HARD X-RAY EMISSION FROM ELLIPTICAL GALAXIES AND ITS CONTRIBUTION TO THE X-RAY BACKGROUND

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ABSTRACT

We explore the implications of the discovery of hard, power-law X-ray sources in the spectra of nearby elliptical galaxies for the origin of the X-ray background (XRB). The spectra of these sources are consistent with models of thermal bremsstrahlung emission from low radiative efficiency accretion flows around central supermassive black holes and are unique in that they approximately match the spectrum of the hard XRB. If such sources, with luminosities consistent with those observed in nearby elliptical galaxies, are present in most early-type galaxies, then their integrated emission may contribute significantly to the XRB. These sources may also contribute to the hard source counts detected in deep X-ray surveys.

Subject headings: accretion, accretion disks — galaxies: nuclei — X-rays: general

1. INTRODUCTION

Although it is now clear that the cosmic X-ray background (XRB) results from the integrated X-ray emission from many discrete sources and that a large fraction of the soft (0.5–2 keV) XRB is produced by active galactic nuclei (AGNs; e.g., Hasinger et al. 1998; Schmidt et al. 1998), the nature of the sources producing the energetically dominant, hard (2–60 keV) XRB remains largely unknown. Most current models for the XRB attempt to explain its origin within the context of AGN unification schemes and suggest that the XRB arises from the integrated emission of AGNs with a range of intrinsic absorbing column densities (e.g., Setti & Woltjer 1989; Comastri, Setti, & Zamorani 1995 and references therein). A population of sources with hard X-ray spectra in the 2–10 keV band have been discovered by ASCA and BeppoSAX (Boyle et al. 1998; Ueda et al. 1998; Giommi et al. 1998), with a fraction of these sources showing evidence for heavy obscuration (Fiore et al. 1999). However, it remains unclear whether obscured AGNs can fully account for the hard XRB. The most recent synthesis models, which include the latest constraints on the luminosity function and evolution of AGNs (Miyaji, Hasinger, & Schmidt 1999), cannot easily reproduce the hard counts observed in the ASCA (2–10 keV) and BeppoSAX (5–10 keV) bands and require a number ratio of type 2/type 1 AGNs much higher than the locally observed value (Gilli, Risaliti, & Salvati 1999). The discrepancies within the context of AGN synthesis models for the XRB suggest the need for an additional population of hard-spectrum sources. In this Letter, we explore the implications of the discovery of hard, power-law X-ray components in the ASCA spectra of six nearby, giant elliptical galaxies (Allen, Di Matteo, & Fabian 1999, hereafter ADF99). If most early-type galaxies contain a hard, power-law source with a luminosity of \(10^{40}–10^{42}\) erg s\(^{-1}\), as may be extrapolated from the detections of such components in both active (e.g., M87) and quiescent galaxies, then the integrated emission from these sources, distributed over a larger redshift interval, can make a significant contribution to the hard XRB.

Dynamical studies of elliptical galaxies indicate the presence of supermassive black holes in their nuclei, with masses in the range \(10^8–10^{10} M_\odot\) (e.g., Magorrian et al. 1998). As discussed by ADF99 and Di Matteo et al. (1999c, hereafter DM99), the hard X-ray components detected in nearby giant elliptical galaxies are likely to be due, at least in part, to accretion onto their central black holes. In the cores of elliptical galaxies, accretion from the hot interstellar medium may proceed directly into a hot, low radiative efficiency regime (e.g., Fabian & Rees 1995). DM99 show that the hard X-ray components observed in these systems are consistent with models of thermal bremsstrahlung emission from hot, radiatively inefficient accretion flows with temperatures of 50–100 keV. Given that the XRB spectrum in the 3–60 keV band is also well described by a bremsstrahlung spectrum with \(kT \sim 40\) keV, the hard X-ray sources in elliptical galaxies represent a unique class of object with emission spectra that closely match that of the XRB (see also Di Matteo & Fabian 1997).

