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SPECTRAL EVOLUTION OF ACTIVE GALACTIC NUCLEI PENROSE COMPTON SCATTERING PROCESSES AND GAMMA RAY EMISSION FROM SEYFERT GALAXIES

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ABSTRACT

In black hole spectral evolution models for active galactic nuclei (AGN), present epoch Seyfert galaxies evolve from an earlier precursor active galaxy (PAG) stage at redshift $z \sim 7$ where they acted as the thermal sources responsible for the residual cosmic X-ray background (RCXB). The Seyfert galaxies which emerge in this context emit Penrose Compton Scattering (PCS) gamma ray transients on the order of hours with a kinematic cutoff in the spectrum $\lesssim$ 3 MeV. The EGRET/OSSE/COMPTEL/BATSE instruments on the Gamma Ray Observatory (GRO) are appropriate instruments to carry out further tests of this model by studying: 1) PCS gamma ray transient emission from individual galaxies and, 2) the possibility that present epoch PCS gamma ray emitting Seyfert galaxies contribute observable temporal variability to the excess diffuse gamma ray background component $\lesssim$ 3 MeV.

I. PRECURSOR ACTIVE GALAXIES (PAG) AND THE COSMIC X-RAY BACKGROUND

Black hole accretion disk dynamo processes are generally regarded as the central power source for AGN (Rees 1984). If such AGN begin their activity with Jeans mass $\gtrsim 10^6$ M⊙ black holes of pre-galactic origin then the X-ray radiation emitted during their lifetime will undergo the phenomenon of "spectral evolution" (Leiter & Boldt 1982; Boldt & Leiter 1986, 1987). When accretion disks are first formed at the onset of galaxy formation the accretion rate occurs at a high value of the luminosity/size compactness parameter $L/R > 10^{30}$ erg/cm-sec. Such high values of L/R generate dynamic constraints (Cavaliere & Morrison 1980; Guilbert, Fabian, & Rees 1983), which suppress nonthermal black hole accretion disk dynamo processes in favor of thermal processes. This causes the spectrum of X-ray radiation emitted by early AGN to be predominantly thermal.

Since the hard X-ray radiation from thermal processes in the PAG accretion disk comes from a region of ~10 gravitational radii, L/R can be written in terms of L/L_{Edd} as

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

where

$$L_{Edd} = 4\pi GMm_p c/\sigma_T \quad (2)$$

is the Eddington luminosity. In the Eddington limited precursor active galaxy (PAG) state, $L/L_{Edd} \cong 1$ implies that the compactness parameter L/R is greater than 10^{30} erg/cm-sec and X-ray radiation is emitted in form of a thermal, flattened Comptonized spectrum similar to that of the residual cosmic X-ray background (RCXB) (Zdziarski 1988).

At the end of the PAG lifetime the Eddington ratio falls to $L/L_{Edd} \cong 0.01$ (i.e. $L/R \lesssim 10^{30}$ erg/cm-sec) and nonthermal black hole accretion disk dynamo processes (Rees, Begelman, Blandford, & Phinney 1982) become important, generating a broad band of non-thermal radiation including X-rays and gamma rays. Under these conditions the PAG spectrally evolve into Seyfert galaxies.

Spectral evolution of PAG into Seyfert galaxies is a consequence of the decrease with age of the compactness parameter associated with the central black hole accretion disk dynamo power source. Taking such spectral evolution into account leads to the possibility that the residual cosmic X-ray background (RCXB) is made up of a superposition of discrete PAG sources at high redshift, where the co-moving number density of PAG required is comparable to that of present epoch Seyfert galaxies.

II. THERMAL COMPTONIZATION IN BLACK HOLE ACCRETION DISK SOURCES

If Precursor Active Galaxies (PAG) are the source of the residual cosmic X-ray background (Leiter & Boldt 1982) then observational constraints (Boldt & Leiter 1987) require that they:

a) originate at a redshift $z \sim 7$ with a luminosity in X-rays $\sim 10^{45}$ erg/sec,

b) have a constant comoving density $\cong 4 \times 10^{-4}$ MPC^{-3},

c) have a lifetime $\cong 5\times10^{8}$ years during which they emit a thermal comptonized spectrum like that of the RCXB.

d) satisfy the observational constraint that the sky surface density of discrete RCXB sources is $\gtrsim 5000$ sources/deg^2.

