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PRECURSOR ACTIVE GALAXIES AND THE COSMIC X-RAY BACKGROUND

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ABSTRACT

It is argued that the cosmic X-ray background (CXB) is not dominated by sources that are usual active galaxies or quasars. A comparable number of objects, young galaxies at $z \lesssim 4$ containing massive black holes surrounded by hot optically thin accretion disks, constitute the precursor active galaxies (PAG) postulated here for producing the thermal type spectrum required for the CXB. An evolutionary track for such PAG objects is described which would lead to the active galaxies observed as individual non-thermal sources. Unresolved emission from active galaxies at $z < 1$ could then readily account for most of the non-thermal background observed in the gamma-ray band.

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Data on the isotropic extragalactic X-ray background (> 3 keV) obtained with the HEAO-1 A2 instrument[1] yield that the spectrum over the energy band of maximum flux is well described by a thermal model involving an optically thin hot plasma at an observed temperature of a half-billion degrees ($kT = 40 \pm 5$ keV). However, the spectra for known strong X-ray sources in the present epoch (i.e. active galaxies, clusters of galaxies) obtained with the same HEAO-1 instrument[2,3] indicate that similar objects at high redshifts would not lead to a natural explanation for most of this background. Yet, deep-field exposures to soft X-rays (< 3 keV) with the HEAO-2 Einstein Observatory[4] suggest that the number of dim point sources could be ample. This would imply that either (1) these dim sources are generally unrelated to relatively bright nearby objects or (2) they represent an earlier stage in the evolution of sources such as those in the present epoch. Possible short-lived thermal X-ray emission by galactic winds peculiar to an earlier epoch has been defined theoretically by Bookbinder et al.[5]. As pointed out by Leiter[6], however, the evolution of the X-radiating system associated with an active galactic nucleus involving a massive compact object could be pronounced, thereby obviating the need for postulating new sources. In this connection, we pursue the suggestion by Carr[7] that most of the cosmic X-ray background (CXB) arises from thermal X-ray emission associated with black hole accretion disks for compact objects that were formed before galaxies. As we shall discuss here, however, we favor a model where the onset of significant X-radiation is phased within the epoch of galaxy formation and where the interaction between a massive black hole of pregalactic origin and a young galaxy could eventually lead to the formation of a non-thermal source as well.

The spectral characteristics of the composite X-ray flux associated with the extragalactic sky is shown in Figure 1; the spectral density for the overall surface brightness is plotted here as a function of photon energy. The curve labelled "total flux" is the best-fit thermal spectrum for the CXB measured with the HEAO-1 A2 instrument[1]. The power-law "A" represents the composite X-radiation from dim sources directly detected in deep exposures with the HEAO-2 Einstein Observatory[4] under the idealization that they all have power-law spectra of energy index $\alpha \approx 0.7$. The power-law "B" represents the composite flux from active galaxies such as the bright ones measured with HEAO-1[3], assuming no evolution in the integration to $z = 1$. An extrapolation of "B" to the gamma-ray regime (> 0.5 MeV) suggests that such sources could well account for most of the cosmic gamma-ray background[8] observed. However, as exhibited by Figure 1, they account for a relatively small part of the CXB.

For a survey limit of 2.6×10^{-14} ergs cm^{-2} s^{-1} (1-3 keV), the deep exposures with the HEAO-2 Einstein Observatory[4] yield 19 ± 8 extragalactic sources deg^{-2}, comparable to the number of quasars[9] brighter than $B \approx 20^m$. Assuming that these sources have power-law X-ray spectra of energy index $\alpha = 0.7$ and that the slope (a) of the log N - log S relation at the survey limit and above is greater than unity we obtain that these <u>observed</u> sources account for a percentage of the CXB which, at 3 keV, is given by $(\frac{a}{a-1})$ (7.1 ± 2.9)%. For Figure 1 we have used $a = 1.5$, as discussed by Giacconi et al.[4]. A subsequent direct determination[10] of the log N - log S relation for these dim sources with HEAO-2, however, indicates that the slope is steeper and could be closer to $a = 2$. Yet, the log N - log S relation for quasars must flatten[11] since the number brighter than $B = 22.5^m$ is less than ~ 50 deg^{-2}. If we assume that most of the CXB arises from quasars, we thereby appear to have a paradox for the required source count. Extrapolating the HEAO-2 source count via a log N - log S relation of constant slope (a) for objects dimmer than the survey limit, we obtain that the number of sources required to fully account for the background is $\sim 2 \times 10^3$ sources deg^{-2} for a = 1.5 and $\sim 10^3$ sources deg^{-2} for a = 2. Since these estimates are an order of magnitude larger than the number of usual quasars considered we are led to examine the possibility that the onset of thermal X-radiation preceeds the formation of non-thermal radiating components.