2. HARD X-RAY EMISSION FROM ELLIPTICAL GALAXIES

2.1. The Observed Power-Law Components

ADF99 discuss ASCA observations of six nearby, giant elliptical galaxies (M87, NGC 4696, and NGC 1399—the dominant galaxies of the Virgo, Centaurus, and Fornax clusters) and three other giant elliptical galaxies in the Virgo Cluster (NGC 4472, NGC 4636, and NGC 4649). All of these galaxies (with the exception of NGC 4696, which had not previously been studied in as much detail as the other systems) exhibit clear stellar and gasdynamical evidence for central, supermassive black holes in their nuclei, with masses in the range \(10^8–10^{10} M_\odot\) (e.g., Magorrian et al. 1998). The ASCA spectra for these systems reveal the presence of hard, power-law emission components with energy indices \(-0.5 < \alpha < 0.5\) (weighted-mean value \(\alpha = 0.22\); a discussion detailing the reasons that the sources are unlikely to be heavily obscured AGNs is given by ADF99) and intrinsic 1–10 keV luminosities of \(2 \times 10^{40}–2 \times 10^{42}\) ergs s\(^{-1}\). These spectral slopes are harder and the luminosities are lower than typical values for Seyfert galaxies, identifying these objects as, potentially, a new class of X-ray source. The presence of hard components in all six
galaxies studied also suggests that such sources may be ubiquitious in early-type galaxies.

2.2. An Empirical Comparison

We first compare the spectra of the power-law sources observed in nearby elliptical galaxies with the 1–10 keV XRB. ASCA and BeppoSAX observations of the cosmic XRB in the 1–7 keV band can be well described by a simple power-law model with an energy index $\alpha = 0.38$–0.47 and a normalization $L = 8$–11 keV s$^{-1}$ cm$^{-2}$ s$^{-1}$ keV$^{-1}$ at 1 keV (Gendreau et al. 1995; Chen, Fabian, & Gendreau 1997; Miyaji et al. 1998; Parmar et al. 1999). We have simulated the spectrum obtained by adding a 70%–80% contribution to the 1–10 keV flux from power-law sources with an energy index $\alpha = 0.22$ (modeling the emission from the elliptical galaxies) to the established $\pm 30\%$ contribution, in the same band, from unabsorbed Seyfert 1 galaxies and QSOs (as determined from ROSAT and ASCA; e.g., Schmidt et al. 1998; Boyle et al. 1998). These latter sources have been characterized by a power-law spectrum with an intrinsic energy index $\alpha = 0.9$, with a reflection component accounting for emission reprocessed by cold material close to the central X-ray sources (Magdziarz & Zdziarski 1995). Note that the use of a simpler power-law parameterization for the type 1 AGNs, with an apparent energy index $\alpha = 0.7$ (Turner & Pounds 1989), leads to similar results.

The simulated spectrum, as would be observed with the ASCA Solid-state Imaging Spectrometers (SISs) from a 250 ks exposure (matching the total exposure time analyzed by Gendreau et al. 1995) is shown in Figure 1. The flux in the simulated spectrum matches the cosmic XRB flux observed by Gendreau et al. (1995). We do not account for the internal background in the SIS detectors, which provides an additional contribution to the total count rate detected by those authors.

Following standard X-ray analysis methods, we have fit the simulated spectrum in the 1–10 keV range with a simple power-law model. We find that this model provides a good description of the simulated data (reduced $\chi^2$ ~ 0.9 for 200 degrees of freedom, after regrouping to a minimum of 20 counts per channel) and returns a best-fitting slope of $\alpha = 0.40 \pm 0.02$ or $\alpha = 0.48 \pm 0.02$ (90% errors determined from Monte Carlo simulations) for simulations with 20% and 30% contributions to the 2–10 keV flux from type 1 AGNs, respectively. These results are in excellent agreement with those for the real XRB.

This simple exercise illustrates that, independently of the model used to explain the hard, power-law emission components in the elliptical galaxies, their observed 2–10 keV spectra match that of the XRB in this band once the expected contributions from QSOs and AGNs are also accounted for.

3. BREMSSTRAHLUNG EMISSION FROM ELLIPTICAL GALAXY NUCLEI

In previous papers (DM99; Di Matteo et al. 1999b), we have shown that the broadband spectral energy distributions for the nuclear regions of the six elliptical galaxies studied by ADF99 can be explained by low radiative efficiency accretion models (i.e., advection-dominated accretion flows [ADAFs]; see Narayan, Mahadevan, & Quataert 1998 and references therein) in which accretion occurs from the hot, gaseous halos of the galaxies at rates comparable to their Bondi accretion rates and in which a significant fraction of the mass, angular momentum, and energy in the accretion flows is removed by winds (Blandford & Begelman 1999). Within the context of these models, the systematically hard, observed X-ray spectra can be accounted for by the energetically dominant bremsstrahlung emission produced by such flows, with electron temperatures of ~50–100 keV. In this section, we explore the implications for the XRB of this interpretation for the origin of the hard X-ray emission in elliptical galaxies.

