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AS A MEASURE OF HISTORY**

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The Cosmic X-ray Background As A Measure of History

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Analysis of the cosmic X-ray background within the context of accretion driven AGN indicates that most black hole galactic nuclei must be dormant at present but suggests that they were X-ray bright during a brief epoch signaling an early phase of galaxy formation.

I. INTRODUCTION

There are only two bands of the electromagnetic spectrum where the sky is dominated by a clearly isotropic extragalactic background. The most celebrated is the microwave band [1] in which resides the 2.7°K black body relic radiation cooled from an early stage of the expanding universe when its energy equivalent mass density exceeded that of ordinary matter. The other is the X-ray band [2] where we find a well defined component associated with more recent epochs in which subrelativistic matter dominates. This CXB (Cosmic X-ray Background) has a characteristic photon energy corresponding to an equivalent Boltzmann temperature of $\sim 3 \times 10^8$ °K. Since the Planck spectrum of the 2.7°K background is undistorted, Compton scattering with ionized matter must be minimal. Hence, there is not an extensive intergalactic plasma contributing to the CXB; rather, the CXB is primarily from unresolved discrete sources.

The X-ray luminosity density in the present-epoch universe is mainly due to galaxies with manifestly active nuclei [3] even though such objects represent less than 1% of all galaxies. Based on general energetics arguments Daly [4] has emphasized that producing the CXB via accretion-

powered black hole AGN (Active Galactic Nuclei) is more tenable than doing so via other plausible scenarios, at least for an underlying cosmology corresponding to $\Omega = 1$. As we shall exhibit, the CXB flux then provides us with a revealing measure of the entire amount of accreted matter responsible for the growth of supermassive black hole galactic nuclei, integrated over *all* history.

2. COSMIC X-RAY BACKGROUND

The nearest X-ray bright AGN, at $z \leq 0.02$, exhibit a highly anisotropic distribution indicative of the underlying large-scale structure of the present-epoch space sampled [5]. Evidently then, a region of this size is still too small a portion of the universe for invoking the *cosmological principle* of spatial homogeneity and isotropy [6]. These foreground sources (within $z < 0.02$), however, make no more than a 1% contribution to the total flux of extragalactic X-rays [3]; the bulk of the *total* flux comes from the X-ray sources at much larger redshifts that constitute most of the CXB. This CXB is in fact remarkably isotropic [7], thereby demonstrating that the matter-dominated regime of the universe that it traces is indeed consistent with the cosmological principle.

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In effect, this validates our use of light travel look-back time as the appropriate “third dimension” coordinate for tracking the pronounced evolution of AGN sources of the CXB in cosmic time.

The principal component of the CXB intensity (I) has a spectrum in photon energy $[E(\text{keV})]$ which may be integrated in closed form. This energy spectrum ($I_E \equiv dI/dE$) characteristic of the CXB [8], based on observations over the 3-50 keV band with HEAO-1 proportional counters [9], is well described by

$$I_E = 7.8 E^{-0.29} \exp(-E/W) \text{ cm}^{-2}\text{s}^{-1}\text{sr}^{-1}, \quad (1)$$

where $W = 40 \text{ keV}$.

Results from HEAO-1 scintillators indicate that this spectrum [as given by eq.(1)] provides a good fit to the data up to $\sim 100 \text{ keV}$ [10] while recent CCD data from the ASCA X-ray observatory [11] show that it also remains valid all the way down to 1 keV , below which a softer component associated with our galaxy becomes evident. Expressed as $E(I_E)$ this spectrum peaks at $E = 28.4 \text{ keV}$. The total omnidirectional energy flux associated with integrating eq.(1) over all energies is

$$4\pi I = 2.8 \times 10^{-6} \text{ ergs s}^{-1} \text{ cm}^{-2}. \quad (2)$$

Considering the more inclusive background observed over a broader HEAO-1 bandwidth [10] increases this flux by only $\sim 20\%$ (for energies up to 0.5 MeV). Thus, the principal background component having the spectrum given by eq.(1) provides an especially good measure of the total CXB flux.