In general, the thermal type spectrum observed for the CXB can be associated with two kinds of black-hole accretion disk radiation mechanisms, viz:

a) Bremsstrahlung from an optically thin hot plasma of the disk.[7,12]

b) Unsaturated Comptonization[13] of soft photons by hot thermal electrons in the inner region of the disk, optically thin to absorption, where e^+e^- pair production cooling effects[14] can limit the electron temperature (T_e) to $T_e \approx 2 \times 10^9$ K for a source luminosity close to the Eddington limit.

As indicated later, the consistency of our model requires that the main sources of the CXB radiate at a level close to the Eddington luminosity limit. Since case (a) is constrained to luminosities less than about one percent of this limit[12], we concentrate on case (b). For reasonable sizes of the emitting hot optically thin inner disk region[13] (i.e. $\lesssim 10^2$ GM/c^2), e^+e^- cooling[14] provides a thermostat whereby kT $\lesssim$ 0.2 MeV, implying that z $\lesssim$ 4 for most such sources of the CXB. The same condition applies to case (a) since the Gaunt factor for optically thin thermal bremsstrahlung emission at kT $\gtrsim$ 0.2 MeV would fail to provide an acceptable fit to the CXB spectrum observed (R. Shafer, private communication). Therefore, this suggests that a black-hole disk accretion phase earlier than that corresponding to z $\approx$ 4 is absent and that we should restrict the model accordingly. For photon energies much less than the observed redshifted value of kT ~ 40 keV the CXB exhibits an effective energy spectral index[1,3] $\alpha \approx 0.4$. In this restricted regime, the

CXB spectrum may be adequately synthesized by a superposition of sources having power-law spectra with $\alpha \approx 0.4 \pm 0.1$ (G. De Zotti, private communication). For a source temperature five-fold higher than that observed for the CXB (i.e., (1+z) 40 keV = 200 keV), case (b) provides spectral indices within this acceptance band for values of the Kompaneets parameter (i.e. $y \approx 1$-2) amply characteristic of the model[13]. For photon energies $E \approx kT$, all these power-law spectra are modified by the required exponential roll-off, viz: $\exp(-E/kT)$.

We start with Carr's suggestion that black holes are generated and evolve toward masses up to $\sim 10^9\ M_o$ by pregalactic processes beginning at $z > 100$. However, as already indicated, the thermostat associated with the temperature observed for the CXB would imply that these black holes develop significant accretion disks at $z \lesssim 4$. We note that prior to the formation of these disks, random pregalactic processes which involve spherical accretion are not expected to be efficient for X-radiation[15]. Therefore, we conclude that the X-radiation associated with accretion must be relatively unimportant until galaxy formation processes supply the matter associated with an ample accretion disk. Furthermore, pregalactic processes associated with random accretion should not cause appreciable spin-up of the black holes because the capture cross-section for negative angular momentum particles (i.e. opposite to the hole's spin) is greater than that for positive angular momentum[16]. Beginning at $z \lesssim 4$, within the epoch of galaxy formation, these massive black holes acquire significant accretion disks for the first time and become the "seeds" which distinguish precursor active galaxies (PAG) from galaxies which will evolve normally. These PAG sources of the CXB postulated here are characterized in Table 1 and will be explained in what follows. In this model, these PAG objects would be the thermal sources of the sort described by

Carr as required for the CXB, but necessarily cooler than previously considered (i.e. $kT \lesssim 0.2$ MeV). In the process of disk accretion on a time scale of $\sim 10^8$ years, however, the central massive black hole of a PAG could increase in mass by $\Delta M/M \gtrsim 1.5$ and be spun-up[17] to a "canonical Kerr hole". By this time black hole ergospherically induced electron-positron injection[6,18,19] could trigger and surge electromagnetic disk dynamo mechanisms[20,21]. Furthermore, the efficiency for energy transfer to the relativistic particles required for non-thermal radiation processes (e.g. synchrotron) could by then begin to increase appreciably, as the size of the acceleration region grows[22]. Hence, during transition, there may be some young active galaxies which are not yet sufficiently luminous non-thermal disk-dynamo synchrotron sources to be readily identified as such while their thermal disk X-ray emission is still large.