3.1. The XRB Model

We consider the integrated emission from unresolved sources, with hard bremsstrahlung spectra and luminosities consistent with those observed in the six nearby elliptical galaxies studied by ADF99. We first constructed a standard co-added source spectrum by combining the results from fits to the observed spectral energy distributions for the galaxies with twotemperature ADAF models (including the effects of winds), as discussed by DM99. The contributions to the co-added spectrum from the three central cluster galaxies were downweighted by a factor of $10^5$ to reflect their lower space density. The resulting co-added source spectrum has a bremsstrahlung luminosity of $8 \times 10^{40}$ erg s$^{-1}$ (see also Fig. 2 in DM99). This standard source spectrum was then folded with the appropriate cosmological model to determine the possible integrated contribution from such sources to the 2–60 keV XRB. (This model is essentially the same as that described by Di Matteo et al. 1999a and Di Matteo & Fabian 1997, but now including the constraints on the source spectrum from DM99; see § 5 and Fig. 2 of that paper.)

We assume that the sources are distributed over a redshift range $z_{\min}$ to $z_{\max}$ and write the comoving spectral emissivity from such objects as the product $j(E, z) = n(z)L_E(z)$, where $n(z)$ is the comoving number density of X-ray sources and $L_E(z)$ is the specific luminosity of the individual sources. We adopt a simple prescription for the redshift evolution of the comoving emissivity, $j(E, z) = j_0(E)(1+z)^k$, where $j_0(E)$ is the model spectrum bremsstrahlung emissivity and $k$ is the evolution parameter. The total flux from such
objects is then

\[ I(E) = \frac{c}{4 \pi H_0} \int_{z_0}^{z_{\text{max}}} \frac{(1+z)^{2-2}}{(1+2q_0z)^{\frac{2}{3}}} I_0(1+z) dz, \]  

(1)

where \( q_0 \) is the deceleration parameter, \( H_0 \) is the Hubble constant (we use \( q_0 = 0.5 \) and \( H_0 = 50 \text{ km s}^{-1} \text{ Mpc}^{-1} \)), and \( I(E) \) is the computed XRB intensity in units of keV s\(^{-1}\) sr\(^{-1}\) cm\(^{-2}\) keV\(^{-1}\) at an energy of 1 keV. For our given source spectrum and fixed values for \( z_0 \) (we assume \( z_0 = 0 \), \( z_{\text{max}} \), and \( k \), the only free parameter in equation (1) is the local source number density \( n(z_0) \), which we determine by normalizing \( I(E) \) to the observed XRB.

The XRB spectra predicted by a series of “best-fit” models are shown in Figure 2. The dashed line shows the result due only to bremsstrahlung sources. The solid line shows the improved result when we include a 30% contribution to the 2 keV flux from unabsorbed AGNs (corresponding to a ~20% contribution to the 2–10 keV flux), characterized by a canonical power-law spectrum with an energy index \( \alpha = 0.7 \). (Both curves assume \( z_{\text{max}} = 1.0 \) and \( k = 3 \).) In this case, the normalization of the XRB requires a local comoving number density of bremsstrahlung sources, \( n(z_0 = 0) = 2 \times 10^{-3} \text{ Mpc}^{-3} \). The dotted line in Figure 2 shows the result for \( z_{\text{max}} = 1.8 \) (other parameters the same) in which case \( n(z_0 = 0) = 8 \times 10^{-4} \text{ Mpc}^{-3} \) (the most distant sources contribute most to the total model flux). These values for the comoving number density of emitting sources are in good agreement with the observed number density of bright, early-type galaxies in the nearby universe (\( n \sim 10^{-3} \text{ Mpc}^{-3} \); e.g., Marinoni et al. 1999 and Heyl et al. 1997).

4. DISCUSSION

We have shown that our model provides a good match to the observed XRB, with a required number density of emitting sources in good agreement with the observed number density of early-type galaxies in the nearby universe (for \( z_{\text{max}} \geq 1 \) and \( k \sim 3 \)). The requirement for most or all early-type galaxies to have hard X-ray spectra and luminosities consistent with the objects studied by ADF99 may be relaxed once more realistic models for the XRB are considered, including a fractional contribution from heavily absorbed Seyfert 2 nuclei (e.g., Gilli et al. 1999). This will then allow for a broader range of luminosities and/or a lower number density for the bremsstrahlung sources. (In this case, the relative contribution from these sources to the 2–10 keV XRB intensity will also be rescaled to <70%.) The required comoving number density of bremsstrahlung sources is also decreased as \( z_{\text{max}} \) is increased toward \( z_{\text{max}} \sim 2 \).

