GAMMA-RAYS FROM ACTIVE GALACTIC NUCLEI

M. Kafatos
Department of Physics, George Mason University, Fairfax, VA
and Laboratory for Astronomy and Solar Physics, NASA, Goddard
Space Flight Center, Greenbelt, MD, U.S.A.

Gamma-ray observations from active galactic nuclei (AGN) are important in trying to understand the nature of their central sources. A handful of mechanisms can give rise to γ-rays either from nonthermal or from thermal processes. Hot accretion disks around massive black holes in the centers of AGN could provide the required thermal electrons, pions and relativistic electrons and positrons to explain both the X-ray and γ-ray emission.

I. OBSERVATIONS

Up to this date, γ-ray continua have been detected from three AGN. The observations have been summarized in numerous references (Bignami et al. 1979; Kafatos 1980; Kafatos, Shapiro and Silberberg 1981; Fichtel and Trombka 1981). The three active galaxies are Centaurus A, a radio galaxy; NGC 4151, a Seyfert galaxy; and 3C 273, a quasar. Their fluxes per log-energy interval over the entire electromagnetic spectrum are shown in Figure 1, kindly provided by Dr. D.J. Thompson. I have added for completion the 100 GeV upper limit for 3C 273 and the E⩾300 GeV observation of Cen A (cf. Kafatos 1980 for references). Detailed observed spectra for the X-ray, γ-ray energies can be found in Fichtel and Trombka (1981). The spectrum of 3C 273, for example, can be fit with the empirical law $0.016\ E^{-1.4}\ \{1+(E/2\times10^{3})^{1.3}\}^{-1}$ photons $cm^{-2}\ s^{-1}\ keV^{-1}$ from the X-ray to the γ-ray range, with upper energies of hundreds of MeV. Gamma-ray luminosities are estimated to be 10^{45} erg/s for NGC 4151 and energies less than 3 MeV; 10^{44} erg/s for Cen A and energies less than 10 MeV; 3×10^{46} erg/s for 3C 273 for energies in the range 50-500 MeV (Kafatos, Shapiro and Silberberg 1981). I estimate that γ-rays make up at least 10% of the bolometric luminosity in these three AGN, perhaps as much as 50%. The spectra of the AGN steepen sharply from the X-ray range to the γ-ray range as seen in Figure 1. The energy around which steepening occurs is a few MeV. This is an important clue as we will see later. Three sources is not, obviously, a large sample to make strong statements. The observations up to now leave open the possibility that many AGN will be shown to be strong γ-ray continuum emitters. The data up to now were

Richard M. West (ed.), Highlights of Astronomy, Vol. 6, 505–510.

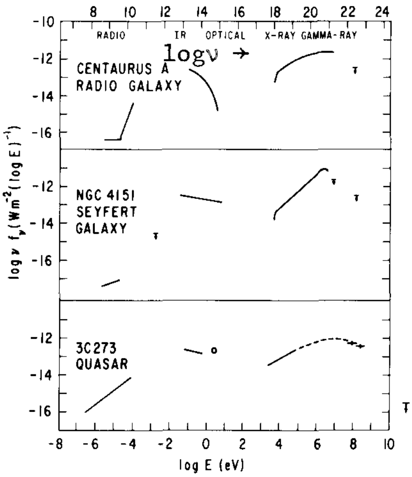

Figure 1. Fluxes per log-energy interval for the AGN that show gamma-ray emission

collected by the SAS-2 and COS-B satellites. Future γ-ray satellites are the Gamma-I, a joint French, Soviet satellite and the American NASA Gamma-Ray Observatory (GRO). The observational situation will be greatly improved with the launch of GRO, predicted to be sensitive to 10^{-4} photons cm^{-2} s^{-1} MeV^{-1} at 0.5-1 MeV and 10^{-5} photons $cm^{-2}s^{-1}$ MeV^{-1} at 1-10 MeV; at high energies its sensitivity will be $2x10^{-11}$ photons $cm^{-2}s^{-1}$ MeV^{-1} (at 100 MeV) and $2x10^{-13}$ photons cm^{-2} $s^{-1}MeV^{-1}$(at 1 GeV) (D.A. Kniffen, private communication).