As pointed out by Thorne[17], the spin-up of a black hole via a radiating accretion disk reaches an equilibrium "canonical" value ($a/M \approx 0.998$) when the hole's mass increases by $\Delta M \approx 1.5$ M (initial). Assuming that the radiation efficiency (ε) is constant and that the luminosity (L) is proportional to the Eddington limit (L_{Edd}), this increase of mass is achieved in a time (Δt) after the formation of the accretion disk, given by

$$(\Delta t) \approx 4 \times 10^8 \, \varepsilon(1-\varepsilon)^{-1} R^{-1} \text{ years} \qquad (1)$$

where $R \equiv L/L_{Edd}$. Under such conditions the black hole mass and size increase exponentially with a characteristic growth time given by equation (1). More realistically (ε) changes during the accretion process. Initially, when $\varepsilon \approx 0.06$, this growth time could be as short as 3×10^7 years (i.e. for $R \approx 1$). At spin-up[17], however, $\varepsilon \approx 0.3$ and the characteristic time for further growth would be at least an order of magnitude longer (i.e. with $R < 1$). If the accretion rate is then limited by a high angular momentum configuration of remaining gas, such as in a spiral galaxy, we subsequently expect $R \ll 1$ and that any further growth within a Hubble time (i.e. $\sim 10^{10}$ years) is relatively minor. In support of this idea we note that the amorphous nature of the spiral galaxies associated with Seyfert nuclei may well be caused by a process which slowly feeds material from outer regions into the center[23].

By the time of spin-up, given by equation (1), the innermost stable orbit of the accretion disk has amply penetrated the ergosphere[24], and electron-positron injection processes associated with a canonical Kerr black hole are "switched on". The time (Δt) to reach this state is the effective lifetime of the PAG phase (see equation 1). This canonical state of spin is insensitive to small (< 10%) fluctuations in the matter accretion rate and the counter-torques due to radiation[17]. In this context, the evolution of a PAG into a system involving a canonical Kerr hole may be viewed as an essentially irreversible process. Such behavior is of the type needed for describing the observed evolution[25] whereby the sources of the CXB (e.g. PAG objects at $z \lesssim 4$) lead to the active galaxies observed at later epochs. Since a broad band of non-thermal radiation can eventually be generated at a relatively high efficiency[26] (i.e., at the expense of weakened thermal disk emission[20,21]), the thermal disk component could be masked for many of the brightest active galaxies, but might sometimes be observable. In this connection, it is interesting to note that the spectrum measured for the quasar 3C273 is consistent[27] with a substantial contribution from a thermal X-ray component at $T \gtrsim 10^9$ K, while the broad-band X-ray spectrum of QSO 0241+622 is incompatible with such a feature[28]. The PAG objects associated with Seyfert nuclei might involve galaxies where the amount of gas available for accretion from a low angular momentum configuration (e.g. in a central bulge) is not large compared with that of the initial black hole. In this situation (e.g. involving a spiral galaxy) we expect that a luminosity as high as 10^{47} ergs s^{-1} (i.e. Eddington limit for 10^9 M_O) could not last much beyond spin-up. For appreciably longer time scales we assume R<<1; the resulting active galaxies could thereby survive to be observed in the present epoch (e.g. as Seyfert galaxies) with much lower luminosities but with non-thermal spectra extending well into the gamma-ray band.

The thermal component of the CXB corresponds to a surface brightness of 2.0×10^{-7} ergs $(cm^2\ s\ sr)^{-1}$. For a Friedman cosmology with $q_O \lesssim 0.5$, H_O = 100 h km s^{-1} Mpc^{-1} and with most sources of the CXB at $z \approx 4$, the bolometric luminosity for the sum of all these sources, in their proper frame, is $\Sigma L \geq 8 \times 10^{52} h^{-2}$ ergs s^{-1}. Considering that the number of sources required for the CXB is N(CXB) $\approx (4\text{-}8) \times 10^7$, the implied average bolometric luminosity per source ($\bar{L} \geq 10^{45}$ h^{-2} ergs s^{-1}) can be readily associated with the massive central black-holes postulated here (i.e., $10^9 \gtrsim M/M_O > 10^7$) since the limit R > 0.3 is required to constrain the PAG lifetime from being much greater than ~ 10^8 years (see equation 1). If the central black-hole of a PAG were initially much less massive than ~ 10^7 M_O, then it would take substantially more than 10^8 years (beyond spin-up) to grow toward a mass where the luminosity could reach the level required here for sources at $z \approx 4$. Hence, such objects would not qualify as PAG sources of the CXB.

