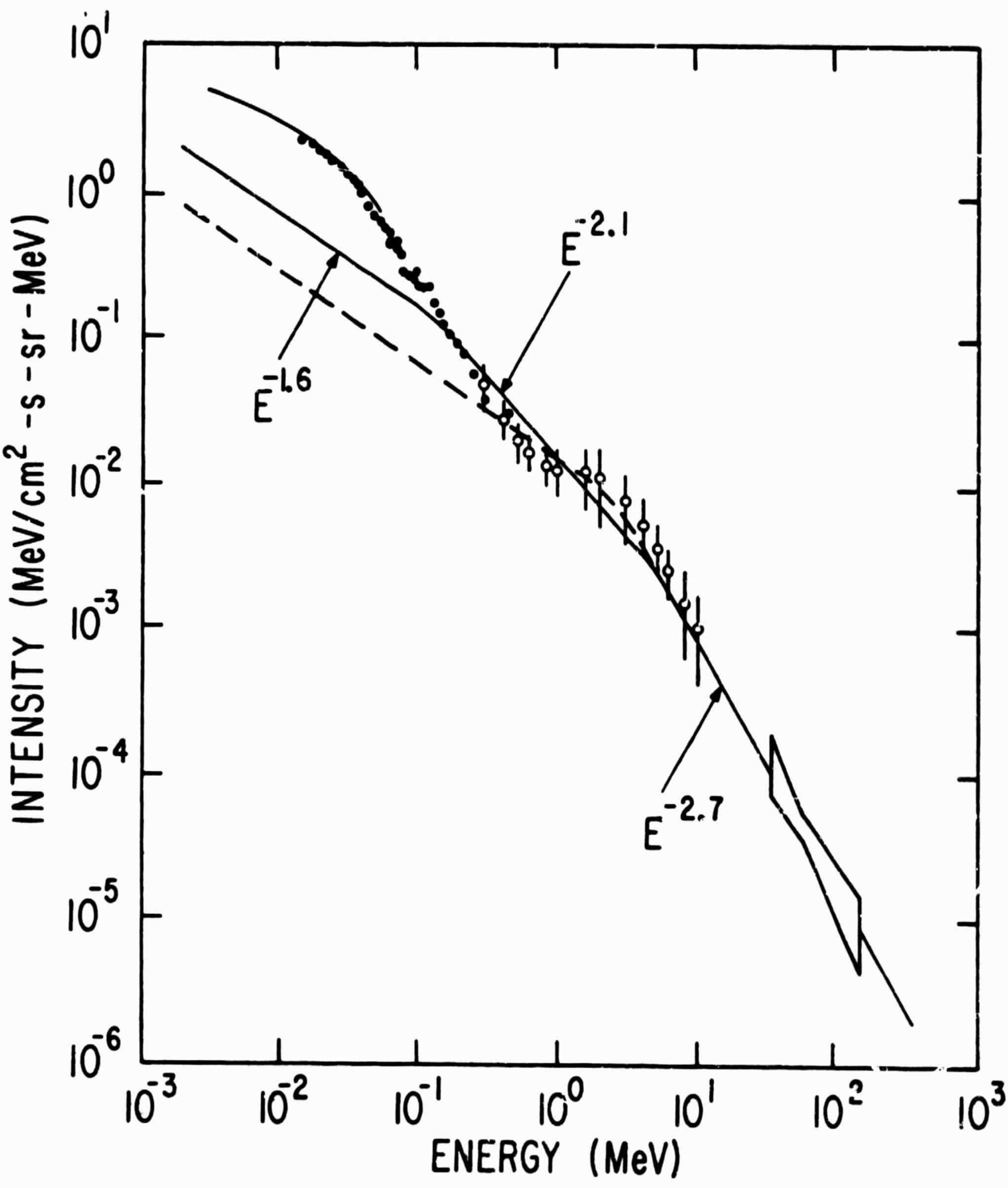
FIGURE CAPTION

Fig. 1.

Energy spectrum of the diffuse X-ray and γ-ray background (solid curve from 3 to 50 keV -- ref. 7; filled circles -- preliminary HEAO-1 data reported in ref. 2; open circles -- ref 3; 30 to 150 MeV data -- ref 4). Solid and dashed lines show possible active galaxy contributions to the diffuse background (see text for discussion); a power law approximation to the photon spectrum is indicated for three energy regions.


10^{1}
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
INTENSITY (MeV/cm^2 -s -sr - MeV)
$E^{-2.1}$
$E^{-1.6}$
$E^{-2.7}$
10^{-3}
10^{-2}
10^{-1}
10^{0}
10^{1}
10^{2}
10^{3}
ENERGY (MeV)