Taking electron-positron pair production effects into account, Zdziarski (1988) showed that the energy source of such PAG could be described in terms of comptonization of thermal cyclo-sychrotron photons in equipartion magnetic fields around a spherically accreting $\gtrsim 10^6$ solar mass black hole.

In general it is physically more realistic to expect the accreting plasma around a black hole in a PAG to possess enough angular momentum to form a disk. However, when the proton thermal energy is comparable to the proton gravitational energy in the hot optically thin inner region of an accretion disk, the plasma inflow resembles dissipative spherical accretion Meszaros (1975) in terms of dynamic quantitites averaged over spherical shells. In this context spherical accretion can be used as an approximation in describing the hot optically thin inner region of an accretion disk where the accreting plasma forms into a quasi-spherical torus.

From this point of view the spherical accretion calculation of Zdziarski (1988) can be used as a first order approximation to describe the quasi-spherical accretion flow in the hot inner region of the accretion disk as long as there are no internal or external sources of soft photons present stronger than that produced by thermal cyclo-synchrotron radiation generated in equipartition magnetic fields.

The PAG internal soft photon constraint required for the validity of this calculation can be addressed by noting that Dermer (1988) has shown that for the case of a two-temperature hot inner region of an accretion disk additional internal soft photons, generated by synchrotron emission from the positrons emitted by pion decay, will be negligible compared to thermal cyclo-sychrotron photons as long as the proton temperature is is constrained to remain $kT_p \lesssim 20$ MeV. Since the proton cooling rate is increased as a result of more frequent Coulomb interactions associated with the copious production of electron-positron pairs though photon-photon absoption, this constraint will most likely be satisfied for dimensionless PAG accretion rates $\dot{m} \gtrsim 1$, above those values which allow a stable optically thick annulus to form inside of the hot inner region, Begelman, Sikora, & Rees (1986).

The external soft photon constraint required in this context can be addressed by calculating the ratio (I_s/I_x) of the externally generated soft photon flux I_s, from the optically thick regions of the accretion disk to that of the X-ray flux I_x emitted by the hot inner region of the accretion disk.

The Zdziarski (1988) PAG calculation is insensitive to the presence of external sources of soft photons of energy E_s other than that generated by thermal cyclo-synchrotron processes if

$$I_s/I_x < (I_s/I_x)_{max} = (E_s/E_x)^{1-\alpha} = 1.3 \times 10^{-5} \quad (3)$$

where $E_x \sim 100$ KeV, $E_s \sim 0.01$ KeV, and $\alpha \sim 0.3$ is the low energy spectral index of the comptonized PAG spectrum (Zdziarski, A. A. (1989) private communication).

For an optically thick accretion disk with a hot, optically thin, quasi-spherical two-temperature inner region, Novikov & Thorne (1972), White & Lightman (1988), we find that

$$I_s/I_x \sim (r_x/r_s)^3 \quad (4\text{-a})$$

where

$$r_x \sim 10\, r_G \,, \quad r_s \sim 5 \times 10^3 (\dot{M}_{\odot} / M_8)^{2/3} r_G \,, \; r_G = GM/c_2 \quad (4\text{-b})$$

with $\dot{M}_{\odot}$ in units of solar masses per year.

Then since

$$\dot{M}_{\odot} / M_8 = (1.3/6\epsilon) [L/L_{Edd}] \,, \qquad \epsilon < 1 \quad (5)$$

equations (3), (4-a,b) and (5) imply that

$$L/L_{Edd} > 10^{-1} \epsilon \quad (6)$$

which is automatically satisfied by the Eddington limited PAG which make up the residual cosmic X-ray background.