The total number of PAG objects N(PAG) making up the CXB is fixed by the model in terms of the local density of active galaxies. A fundamental aspect of this model is that the density of PAG objects in co-moving coordinates remains constant during the time (Δt) of spin-up and that the co-moving density of active galaxies after production equals that of the associated PAG objects. Under the assumption that the PAG population is produced at a look-back time corresponding to $z = 4$, N(PAG) is given by

$$N(PAG) = (1.4\text{-}8.9) \times 10^{8} \, \phi \, \Delta\tau \, h^{-3} \tag{2}$$

where the limits indicated correspond to $q_o = 0.5$ and $q_o = 0.01$ respectively, $\Delta\tau$ is the look-back temporal interval of the PAG phase in units of the age of the Universe, and ϕ is the co-moving density of PAG objects in units of 10^{-4} Mpc^{-3} (i.e., the value measured[22] for the local density of Seyfert galaxies and consistent with the local luminosity function for X-ray active galaxies[3] in the luminosity range $\sim 10^{42} - 10^{45}$ ergs s^{-1} (3-50 keV)). For $\phi \gtrsim 1$ and $\Delta\tau \approx 10^{-2}$ (i.e., corresponding to $\sim 10^{8}$ years) equation (2) indicates that the number of PAG objects could well be a value that matches the number of sources required for the CXB, viz: N(CXB) $= (4\text{-}8) \times 10^{7}$. The total mass involved in all the pregalactic black holes that precipitated these sources would be less than 10^{-4} of the known mass in galaxies. For the situation that most PAG objects are within $\Delta\tau = 10^{-2}$ at $z \approx 4$ we note that $\Delta z < 8 \times 10^{-2}$ (1+z), assuring that the fractional spread in observed temperatures due to redshift would be less than 8%, compatible with the CXB spectral data.

In summary, the CXB could well be dominated by distant sources that are not usual active galaxies or quasars. Observations require that they be sources with a relatively low ratio of optical to X-ray luminosity (i.e., dominantly X-ray objects). PAG objects at $z \lesssim 4$ involving a massive ($10^{9} \gtrsim \frac{M}{M_{o}} > 10^{7}$) black hole surrounded by a hot optically thin accretion disk radiating near the Eddington luminosity limit with an effective temperature ~ 2 x 10^9 K would meet this condition and readily yield the correct CXB spectrum and intensity. Furthermore, this model has the additional advantage of providing an evolutionary track which links both the CXB and the non-thermal gamma-ray background directly to active galaxies, implying that massive black holes are indeed associated with their internal dynamics (as suggested by X-ray observations[29] involving temporal variability). While the PAG sources of the CXB postulated here would have low optical continuum emission relative to quasars, strong emission lines comparable to those of quasars generated from a broad-line region photo-ionized[30] by the central X-ray source could lead to a direct identification of these objects. Since the average X-ray flux expected from a PAG is an order of magnitude below the survey limit for the HEAO-2 Einstein Observatory they would not be well represented in the "complete" sub-sample observed, but some of the dimmest unidentified objects detected should be considered candidates.

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FIGURE CAPTION

Figure 1 Spectral density for the surface brightness of the extragalactic X-ray sky as a function of photon energy. The curve labelled "total flux" is the best-fit thermal spectrum (kT = 40 keV) for the background measured by Marshall et al[1]. The power-law "A" represents the composite flux due to sources detected above the survey limit in the HEAO-2 deep exposures by Giacconi et al.[4]. The power-law "B" represents the composite flux from active galaxies with $z \leq 1$, based on the local luminosity function determined[3] with HEAO-1 A2 and assuming no evolution, with $q_0 = 0$. The dashed lines are extrapolations.

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TABLE 1: PAG SOURCES OF THE CXB

1. Central Mass: $M_9 \lesssim 1$ ($M_9 \equiv 10^{-9}\, M/M_{o}$)

2. Black-hole Specific Angular Momentum: $0 \leq a/M < 0.998$ ($a = J/M$)

3. Luminosity (10^{47} ergs s^{-1}): (0.4 - 1.3) M_9

4. Number: (4 - 8) x 10^7

5. Thermal Characteristics

   a) Temperature: 2 x 10^9 K

   b) Size: $\lesssim 10^2\, GM/c^2$ = (2 x $10^{16}\, M_9$) cm

   c) Emission Mechanism: Unsaturated Comptonization (with Kompaneets parameter y = 1 - 2)