Gamma-ray lines have been detected from Cen A (Hall et al. 1976), including the 4.5 MeV ^{12}C line. Our own galactic nucleus has also been observed to emit both X-ray and γ-ray continua as well as the 511 keV positron annihilation line-Matteson 1982; Leventhal, MacCallum and Stang 1978). The galactic gamma-ray source with a maximum continuum luminosity of $\sim 4x10^{38}$ erg/s and positron production rate of $\sim 4x10^{43}$ e^+/s is orders of magnitude fainter than Cen A and, therefore not an AGN gamma-ray source. It is examined elsewhere in greater detail (Ramaty, present volume). The weakness of the galactic center source may have to do with the size of the black hole, in this case possibly a stellar rather than supermassive one. The emission mechanism may, though, be similar to that of AGN, namely Componization in a hot, optically thick in gamma-rays, accretion disk (Kafatos and Eilek 1982a). No 511 keV feature has so far been detected from any AGN.

Gamma-ray variability is suspected in the case of NGC 4151 for which the 0.2-5 MeV flux seen by Perotti et al. (1979) was not seen at a later time (Zanrosso et al. 1979). In the case of 3C 273, however, the γ-rays detected by COS-B don't seem to be variable over a period of about two years (Fichtel, private communication). This is not too surprising since, as McBreen (1979) showed (cf. Kafatos 1980) the 500 MeV γ-rays detected by COS-B would have to come from a region of size ≳ 7 light months; otherwise $\gamma\gamma \rightarrow e^+e^-$ scattering of these γ-rays with the X-rays would deplete them. It is, of course, possible that γ-rays of energy up to about 30 MeV are emitted near the black hole as long as the mass of the black hole can be as high as 10^{10} $M_\odot$ (Kafatos 1980). Cen A is, of course, variable at X-rays but not much is known about variability for energies greater than 100 keV. To this date we cannot unequivocally state that there is any evidence of variability in the gamma-ray region of the spectrum (say for energies greater than hundreds of keV). Future observations should shed some light on this very important question. Variability would help us in deciding where the γ-rays are coming from and provide some important clues on the nature of the central source.

In what follows I examine the best candidate mechanisms for X-ray and

https://doi.org/10.1017/S1539299600005517 Published online by Cambridge University Press

γ-ray production in AGN. I have tried to include most of what has appeared in the literature and have included a discussion of X-ray mechanisms because in some models the same environment is responsible for both X-ray and γ-ray productions. Some of the mechanisms directly address the nature of the central engine (e.g. Comptonization) whereas others do not. In what follows X-rays are meant radiation of energy up to about 100 keV, whereas γ-rays above that energy and particularly above 1 MeV.

II. X-RAY PRODUCTION MECHANISMS

X-rays can be produced by nonthermal processes (synchrotron; synchrotron-self-Compton or SSC) in which the electrons responsible are ultra-relativistic; and by thermal processes in which the electrons responsible are mildly relativistic or even relativistic but still obey a thermal distribution (Comptonization).

1. Nonthermal

It is unlikely that the observed X-rays from AGN are due to the synchrotron mechanism (Holt and McCray 1982); t_C-the characteristic time scale for Compton production of X-rays-would be much shorter than t_S-the characteristic time scale for synchrotron radiation alone, unless of course the magnetic fields are very strong. Such conditions are unlikely to hold in the central sources of AGN but may hold in jets. Jets are, however, beyond the scope of the present paper. Self-synchrotron-Compton can be responsible for the observed X-rays. In the SSC model (Jones et al. 1974) the X-rays result from the first order Compton scattering of the radio photons which are produced by the synchrotron mechanism. The resultant X-ray flux can be related to the magnetic field and the geometry. The advantage of this mechanism is that the same electrons are responsible for the production of the radio and infrared emission as well as the X-ray emission. SSC does not though say anything about the central engine and moreover if the γ-ray spectra steepen around a few MeV-as it seems to be the case-there would be no natural explanation for this steepening.