In this context the source of PAG is due to thermal comptonization processes in the hot (kT_e 100 KeV) optically thin, quasi-spherical inner region of an accretion disk around a centrally rotating black hole, and the Zdziarski (1988) can be used to calculate the comptonized spectrum from the hot, spatially thick, inner region of the PAG accretion disk.

III. SEYFERT GALAXIES WHICH SPECTRALLY EVOLVE FROM PAG EMIT PENROSE COMPTON SCATTERING (PCS) GAMMA RAY TRANSIENTS ≲ 3 MEV

At the end of the PAG lifetime, a reduction in the compactness Luminosity/Size parameter dynamically causes the PAG to spectrally evolve into active galactic nuclei (AGN), which have the canonical nonthermal x-ray spectrum associated with Seyfert galaxies and an average Seyfert black hole mass $M_s = 2 \times 10^7 M_{\odot}$.

Since the total accreted black hole mass divided by the inital PAG black hole mass is greater than 1.5 for these Seyfert galaxies, their central black holes are spun-up into a canonical Kerr state with angular momentum density a/M = 0.998 (Thorne 1974). This allows the turbulent, hot, optically thin inner region of the accretion disk to penetrate the ergosphere. Hence for Seyfert galaxies which spectrally evolve from the PAG the extraction of black hole rotational energy in terms of Penrose Compton Scattering (Piran & Shaham 1977; Leiter 1980) can occur.

The ergosphere around a Kerr black hole has the fundamental property that inertial frames are dragged around by the rotation of the black hole with respect to an inertial frame at infinity. With respect to a "local non-rotating inertial frame" in the ergosphere, electrons within a blob of hot plasma in the Penrose target zone bounded by the marginally bound r_{mb} and marginally stable r_{ms} orbit will undergo Compton Scattering with blueshifted photons entering the ergosphere. The blueshifted photon energy in the target zone is 10 to 30 time higher than the energy of the photons emitted from the hot, optically thin inner region of the accretion disk. For $\sim$ 100 KeV photons injected into the target region, blueshifting will cause electrons in a local nonrotating inertial frame in the target region to Compton scatter with photons $\gtrsim$ MeV. The average proper time that the plasma blob spends orbiting within the target region between the radii r_{ms} and r_{mb} in the ergosphere, when redshifted to an observer at infinity, is the observed PCS transient gamma ray emission time. It can be shown to be

$$\Delta T_{PCS} \cong 10 \text{ hours } (M_S/(10^8 M_\odot)) \quad (7)$$

For Compton scattering in the ergosphere to be a Penrose Process the recoil electron has to be injected into the canonical Kerr black hole in a negative energy retrograde orbit opposing the black hole's rotational motion. The kinematic requirement for this to occur is that the retrograde recoil electron must be given a velocity boost of at least half the speed of light. This requires the blueshifted photon to have an energy $\gtrsim$ 1/2 MeV on the order the the rest energy of the recoil electron. When this occurs the $>$ MeV Penrose Compton Scattered (PCS) photon is ejected from the ergosphere without being re-redshifted since it picks up energy from the rotational energy from the Kerr black hole).

Seyfert galaxies operator at $\sim$ 1% of their Eddington luminosity and the steady state MeV gamma ray luminosity from them is an order of magnitude less than this. Hence the optical depth to photon-photon absorption (Heterich 1974, Svenson & Zdziarski 1989) in an ergospherical region R $\sim$ 3 gravitational radii is less than unity since

$$\tau_{\gamma\gamma} \gtrsim (2.5)\ L(MeV)_{45}/R_{15} \qquad (8)$$

$$\gtrsim 0.25\ L_{45}/R_{15} \qquad (9\text{-a})$$

$$\gtrsim 0.0025\ L_{Edd_{45}}/R_{15} < 1 \qquad (10\text{-b})$$

and the stochastically emitted PCS gamma ray transients escape from the ergosphere.