6. Redshift(z): 4

7. Redshift Spread (Δz): 0.3 (q_o = 0.01)
   0.4 (q_o = 0.5)

8. Composite Luminosity (10^{54} ergs s^{-1}):* 1.4 (q_o = 0.01)
   0.3 (q_o = 0.5)

9. Co-moving Density (10^{-4} Mpc^{-3}):* 1 (q_o = 0.01)
   7 (q_o = 0.5)

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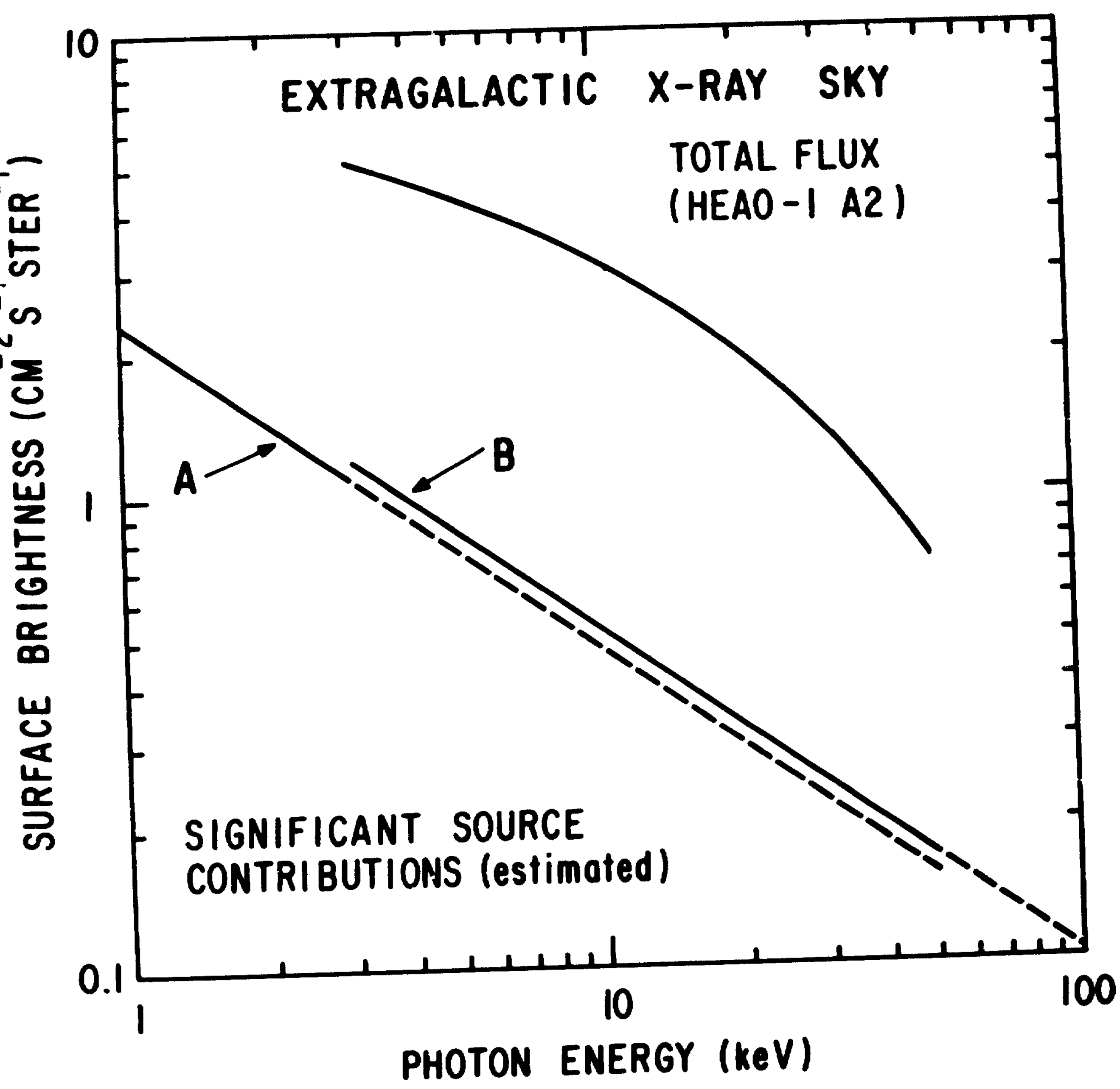
*For $h = H_o/(100\ kms^{-1}\ Mpc^{-1}) = 0.5$

H_o = Hubble constant q_o = deceleration parameter



EXTRAGALACTIC X-RAY SKY
TOTAL FLUX
(HEAO-1 A2)
A
B
SIGNIFICANT SOURCE
CONTRIBUTIONS (estimated)
SURFACE BRIGHTNESS (CM⁻² S⁻¹ STER⁻¹)
10
1
0.1
1
10
100
PHOTON ENERGY (keV)