2. Thermal

Alternatively, the X-rays may arise from the Comptonization of seed photons by a hot, thermal electron gas. Henceforth, we refer to this mechanism as "Comptonization". This process has been described in great detail in the literature (Shapiro, Lightman and Eardley 1976; Katz 1976). The repeated Compton scatterings give a "non-thermal" appearance (power law) to the observed spectrum. The soft photons that interact with the thermal electrons are formed in the general neighborhood of the central black hole, either by the cool disk (Novikov and Thorne 1973) or by cool clumps in the hot, inner region of the accretion disk. The great advantage of this mechanism is that it is directly tied to the nature of the central source and it naturally explains the MeV steepening of the AGN spectra (see below). The relevant parameter is the Comptonization parameter y where y is defined by $y = \langle \text{fractional energy change per scattering} \rangle \times$

⟨number of scatterings⟩. Here the brackets refer to mean values. Large amplification of the incoming soft flux occurs when $y \sim 1$ (Shapiro, Lightman and Eardley 1976). The resulting energy losses of the electrons act as a thermostat (see also Liang 1979) i.e. the condition $y \sim 1$ is a rather stable one. The y parameter is related to the energy flux spectral index Γ (the energy flux is in kev cm^{-2} s^{-1} keV^{-1}) by the approximate relation

$$\Gamma \sim 0.72\ y^{-0.917} \tag{1}$$

for $T_e \sim 10^9$ K appropriate to the hot, inner region of an accretion disk (Shapiro, Lightman and Eardley 1976; Eilek and Kafatos 1982). It is easy then to understand why AGN seem to have a mean Γ (Rothschild et al. 1982) in the range 0.6-0.7: This is equivalent to $y \gtrsim 1$, the stable condition. The mean AGN spectrum from Rothschild et al. (1982) is shown in Figure 2. I have included theoretical spectra for the hot, accretion disks of Eilek and Kafatos (1982) which show that y = 1-3 fits are excellent.

III. GAMMA-RAY PRODUCTION MECHANISMS

A plethora of mechanisms has been proposed for specific sources or will give rise to γ-rays without their authors specifically mentioning any sources. I briefly summarize these to turn my attention to the hot, accretion disk model which can alone explain both the X-rays and the γ-rays.

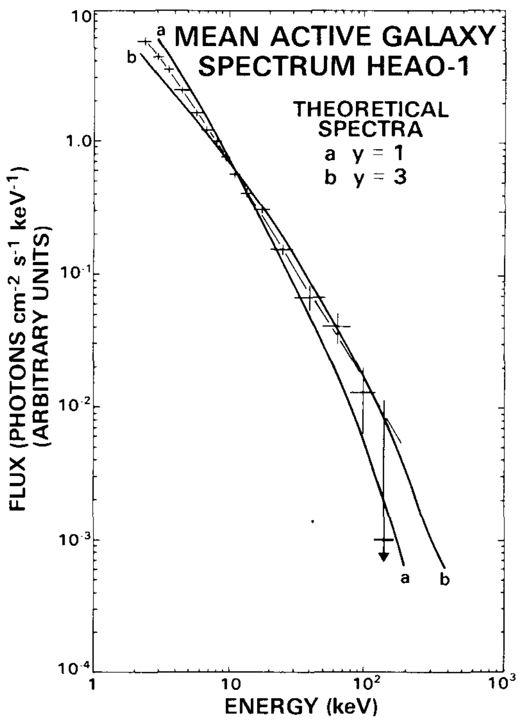

Figure 2. Comptonization fits to the mean AGN spectrum

Synchrotron γ-rays can be produced in the electric dynamo model of Lovelace, MacAuslan and Burns (1979) up to ∼ 500 GeV but this mechanism does not apply to low energy γ-rays.