3. BLACK HOLE GROWTH

AGN are generally regarded to be powered by the accretion of matter induced by the gravity field of a massive black hole at the core [12]. The resulting bolometric luminosity (L_{bol}) is related to the rate of mass infall as

$$L_{\text{bol}} = \epsilon c^2 (dM/dt), \quad (3)$$

where ϵ is the efficiency for the conversion of accreted mass energy into radiation. In typical cases this luminosity is limited by the ambient mass fuel supply available for accretion. However, there is a limiting luminosity determined by the mass (M_{BH}) of the black hole itself. In particular, L_{bol} can not exceed the Eddington limit ($L_{\text{Edd}} = 1.26 \times 10^{38} M_{\text{BH}}/M_{\odot} \text{ ergs/s}$) where outward radiation pressure would cancel out the black hole's gravitational pull on infalling matter. The growth of black hole mass (M_{BH}) arising from accretion is given by

$$c^2 (dM_{\text{BH}}/dt) = L_{\text{bol}}/\epsilon - L_{\text{bol}}. \quad (4)$$

In terms of the Eddington ratio ($\lambda \equiv L_{\text{bol}}/L_{\text{Edd}} \leq 1$) this expression [eq.(4)] for mass growth becomes: $(dM_{\text{BH}}/dt) = M_{\text{BH}}/\tau$, where the effective e-folding time (τ) for black hole mass growth is then

$$\tau = \tau_{\text{Edd}} / [(\lambda (\epsilon^{-1} - 1))], \quad (5)$$

for $\tau_{\text{Edd}} \equiv Mc^2/L_{\text{Edd}} = 4.5 \times 10^8 \text{ years}$.

For a Schwarzschild (i.e., non-spinning) black hole $\epsilon \leq 0.06$. For a spun-up “canonical Kerr” hole $\epsilon \leq 0.3$ [13]. The spin-up time from a Schwarzschild to a canonical Kerr hole is comparable to the characteristic time (τ) for mass growth. We note that, for $\epsilon = 0.06 - 0.3$, $\lambda \tau = (3 - 20) \times 10^7 \text{ years}$. For canonical Seyfert AGN, $\lambda \ll 1$.

4. SURFACE BRIGHTNESS

The observed redshifted surface brightness (I) of an extended source is given by:

$$I_{\text{observed}} = (1+z)^{-4} I_{\text{source}}. \quad (6)$$

As stressed by Sandage and Perlmutter [14], this surface brightness relation is completely general for an expanding universe, independent of *both* Ω and H_0 . Considering discrete sources of number density (n) and mean luminosity (L) at cosmic time (t), we use eq. (6) to obtain the expression for

the surface brightness of the sky arising from emission integrated over the time history of interest, viz:

$$4\pi I = c \int (1+z)^{-4} nL dt. \quad (7)$$

Using the comoving density $n \equiv n(1+z)^{-3}$ in defining the comoving luminosity density as $q \equiv (n L)$ then yields the succinct and useful expression

$$4\pi I = c \int (1+z)^{-1} q dt. \quad (8)$$

5. ACCRETION HISTORY

Taking $q = (n L_{\text{bol}})$ as the comoving luminosity density arising from the *bolometric* luminosity of the associated black hole galactic nuclei, eq.(4) implies that the comoving mass density of accreted matter (ρ_A) accumulated over the time history of interest is

$$\rho_A = c^{-2} \int (\epsilon^{-1} - 1) q dt. \quad (9)$$

As pointed out by Soltan [15], eq.(9) is basically equivalent to eq.(8) in content, both being integrals over the radiative history. However, if we consider the sky surface brightness (I) as that of the CXB, we must take into account that the appropriate q for X-radiation in eq.(8) is then a fraction ($1/\eta$) of the bolometric q in eq.(9), since $\eta \equiv L_{\text{bol}} / L_X \geq 1$ (where $L_X \equiv$ broadband X-ray luminosity). From these two equations (8, 9) we obtain that the present-epoch mass density of black hole growth arising from accretion (ρ_A) is proportional to the total CXB omnidirectional flux ($4\pi I$), viz:

$$\rho_A = c^{-3} [\langle \eta (\epsilon^{-1} - 1)(1+z) \rangle] (4\pi I), \quad (10)$$

where the proportionality constant depends on η , ϵ and z via the indicated average over the relevant history of accretion. Using the flux given by eq.(2) in eq.(10), under the assumption that $\eta \geq 2$ and $\epsilon < 0.3$, gives the lower limit

$$\rho_A > 7.5 \times 10^3 (1 + \langle z \rangle) M_\odot / \text{Mpc}^3. \quad (11)$$

Since the Seyfert galaxies observed with the Compton Gamma Ray Observatory exhibit spectra that, on average, peak in $E(L_E)$ at $E \approx 90$ keV [16] their main contribution to the CXB, which peaks in $E(I_E)$ at $E = 28$ keV, is expected to be coming from redshifts at $z \approx 2$. Indeed the X-ray luminosity evolution for AGN obtained with ROSAT [17], for the case $\Omega = 1$, increases strongly with redshift only up to $z \approx 2$ and is then relatively flat up to $z = 3$. On the other hand, the evolution of comoving density for the optically brightest quasars peaks at $z = 3.3$ [18]. Hence, it is reasonable to anticipate that $\langle z \rangle \geq 2$ for the CXB; using this in eq.(11) yields

$$\rho_A > 22 \times 10^3 M_\odot / \text{Mpc}^3. \quad (12)$$

Data from the HEAO-2 Einstein Observatory and ROSAT have been used by Boyle et al. [17] to determine that, at X-ray luminosities $\geq 10^{42} h^{-2}$ ergs s^{-1} (0.3-3.5 keV) for $h \equiv H_0 / (50 \text{ km } s^{-1} / \text{Mpc})$, the number density of detectable AGN is comparable to that of Seyfert 1 galaxies at $M_B < -17.5$ [19]. According to the unified model for Seyfert galaxies [20] Seyfert 1 AGN are the same as Seyfert 2 but viewed from a direction that avoids the obscuring matter intrinsic to such objects. Although Seyfert 2 galaxies are likely to dominate the AGN population their X-ray spectra are highly absorbed, making these sources relatively inaccessible within the soft X-ray spectral band considered by Boyle et al. [17]. Assuming that the AGN in the sample used by Boyle et al. are mainly Seyfert 1 galaxies and that the number of Seyfert 2 galaxies is 2.3 times greater [19] we obtain $n_{\text{AGN}} \approx 6 \times 10^{-5} h^3 \text{ Mpc}^{-3}$. We can then employ the mass function for Seyfert 1 galaxies [21] to infer that the corresponding total present-epoch mass density of all Seyfert AGN nuclei is

$$\rho_{\text{AGN}} \approx 2 \times 10^3 h M_\odot / \text{Mpc}^3 \quad (13)$$

with

$$\langle M_{\text{AGN}} \rangle \approx 3 \times 10^7 h^{-2} M_\odot. \quad (14)$$

From equations (12 - 13) we conclude that $\rho_A > 10 h^{-1} \rho_{\text{AGN}}$. This indicates that the total

density of supermassive BGN (Black hole Galactic Nuclei) in the present epoch (ρ_{BGN}) is substantially larger than ρ_{AGN} and hence dominated by dormant objects, consistent with direct stellar-kinematic evidence for dark central masses noted in several “inactive” galaxies [22]. We find that the present accumulated mass density (ρ_A) of accreted matter inferred from the CXB corresponds to a mean mass growth per AGN

