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SPECTRAL-LUMINOSITY EVOLUTION OF ACTIVE GALACTIC NUCLEI AND THE COSMIC X- AND GAMMA RAY BACKGROUND

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ABSTRACT

Coherent electromagnetic dynamo acceleration processes, which act on charged particles within the context of black hole accretion disk scenarios, are generally regarded as the underlying central power source for active galactic nuclei (AGN) (Rees 1984). If the precursor active galaxies (PAG) for such AGN are formed at high redshift and contain initial seed black holes with mass $\sim 10^4$ solar masses, then the Eddington limited X-ray radiation emitted during their lifetime will undergo the phenomenon of "spectral-luminosity evolution". When accretion disks are first formed at the onset of galaxy formation the accretion rate occurs at very high values of luminosity/size compactness parameter $L/R > 10^{30}$ erg/cm-sec. In the absence of extended structure, such high values of L/R generate dynamic constraints (Cavaliere & Morrison, 1980; Guilbert, Fabian, & Rees, 1983) which <u>suppress coherent, black-hole/accretion disk dynamo particle acceleration processes.</u> This inhibits nonthermal radiation processes and causes the spectrum of X-radiation emitted by PAG to be predominantly thermal. A superposition of PAG sources at $z \gtrsim 6$ can account for the residual cosmic X-ray background obtained from the total cosmic X-ray background (CXB) after subtraction of foreground AGN sources associated with present epoch Seyfert galaxies (Leiter & Boldt 1982 ,1990); (Boldt & Leiter 1984, 1986, 1987); (Zdziarski 1988). At the end of the PAG lifetime the compactness parameter of the black hole-accretion disk dynamo system falls below $\sim 10^{30}$ erg/cm-sec and coherent dynamo acceleration processes for charged particles become dominant. Under these conditions the black-hole/accretion disk dynamo system can create localized clouds of nonthermal electron-positron pairs above the accretion disk via the photon-photon --> electron-positron process. Because these clouds of electron-positron pairs gain their energy from an <u>incoherent</u> acceleration process above cool regions of the accretion disk, the cloud compactness can <u>exceed</u> $\sim 10^{30}$ erg/cm-sec while still generating a broad band of nonthermal radiation, including X-rays and gamma rays. In this manner the PAG undergo spectral-luminosity evolution into Seyfert galaxies whose spectral structure includes Compton reflection processes from regions of cool matter. (Zdziarksi et.al, 1990, 1991).

I. PRECURSOR ACTIVE GALAXIES (PAG) AND THE CXB

PAG initially undergo Eddington limited accretion. Since the hard X-radiation from thermal processes in the PAG accretion disk comes from a region on the order of 10 gravitational radii, L/R can be written in terms of L/L_{Edd} as

$$L/R = (L/L_{Edd})\ 10^{32}\ \text{erg/cm-sec} \tag{1}$$

where

$$L_{Edd} = 4\pi G M m_p c/\sigma_T \tag{2}$$

is the Eddington luminosity, σ_T is the Thomson scattering cross section, m_p is the proton mass, M is the mass of the central black hole, G is the gravitational constant and c is the speed of light.

Since $L/R > 10^{30}$ erg/sec the PAG emit a flat comptonized spectrum with exponential roll-off energy and spectral index on the order of $E \cong 160$ KeV and $\alpha \cong 0$ respectively (Zdziarski 1988). In this context the observed redshifted PAG exponential roll-off energy and roll-off spectral index are consistent with the observational constraints associated with the residual CXB (Leiter & Boldt 1982) given by

$$23\ \text{KeV} \leq E/(1+z) \leq 35\ \text{KeV}, \qquad 0 \leq \alpha \leq 0.2 \tag{3}$$

For Eddington limited accretion the initial PAG black hole mass M_i increases exponentially to M_{PAG}. This is given by

$$M_{PAG} = M_i \exp(A_{PAG}\ \Delta t_{PAG}) \tag{4}$$

$$A_{PAG} = 30\ (\ (1 - \epsilon)/\epsilon\ )\ . \tag{5}$$

In the above Δt_{PAG} is the Eddington limited lifetime of the PAG phase in units of $(2/3H_o) = 1.3 \cdot 10^{10}$ years, corresponding to H_o=50 km/(sec-Mpc), and $\epsilon \lesssim 0.3$ is the accretion disk mass-energy conversion efficiency (Thorne 1974).