Second-order SSC processes have been proposed for the 100-500 MeV radiation from 3C 273 (Jones 1979). In this model 0.1-0.2 keV X-rays are upscattered to 100-200 MeV γ-rays by the same electrons which radiate in the radio via the synchrotron process. This model has problems because the X-rays would have to come from the same region as the high energy γ-rays.

Penrose processes (Kafatos 1980) will give rise to MeV photons via the Penrose Compton process and to GeV photons via the Penrose pair production process. The former would be masked by the thermal radiation of the disk itself, while the latter

https://doi.org/10.1017/S1539299600005517 Published online by Cambridge University Press

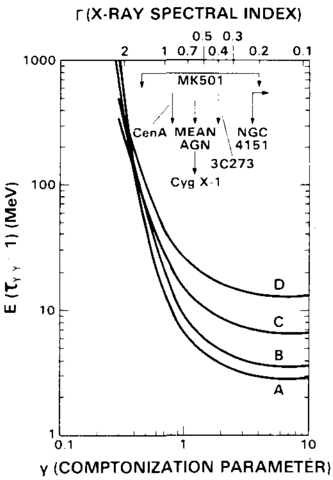

Figure 3. The γ-ray energy at which $\tau_{\gamma\gamma} = 1$ as a function of y or Γ. Various AGN Γ's are also shown. The curves are described in the text. It is seen that $y \gtrsim 1$ is satisfied

would be too weak to make any appreciable contribution except at energies greater than ∿ 1 GeV (Eilek and Kafatos 1982).

An inverse Compton origin for the γ-ray emission from NGC 4151 has been proposed by Schlickeiser (1980). This is a single scattering process but unlike the SSC process the soft photons that are upscattered are in the UV-X-ray region and, therefore, their origin is not tied to the synchrotron photons. The mechanism works because the Klein-Nishina cross section changes in such a way as to steepen the γ-ray spectrum. For NGC 4151 the soft photon enrgy is in the range 30 eV-10 keV and its origin has to be specified.

Kazanas (1982) has proposed a mechanism to explain the 3C 273 γ radiation. In this mechanism a shock wave forms around a non-rotating black hole. Although reasonable fits to the COS-B data of 3C 273 are obtained, the required black hole mass is rather high, $\gtrsim 10^{10}\ M_\odot$.

Rees et al. (1982) have proposed that ion-supported tori are responsible for the origin of the radio jets in AGN. Although γ-ray formation is expected in such a model, no detail spectra have been computed.

Perhaps the most natural model that can account for both the X-ray and γ-ray emission from AGN is the two-temperature disk model. Eilek and Kafatos (1982) have made general relativistic accretion disk models applicable both to the Kerr and Schwarzchild metrics. In this model the ion temperature T_i is much larger than T_e and close to a few $\times 10^{12}$ K in the Kerr metric for accretion rates approaching the Eddington limit. Gamma-ray emission is then assured from the pion production as well as e^+e^- relativistic production. The X-rays are produced by Comptonization of soft photons from the cool disk and the hot, thermal electrons with $T_e \sim 10^9$ K. Due to the high opacity of $y \gtrsim 1$ models to γγ scattering, γ-rays more energetic than a few MeV do not escape from the disk; they are, instead, degraded to X-rays when the scattering products e^+e^- radiate. Relativistic electron-positron pairs also radiate. The net effect is that in such optically thick to γγ scattering models the X-ray origin is closely tied to the γ-ray origin. The relevant relation for the optical depth to $\gamma\gamma \rightarrow e^+e^-$ is written as follows

$$\tau_{\gamma\gamma} \sim 5\times10^{-2}\ D^2_{Mpc}\ \ E_T(\mathrm{keV})\ N(2E_T)\ R^{-1}_{1d} \qquad (2)$$