PCS gamma ray transient emission processes from Seyfert Galaxies have the following observational signatures (Leiter 1980; Piran, Shaham, 1977):

(a) PCS gamma ray spectra are flat over the energy range 300 KeV $\leq$ E $\leq$ 3 MeV with an upper cutoff energy $\leq$ 3 MeV strongly controlled by the Penrose Compton injected electron rest mass,

(b) PCS gamma ray emission transients occur stochastically with emission times $\sim$ 10 $M_s/(10^8\ M_\odot)$ hours,

(c) PCS gamma ray emission occurs within a solid angle bounded above and below the equator of the Kerr black hole accretion disk by a $\sim$40 degree angle (see figure 1).

IV. TEMPORAL VARIABILITY IN THE $\leq$ 3 MEV DIFFUSE GAMMA RAY BACKGROUND DUE TO PENROSE COMPTON SCATTERING (PCS)

For observations of the diffuse gamma ray background flux restricted to small pixels of the sky, let "N" be the total number of contributing Seyfert galaxies and "S" be the average gamma ray flux of their normal steady state spectrum. Of these N galaxies a subset "n" will emit, in addition to their normal steady state spectrum, a transient $\leq$ 3 MeV component of PCS gamma radiation with an average flux "s", where the dynamics of the PCS gamma ray transient process (Leiter 1980) imply that

$$n \simeq \epsilon N \quad \text{where} \quad \epsilon \sim 0.01 \qquad (10)$$

$$s \simeq \eta S \quad \text{where} \quad \eta \sim 10$$

Then the total Seyfert galaxy contribution to the diffuse gamma ray flux observed within this restricted field of view given by

$$\sum = (NS + ns) = (NS + \sigma) \qquad (11)$$

will contain a temporal variability due to PCS gamma ray transients $\leq$ 3 MeV occurring in σ = ns. Taking into account the 5/2 power law associated with making a Euclidian assumption on