If z_{MAX} is the maximum redshift associated with the onset of the PAG and z_{MIN} is the minimum redshift for this population, corresponding to the associated onset of daughter AGN such as Seyfert galaxies, then the relationship between light-travel lookback times $t_{MAX,MIN}$ in $(2/3H_o)$ units and redshifts $z_{MAX,\ MIN}$ is given by

$$t_{MAX\ ,\ MIN} = [\ 1 - (1+z_{MAX\ ,\ MIN})^{-3/2}\ ]\ . \tag{6}$$

In this context the total PAG lifetime is given by the relation

$$\Delta t_{PAG} = (\ t_{MAX} - t_{MIN}\ )\ . \tag{7}$$

For $z_{MIN} < z < z_{MAX}$, the surface density of PAG sources is given by

$$\sigma_{PAG} = [\ \sigma(t_{MAX}) - \sigma(t_{MIN})\ ]\ \text{sources/deg}^2 \quad (8)$$

$$\sigma(t) = (1.75\ 10^4 \cdot [N_0(PAG)/10^{-4}\ Mpc^{-3}])\ \ [\ t+3(1-t)^{2/3}-3(1-t)^{1/3}\ ] \quad (9)$$

$N_o(PAG)\ Mpc^{-3}$ is the constant co-moving density of PAG, and observational constraints on the flucuations in the CXB (Hamilton, Helfand 1987) require the surface density of PAG sources in equation (8) to be greater than 5000 sources/deg.

The ensemble averaged proper bolometric PAG luminosity, emitted in the form of an X-ray spectrum during the Eddington limited PAG lifetime, is

$$L_{PAG}(t) = 13 \cdot 10^{45}\ (M_i/10^8\ M_o)\ \exp(\ A_{PAG}(t_{MAX}-t)\ )\quad \text{erg/sec.} \quad (10)$$

where M_i is in units of solar mass (M_o).

Using $\Omega = 1$ and $h_{50} = 1$, and equation (6) and (10) to obtain the PAG luminosity evolution function $L_{PAG}(z)$, the total PAG energy flux, in erg/cm^2 -sec-sr, contributed to the RCXB is

$$I_{PAG} = (3t_oc/8\pi)\ N_o(PAG)\cdot \int_{z_{MIN}}^{z_{MAX}} dz(\ L_{PAG}(z)/(1+z)^{-3.5}\ ) \quad (11)$$

where $t_o = 2/3H_o$.

The differential PAG energy flux in units of erg/cm^2 -sec-sr-erg, whose integral yields equation (11) is given by

$$I_{PAG}(E) = (3t_oc/8\pi)\ N_o(PAG)\cdot \int_{z_{MIN}}^{z_{MAX}} dz(\ L_{PAG}(z)\cdot S_{PAG}(E(1+z),\ \alpha)\ /(1+z)^{-2.5}\ ) \quad (12)$$

In (11) and (12) the Eddington limited PAG luminosity evolution function $L_{PAG}(z)$ is obtained from (6) and (10), and the Eddington limited PAG X-ray source spectral function $S(E,\alpha)$ is given by (Zdziarski 1988) as

$$S_{PAG}(E,\ \alpha) = [W_o^{\alpha-1}/\Gamma(1-\alpha)] \cdot E^{-\alpha}\exp(-E/W_o) \quad (13)$$

153 KeV $\leq W_o \leq$ 165 KeV, $0.07 \leq \alpha \leq 0.17$. Note that on the basis of HEAO-1 observations equation (11) obeys the constraint $I_{PAG} \lesssim 2.2\ 10^{-7}$ erg/cm^2-sec-sr.

II. SPECTRAL-LUMINOSITY EVOLUTION OF PAG INTO SEYFERT GALAXIES

At the end of the PAG lifetime the overall compactness parameter L/R of the black-hole/accretion disk dynamo system falls below 10^{30} erg/cm-sec and globally coherent dynamo acceleration processes for charged particles become dominant. Under these conditions the coherent accretion disk dynamo system can create localized regions of nonthermal electron-positron pairs above the accretion disk, which generate a broad band of nonthermal radiation including X-rays and gamma rays, and the PAG undergo spectral-luminosity evolution into Seyfert galaxies (Zdziarksi et al, 1990, 1991). To see this more specifically we convert the Compactness Parameter L/R (erg/cm-sec) into a dimensionless compactness quantity

$$l = (L/R) \cdot (\sigma_T/mc^3) \, , \tag{14}$$

When the appropriate fundamental constants are inserted

$$l = 2.3 \cdot 10^3 \cdot (L/LEdd) \; / \; (R_*/10) \tag{14-a}$$

where $R_* = R/r_G$, and $r_G = GM/c^2$ is the gravitational radius. Solving (14) for L/R we have

$$L/R = (3.8 \cdot 10^{28}) \cdot l \quad \text{erg/cm-sec.} \tag{14-b}$$

Equations (14-a,b) are used in the analysis which follows.