where D_{Mpc} is the distance in Mpc, E_T the threshold X-ray energy for e^+e^- production from gamma-rays and N is the photon flux at the earth (photons $cm^{-2}\ s^{-1}\ keV^{-1}$) and R_{1d} is the gamma-ray emitting region size in light days. For $y \gtrsim 1$, $\tau_{\gamma\gamma} \gtrsim 1$ and the X-ray energy spectral index $\Gamma \sim 0.7$ as observed. This is shown in Figure 3. The curves A,B are for $\dot{M}_*/M_8 = 1$, Kerr metric model with the viscocity parameter $\alpha = 0.1$, where $\dot{M}_*$ is the accretion rate in $M_\odot$/yr, M_8 is the mass of the black hole in 100 million solar masses and where A is for $20r_g$ mean free path of the gamma rays and B for $10r_g$ (r_g is the gravitational radius). Curves C and D are the equivalent of A and B but for sub-Eddington luminosities ($L/L_{Edd} \sim 0.2$, whereas $L/L_{Edd} \sim 1$ in cases A and B).

This model not only can account for individual gamma-ray spectra but also applies to stellar black holes like Cyg X-1 and the galactic center source (Kafatos and Eilek 1982a). It also applies to the X-ray, γ-ray backgrounds (Kafatos and Eilek 1982b). Future gamma-ray observations in the 1-50 MeV region would be important to decide whether this model is applicable to AGN.

REFERENCES

Bignami,G.F.,Fichtel,C.E.,Hartman,R.C.,and Thompson,D.J.:1979,Ap.J. 232, p. 649.
Eilek,J.A.,and Kafatos,M.:1982,Ap.J.,submitted.
Fichtel,C.E.,and Trombka,J.I.:1981,"Gamma Ray Astrophysics",NASA SP-453.
Hall,R.D.,Meegan,C.A.,Walraven,G.D.,Djuth,F.T.,and Haymes.:1976,Ap.J. 210,p.631.
Holt,S.S., and McCray,R.:1982,Ann.Rev.Astr. & Ap. 20.
Jones,T.W.:1979,Ap.J. 233.
Jones,T.W.,O'Dell,S.L.,and Stein,W.A.:1974,Ap.J. 188,p.353.
Kafatos,M.:1980,Ap.J. 236,p.99.
Kafatos,M.,and Eilek,J.A.:1982a,Ap.J.Letters, submitted.
Kafatos,M.,and Eilek,J.A.:1982b, in preparation.
Kafatos,M.,Shapiro,M.M.,and Silbereberg,R.:1981,Comm. on Ap. 9,p.179.
Katz,J.I.:1976,Ap.J. 206,p.910.
Kazanas,D.:1982, preprint.
Leventhal,M.,MacCallum,C.J.,and Stang,P.D.:1978,Ap.J.Letters 225,p.L11.
Liang,E.T.P.:1980,Nature 283,p.642.
Lovelace,R.V.E.,MacAuslan,J.,and Burns,M.L.:1979,in "Particle Acceleration Mechanisms in Astrophysics",ed.Arons,McKee and Max,AIP Conf. 56,p.399.
Matteson,J.L.:1982,in "The Galactic Center",ed.Riegler and Blandford, AIP Conf. Proc. 83,p.109.
McBreen,B.:1979, Astr. & Ap. 71,p.L21.
Novikov,I.D.,and Thorne,K.S.:1973,in "Black Holes",ed. DeWitt and DeWitt (New York:Gordon & Breach).
Perotti,F.,et al.:1979,Nature 282,p.484.
Rees,M.J.,Begelman,M.C.,Blandford,R.D.,and Phinney,E.S.:1982,Nat.295,p.19.
Rothschild,R.E.,et al.:1982,Ap.J., submitted.
Schlickeiser,R.:1980,Ap.J. 236,p.945.
Shapiro,S.L.,Lightman,A.P.,and Eardley,D.M.:1976,Ap.J. 204,p.187.
Zanrosso, E.M., et al.:1979, in "Proc. 16th Int. Cosmic Ray Conf." 1, p. 112.a.