Our sources may also contribute to the hard number counts detected at faint X-ray fluxes by ASCA and BeppoSAX (e.g., Ueda et al. 1998; Fiore et al. 1999). Detailed synthesis models for the XRB, which simulate the integrated emission from AGNs with a range of absorbing column densities, have revealed the need for additional hard-spectrum sources to explain the observed number counts (e.g., Gilli et al. 1999). The 2–10 and 5–10 keV fluxes associated with the power-law sources detected in the nearby elliptical galaxies studied by ADF99 range from 0.6 to 8.7 \times 10^{-12} \text{ ergs cm}^{-2} \text{ s}^{-1}, and from 0.3 to 5.0 \times 10^{-12} \text{ ergs cm}^{-2} \text{ s}^{-1}, respectively. Within the context of our model, a significant fraction of the hard number counts detected at fluxes \( F_X \leq 10^{-14} \text{ ergs cm}^{-2} \text{ s}^{-1} \) may then arise from sources at low redshift. We note that models postulating the existence of an as-yet unobserved population of heavily obscured black holes at redshift \( z \sim 2 \) also predict X-ray fluxes too faint to account for the observed hard counts (Fabian 1999).

The value of \( z_{\text{max}} \) in our model is constrained by the effective temperature of the bremsstrahlung emission in the co-added source spectra: the co-added spectrum must be redshifted to fit the 30 keV rollover observed in the XRB. We note that the high-energy (\( \geq 50 \text{ keV} \)) spectrum predicted by our model is not firmly constrained. The presence of winds/outflows associated with low radiative efficiency accretion flows around supermassive black holes inevitably causes the X-ray spectra of such flows to be dominated by bremsstrahlung emission. (Inverse Compton emission is heavily suppressed in the presence of outflows for any range of \( m \); this, with \( m \sim m_{\text{crit}} \) for the component sources, allows for higher individual bremsstrahlung source luminosities than considered in the earlier work of Di Matteo & Fabian.) However, the wind characterization currently employed in the accretion models is very basic and the spectra produced cannot be used to perform reliable statistical fits to the data. In particular, the presence of an outflow will significantly affect the density and temperature profiles in the central regions of an ADAF (DM99; Quataert & Narayan 1999), where the higher energy (\( h\nu \geq kT \)) emission originates (although the emission in the 2–10 keV band, where the models provide a good match to the power-law components observed in nearby elliptical galaxies, is virtually unaffected). Due to these uncertainties, the value of \( z_{\text{max}} \) cannot be tightly constrained.

The black holes at the centers of nearby elliptical galaxies have masses consistent with being the remnants of an earlier quasar phase. If, as our work may suggest, these systems accrete via low radiative efficiency accretion flows, then a fraction of...
the hard XRB could be produced after the main quasar phase in galaxies and be associated with a change in the dominant accretion mechanism in their nuclei. It is interesting, in this context, that studies with the Hubble Space Telescope have shown that the underlying hosts of essentially all classes of QSOs appear to be massive, elliptical galaxies (McLure et al. 1999).

We stress that our analysis is not intended to explore the full range of parameter space available to either the accretion flow or XRB models or to provide detailed, quantitative results. At present, the theoretical and observational uncertainties involved in such calculations are too large to merit such work. The observational constraints will, however, be significantly improved in the near future with data from the Chandra Observatory, X-Ray Multimirror Mission, and Astro-E.

5. CONCLUSIONS

We have examined the potential importance of the hard, power-law emission components detected in the X-ray spectra of nearby elliptical galaxies for the origin of the hard XRB. In previous papers (ADF99 and DM99), we have shown that these components are likely to be associated with accretion onto the central, supermassive black holes in the galaxies. The emission spectra from these sources can be well explained by bremsstrahlung models, with typical temperatures of 50–100 keV, resulting from low radiative efficiency accretion flows with strong winds. In this Letter, we have shown that the application of such emission models to a plausible redshift distribution of sources, with individual source luminosities in agreement with the ASCA results for nearby elliptical galaxies, can account for a significant fraction of the XRB in the 1–60 keV range, with an implied number density of sources in good agreement with the observed local number density of early-type galaxies. We have argued that the emission from these sources may also contribute to the hard number counts detected at faint X-ray fluxes with ASCA and BeppoSAX.

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