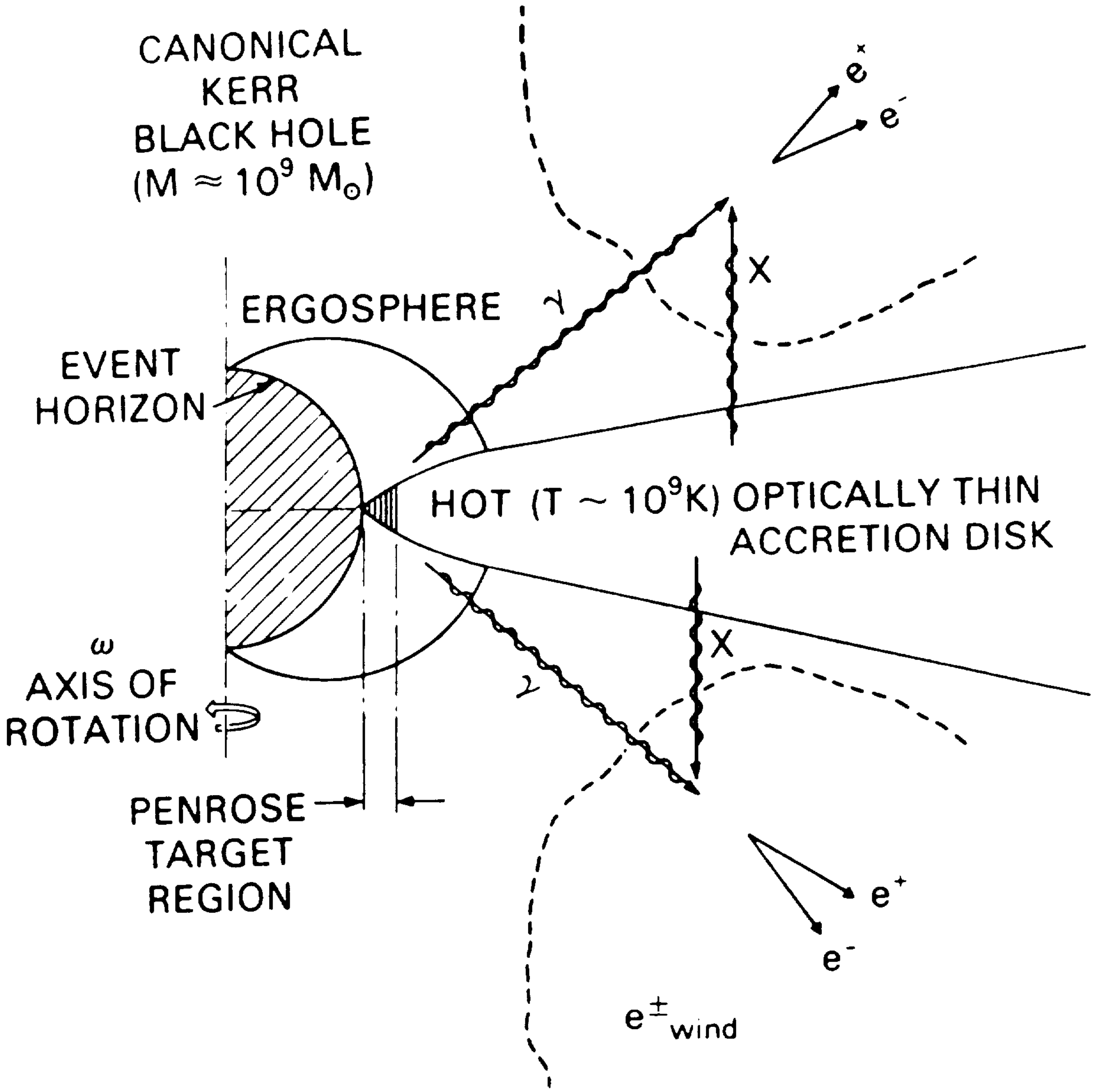

Fig. 1. An optically thin accretion disk with a hot, turbulent inner region, surrounds a massive Kerr black hole, $M_8 \gtrsim 1$, $a/m \lesssim 0.998$. Hot plasma blobs and blue shifted photons are injected sporadically into the Penrose target region ($r_{mb} < r < r_{ms}$) and cause PCS to occur. The resultant γ-ray bursts are focused into an angle of $\theta_{PCS} \simeq 40$ above and below the equator, and range over ~ 300 keV to ~ 2.7 MeV.

the log N - log S relationship, we find the fractional PCS photon counting fluctuation associated with (10) and (11) as

$$\delta(\Sigma)/\Sigma = \delta(\sigma)/(NS + \sigma) = [1/3^{1/2} (N/N')^{1/6}] [\epsilon^{1/2}\eta/(1 + \epsilon\eta)]] / N^{1/2} \tag{12}$$

where N is the total number of contributing Seyfert sources, and N' is the number of resolved Seyfert MeV gamma ray sources.

If N' is taken to be on the order of the number of Seyfert MeV gamma ray sources expected to be resolved with the Gamma Ray Observatory (Bignami (1989), and N is taken to be on the order of the number of AGN resolved in the Einstein Observatory high sensitivity survey, the ratio N'/N is

$$N'/N \gtrsim 10^{-4} \tag{13}$$

Using (13) to evaluate (12) gives

$$\delta(\Sigma)/\Sigma \gtrsim 3/N^{1/2} \tag{14}$$

A practical experiment using the Gamma Ray Observatory (GRO) to detect PCS induced temporal variability in the $\leq$ 3 MeV diffuse gamma ray background is one where flux measurements observed within a solid angle Ω deg^2, and separated by time intervals $\geq$ days, are compared for data accumulated over time intervals $\geq$ hours.

Assuming an excess component of $\leq$ 3 MeV gamma ray photon flux greater than 10^{-2} $cm^{-2}sec^{-1}sr^{-1}$ Webber, Lockwood, Simpson (1981), the number C of photon counts in this excess component is greater than 0.01 cm^{-2}-deg^{-2}-hr^{-1}. For an effective 1 MeV detector area of 50 cm^2 typical of GRO/COMPTEL/OSSE, the statistical photon counting error in a 3 hour measurement is

$$\delta C/C = (0.3*50*\Omega)^{-1/2} = 0.8\ \Omega^{-1/2} \tag{15}$$

In this context PCS induced temporal fluctuations in the < 3 MeV diffuse gamma ray background are observable if