A. PAG State

In the case of an Eddington limited PAG there is no extended structure above the black-hole/ accretion disk dynamo and most of the hard radiation is emitted from a hot inner region of the disk of size on the order of 10 gravitational radii. Hence for a PAG it follows that $R_* \triangleq 10$, $L/LEdd \triangleq 1$. From (14-a,b) we see that this implies that the PAG dimensionless compactness is ~ 2300 which is equivalent to $L/R \triangleq 8.8 \cdot 10^{31}$ erg/cm-sec. Hence coherent nonthermal dynamo particle acceleration processes are inhibited (Cavaliere & Morrison 1980) and the Eddington limited PAG emits thermalized X-radiation (Zdziarski 1988) similar to that of the CXB as described in section I.

B. Seyfert AGN State

At the end of the PAG lifetime the Eddington ratio falls to $L/LEdd \lesssim 0.1$ and at the same time the black-hole/accretion disk develops extended structure above the accretion disk such that $R_*(\text{dynamo}) \triangleq 10^3$. The dimensionless compactness of the dynamo falls to values $\lesssim 23$ and $L/R \lesssim 10^{30}$ erg/cm-sec allows coherent dynamo particle acceleration processes to become dominant. The coherent, nonthermal particle acceleration processes in the black-hole\accretion disk dynamo running at such a low dimensionless compactness produce clouds of nonthermal electron-positron pairs above the cool regions of the accretion disk. Black-hole/accretion disk dynamo processes lead to hard photons that produce such clouds via pair cascades resulting from their interaction with soft photons radiated by the accretion disk (Begelman, Blanford, Phinney 1982).

$$\gamma_{hard} + \gamma_{soft} \text{ -----> } e^{+} + e^{-} .$$

Because of the incoherent nature of the photon-photon pair production process as a charged particle acceleration mechanism, these highly compact (i.e. size $R_{*} \cong 10$, dimensionless compactness $\lesssim 230$, $L/R \gtrsim 10^{31}$ erg/cm-sec) clouds of electron-positron pairs above the black-hole/accretion disk dynamo are not constrained by the coherent acceleration limitations associated with the $\sim 10^{30}$ erg/cm-sec criteria discussed in section I. Hence they can generate via Comptonization and Compton reflection the nonthermal X-ray and gamma ray emission spectra similar to that of Seyfert AGN (Zdziarski 1990, Zdziarski et al. 1991). In addition the Seyfert galaxies which emerge may emit Penrose Compton Scattering (PCS) gamma ray transients (Leiter 1980, Leiter & Boldt 1990) with time variabilty on the order of hours, which have a kinematic cutoff in the spectrum $\lesssim$ 3 MeV. In this context the OSSE/COMPTEL instruments on the Gamma Ray Observatory (GRO) are appropriate instruments to carry out further tests of this model.

III. THE PAG-SEYFERT SPECTRAL EVOLUTION MODEL FOR THE CXB

If the PAG-Seyfert spectral evolution occurs in a supply limited regime similar to that described by low luminosity galaxy evolution models (Murphy, Cohn, and Durisen 1991) , the supply limited luminosity evolution of Seyfert galaxies is given over the redshift region $0 \lesssim z \lesssim z_{MIN}$ by

$$L_{SEY}(z) = L_{SEY} \cdot f(z) \tag{15-a}$$

$$L_{SEY} = 13 \cdot 10^{45} \, (M_{PAG}/10^{8}) \, \lambda_{SEY} \quad \text{erg/sec.} \tag{15-b}$$

$$f(z) = [\{(1+z_{MIN})^{\beta} \cdot \phi(z_{MIN}-z) \cdot \phi(z-z_{ZMIN}+\Delta z)\} + \{(1+z)^{\beta} \cdot \phi(z_{MIN}-\Delta z-z) \cdot \phi(z)\}] \tag{15-c}$$

in (15), M_{PAG} is in solar masses, $\phi(z)$ is the step function and the $\beta \cong 2$ and $\Delta z \cong 3.7$ for the case of a supply limited accretion regime which is dominated by stellar mass loss mechanisms. Figure 1-a shows the total luminosity evolution function $L(z)$, $(0 \lesssim z \lesssim z_{MAX})$ where $L(z) = L_{PAG}(z) + L_{SEY}(z)$.