$$\rho_A / n_{\text{AGN}} > 4 \times 10^8 h^{-3} M_\odot, \quad (15)$$

much larger than the average value cited in eq.(14) for the mass of present-epoch Seyfert nuclei. This implies that the duty cycle for mass accretion (and hence being “on” as an X-ray bright AGN) has been small during the overall lifetime of an average individual black hole galactic nucleus [21]. It suggests that the history of accretion responsible for the CXB was distributed over a much larger underlying population of BGN. Taking $\langle M_{\text{BGN}} \rangle = \langle M_{\text{AGN}} \rangle$ we conclude that the current AGN number density (n_{AGN}) is probably only a few percent that of the underlying population (n_{BGN}) and that $(\rho_{\text{BGN}} / n_{\text{BGN}}) = \langle M_{\text{AGN}} \rangle$. Since the comoving number density of Seyfert galaxies (n_{AGN}) appears to be invariant with respect to redshift for the X-ray sample considered by Boyle et al.[17], at least up to $z = 3$, the constant comoving number density (n_{BGN}) expected for the much larger underlying population would imply that the probability for being “on” is essentially the same throughout the evolution already traced. However, during the early epoch of galaxy formation, when there was ample fuel for accretion, there could well have been a brief phase at $z > 3$ when *all* these nuclei were “on” as Eddington limited X-ray sources [23].

Boyle et al. [17] have used ROSAT and HEAO-2 Einstein Observatory data on AGN observed up to $z = 3$ for determining their X-ray luminosity evolution. The corresponding mean mass value for black hole galactic nuclei at $z = 3$ thereby inferred [24], for $\Omega \leq 1$, is $\langle M_{\text{AGN}} \rangle \geq 7 \times 10^6 (\eta/\lambda) M_\odot$, where we expect $\eta/\lambda > 2$. Since the comoving density of the brightest quasars decreases sharply at

$z \geq 3.3$ [18], this minimum mean mass is taken to characterize the supermassive black holes that *already* exist at the presumed onset of the AGN phenomenon at $z \approx 3$.

Where did these supermassive black holes already present at $z \approx 3$ come from? Haehnelt and Rees [25] consider that, in the course of galaxy generation, the baryonic component of the central part of a newly forming dark matter halo collapses into a self-gravitating structure. They suggest that relatively rapid black hole creation could then occur by protogalactic core collapse via a process of “supply driven” accretion whose initial rate vastly exceeds the Eddington value ($dM/dt \gg M/\tau_{\text{Edd}}$). In this situation radiation is initially trapped (i.e., does not escape). However, in their model, most of the actual mass buildup occurs during the final phase of core collapse when the corresponding Eddington limit for accretion has grown to be comparable to the externally enforced rate and during which time most of the total radiation that eventually escapes actually does emerge. Efficient production of X-rays during this final phase would yield a major CXB component. For Eddington limited accretion the characteristic time for black hole mass growth and spin-up could be as short as 3×10^7 years (see §3). During this phase these objects would qualify as viable candidates for the PAG (Precursor Active Galaxies) proposed for the earliest epoch of CXB generation [26].

As the total CXB intensity (I_{CXB}) is a direct measure of the *entire* history of accretion responsible for producing the supermassive black hole galactic nuclei (BGN) that exist in the present epoch (at $z=0$), we likewise expect that there is a PAG portion (I_{PAG}) of this background that signals the early history of accretion responsible for producing the BGN already present at the onset of the AGN phenomenon, here taken to be at $z \approx 3$. Under the assumption that $(\eta/\lambda)_{\text{AGN}} > 2$, $\eta_{\text{PAG}} \leq \eta_{\text{AGN}}$, $6 > \langle z_{\text{PAG}} \rangle \geq 3$ and that the mean BGN mass at $z = 3$ already greatly exceeds that of possible earlier seed masses, we would then expect [24] that $(I_{\text{PAG}} / I_{\text{CXB}}) > 0.2$. These PAG are not only probable major contributors to the unresolved CXB (as suggested here) but should be

so numerous as to render the surface brightness of such a residual background much smoother on small angular scales than expected on the basis of AGN alone [23, 24]; this is due to the basic aspect of a picture in which $n_{\text{PAG}} = n_{\text{BGN}} \gg n_{\text{AGN}}$. Preliminary evidence obtained from ROSAT [27] suggests that there may indeed be an especially large number of faint unresolved sources of the residual CXB.

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