$$\delta(\Sigma)/\Sigma > \delta(C)/C \tag{16}$$

Using (14), (15) in (16) we find that GRO/COMPTEL/OSSE will be able to observe PCS-induced temporal variability in the $\leq$ 3 MeV diffuse gamma ray background if the total number of contributing Seyfert galaxies per square degree is

$$(N/\Omega) < 14\ deg^{-2} \tag{17}$$

This is a physically reasonable constraint for Seyfert AGN since: (a) the High Sensitivity Survey (HSS) for X-ray emitting AGN performed by the Einstein Observatory has shown that as few as$\sim$10 sources per square degree can account for$\sim$20% of the RCXB at 3 KeV, (b) further measurements with HEAO 1 imply that these AGN sources may also be able to account for as much as 100% of the CXB for energies greater than 100 KeV. Hence it is quite probable that galaxies satisfy the criteria (17) required for GRO/COMPTEL to be able to observe the PCS-induced temporal variability in the $\leq$ 3 MeV diffuse gamma ray background

V. CONCLUSIONS

We have discussed a black hole spectral evolution model for AGN in which the majority of present epoch Seyfert galaxies have spectrally evolved from an earlier epoch of Precursor Active Galaxies (PAG) at redshift $z \sim 7$, a superposition of which acted as the source of the residual cosmic X-ray background (RCXB). As a by-product the process of Spectral Evolution the Seyfert galaxies which evolve from PAG contain canonical rotating Kerr black hole accretion disk dynamo systems which, in addition to emitting a broad band of nonthermal radiation typical of Seyfert galaxies, stochastically emit Penrose Compton Scattering (PCS) gamma ray transients from the ergosphere of the Kerr black hole.

These PCS gamma ray transients occur stochastically and:

(a) are observed over time intervals$\sim$10 hours M_8

(b) have a flat spectrum over 300 KeV $\leq$ E $\leq$ 3 MeV with a universal cutoff $\leq$ 3 MeV,

(c) are focused into a "Penrose focusing angle" $\sim$ 40 degrees above and below the plane of the Kerr black hole accretion disk system.

Since Seyfert galaxies tend to operate at $\sim$ 1% of their Eddington luminosity, the photon-photon absorption optical depth for PCS gamma rays is less than one and they escape to infinity where they can be observed.

OSSE and COMPTEL on the Gamma Ray Observatory are appropriate instruments to carry out further tests by studying:

(a) PCS gamma ray transients from individual Seyfert galaxies whose orientation allows the Gamma Ray Observatory to fall within their respective Penrose focusing angles and,

(b) the possibility that present epoch PCS emitting Seyfert galaxies contribute observable temporal variability to the excess diffuse gamma ray background $\leq$ 3 MeV.

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DISCUSSION

Jim Kurfess:

Why does the Pemrose Compton Scattering (PCS) model for AGN's require transient accretion of material, and not also operate in a steady-state mode?

Darryl Leiter:

Plasma containing electrons must have a tangential velocity in the Penrose Target region, between the marginally bound and marginally stable orbits in the ergosphere, for PCS to occur. This can only occur through transient, accretion via instabilities in the inner disk region.

Alice Harding:

What is the timescale for spin up of the black hole and does it depend on the angular momentum of the accreting material?

Darryl Leiter:

The $a/M = 0.998$ spin-up limit occurs when black hole mass doubles due to disk accretion. For efficiencies greater than 10%, this corresponds to $t > 10^8$ years if accretion occurs at less than the Eddington limit.

Chuck Dermer:

Does your model apply to solar-mass black-hole sources such as cygnus X-1. Also, what correlations do you predict between the X-ray and gamma-ray luminosities during a gamma-ray outburst?

Darryl Leiter:

Since $A/m = 0.998$ will take $> 10^8$ years for an efficiency of 10% and sub-Eddington luminosity, massive AGN galactic black hole are more likely to be spun-up than solar mass objects like CYG-X1. Only if X-ray flaring in the inner disk region is tied to disk instabilities will a correllation occur between PCS gamma-rays and X-ray flares.