We assume that the Seyfert source spectral function $S(E,\alpha)$ has the observed Seyfert -0.7 power law structure given by

$$S_{SEY}(E,\alpha) = (0.083)/(1.6 \cdot 10^{-9}) \cdot (E/3)^{-0.7} \tag{15-d}$$

Then in a manner similar to the case of the PAG in (12) and (13), we calculate the differential energy flux from a superposition of Seyferts which have evolved from PAG at $z = z_{MIN}$ to the present epoch as given by

$$I_{SEY}(E) = (3t_0c/8\pi)\ N_0(SEY) \cdot \int_0^{z_{MIN}} dz\ L_{SEY}(z) \cdot S_{SEY}(E(1+z),\ \alpha)\ /(1+z)^{-2.5} \tag{15-e}$$

Padovani, Burg & Edelson (1990) suggest that the low value observed for the average Seyfert central black hole mass $\sim 2 \cdot 10^7$ Mo favors scenarios in which AGN activity occurs in recurrent bursts over time intervals $\sim 10^8$ years. We adopt this point of view and assume that supply-limited Seyfert AGN activity cycles "on-off" in a quasi-periodic manner related to internal galactic accretion instabilities (Shlosman, Begelman & Frank 1990). If the number of "on-off" cycles of the Seyfert galaxy from light travel look-back time t_{MIN} to the present epoch is given by "n", and the "on time" and "off-time" per Seyfert cycle are given respectively by Δt_{SEY-ON}, $\Delta t_{SEY-OFF}$ then

$$t_{MIN} = n \cdot (\Delta t_{SEY-ON} + \Delta t_{SEY-OFF})\ . \tag{16}$$

Because Seyfert activity cycles on and off stochastically, the observed co-moving density of Seyfert galaxies in the "on" state is equal to the product of the co-moving density of PAG times the probability of a Seyfert being "on" during t_{MIN}, viz:

$$N_0(SEY) = N_0(PAG) \cdot (\ (\ n\ \Delta t_{SEY-ON})\ /\ t_{MIN}\ ). \tag{17}$$

Note that (17) implies that $N_o(PAG) > N_o(SEY)$. In this context the mass of the Seyfert central black hole in the present epoch is given by

$$M_{SEY} = M_{PAG}\ (\ 1 + A_{SEY} \cdot n \cdot \Delta t_{SEY-ON}\ ) \tag{18}$$

$$A_{SEY} = (30\ L(SEY)/LEdd) \cdot (\ (1 - \epsilon)\ /\ \epsilon\ )\ . \tag{19}$$

IV. TECHNIQUES FOR SOLVING THE PAG-SEYFERT MODEL EQUATIONS

(a) We assume a $\gtrsim$ 10% foreground contribution to the CXB from Seyfert galaxies with no luminosity evolution (i.e. $f(z) = 1$ in equation (15-c), and the inputs:

$N_o(SEY) \gtrsim 2\ 10^{-4}\ Mpc^{-3}$, $M_{SEY} \cong 2 \cdot 10^7\ M_o$,

$L(SEY)/LEdd \gtrsim 10^{-2}$, $\Delta t_{SEY-ON,OFF} \lesssim 10^8$ years .

Then we use the Newton-Raphson variation method to solve equations (1)-(19) to determine an initial range of acceptable output parameters, assuming no Seyfert evolution (i.e. f(z) = 1) in (15-c). With the above inputs we calculate the outputs:

$z_{max} \gtrsim 6, \quad z_{min} \gtrsim 4, \quad No(PAG) \gtrsim 10^{-3},$

$M_i \cong 10^4 M_o, \quad \Delta t_{PAG} \cong 5\ 10^8$ years, $\langle L_{PAG} \rangle \cong 10^{45}$ erg/sec

(b) Using the parameters determined above, and now taking into account the full Seyfert galaxy luminosity evolution f(z) given in equation (15-c), we calculate the foreground Seyfert differential energy flux $I_{SEY}(E)$ given by (15-e). Then the total differential energy flux is

$$I_{CXB}(E) = I_{PAG}(E) + I_{SEYFERT}(E) \tag{20}$$

Using (20), and varying the parameters about values determined in (a), an excellent fit of the PAG-SEYFERT spectral evolution model to the observed CXB differential energy flux (erg/erg-cm^2 -sec-sr)

$$I_{CXB}(E) = 5.7 \cdot (E/3KeV)^{-0.29} \cdot \exp(-E/40Kev) \tag{21}$$

over (3 KeV $\leq$ E $\leq$ 50 KeV) can be obtained as shown in figure 1-b.

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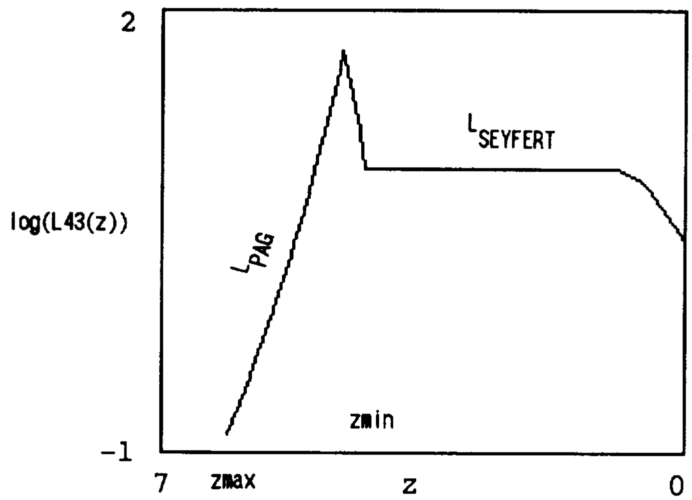

Figure 1-a. Logarithmic Plot of the Luminosity Function L43(z) (Associated With Eddington Limited PAG -- Supply Limited Seyfert Spectral Evolution) Is Similar to That of Low Luminosity Galaxy Evolution Models of Murphy, Cohn, & Durisen (1991)

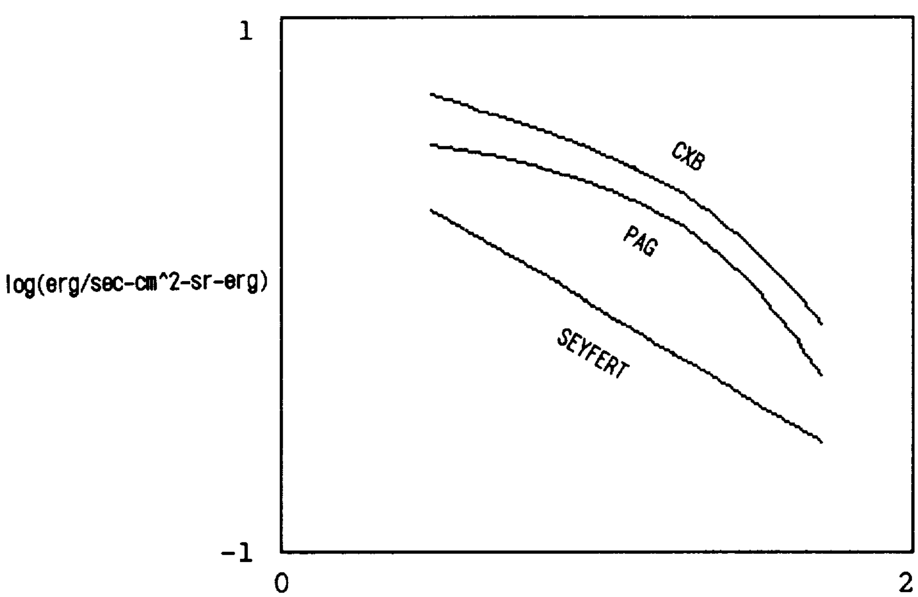

Figure 1-b. Model Fit of PAG + SEYFERT = CXB Spectra Within 2% Error Associated With: Luminosity Evolution Function L43(z) In Figure 1-a. And a 36% Seyfert X-ray Foreground At 3 KeV, zmax = 6.12, zmin = 4.46, $M8_i$ = 0.0001, ϵ = 0.1 W_0 = 153 KeV, α = 0.07, No(SEY) = 0.0004 1/Mpc^3, $M8_{Sey}$ = 0.23