On the Origin of the Hard X-Ray Background

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ABSTRACT

Several models for the hard X-ray Background (XRB) suggest that it is due to the emission from heavily obscured AGN. Recent studies have revealed the presence of a new population of hard X-ray sources which must contribute significantly to the XRB. However, whether the majority of these sources are obscured AGN or some other type of object at present remains unclear. Here, we further examine the possibility that a significant fraction of the XRB comes from a population of galaxies undergoing advection-dominated accretion in the high-$\dot{m}$ regime and thus produce intrinsically hard spectra. When the accretion rate is close to $\dot{m}_{\text{crit}}$, above which an advection-dominated accretion flow (ADAF) no longer exists, the major contribution to X-ray emission is due to inverse Compton scattering of the soft seed photons produced by cyclo-synchrotron radiation. In this regime, the resulting ADAF spectra are relatively hard with a fairly constant X-ray spectral index $\alpha \sim 0.2 - 0.4$ and a spectral cut-off at $\sim 200$ keV. We show that the integrated emission from such sources can provide a good fit to the hard (> 2 keV) X-ray background, provided that the spectrum is dominated by the contribution from objects located at redshifts $z \sim 2 - 3$. The model requires most of the contribution to the XRB to be due to objects accreting at $\dot{m}_{\text{crit}}$.

Key words: galaxies: active – galaxies: nuclei; accretion, accretion disks – X-rays: general – galaxies

1 INTRODUCTION

The origin of the X-ray background (XRB) is still largely an unsolved problem. Recent progress indicates that the XRB is probably due to contributions from different types of discrete sources. Although Active galactic Nuclei (Seyferts and Quasars, hereafter AGN) provide a large fraction of the soft XRB below $\sim 2$ keV (Shanks et al. 1991; Hasinger et al. 1998; Schmidt et al. 1998; Schmidt et al. 1998; Schmidt et al. 1998) their spectra are too steep to explain the hard (> 3 keV) XRB. Also, as a larger sample of QSOs became available, detailed studies of the QSO X-ray luminosity function (Boyle et al. 1994) and the source number count distribution (Georgantopoulos et al. 1996) have shown that QSOs are unlikely to form more than 50 per cent of the 2–10 keV XRB, even at 1 keV. Models based on the unified Seyfert scheme, in which a large fraction of the emission from AGN is absorbed by obscuring matter (Madau et al. 1994; Celotti et al. 1995; Comastri et al. 1995) seem to account for the amplitude and the general shape of the hard XRB. However, in these models it is not clear whether cosmological evolution can ultimately smooth out the predicted absorption edges and emission lines (e.g. Gilli et al. 1998) in the 2–10 keV spectral range, produced by iron and other metals (Matt & Fabian, 1994), to a level which is consistent with the XRB spectrum statistical errors. In fact, recent ASCA observations (e.g. Gendreau et al. 1995) showed that the spectrum of XRB is typically very smooth and well approximated by a power law of spectral index $\alpha = 0.4$. Thus, to explain the origin of XRB we might have to postulate the existence of a new population of hard X-ray emitting sources.

Recent deep ROSAT surveys have begun to resolve such sources at the faintest soft-X-ray flux limits (Vikhlinin et al. 1995; Boyle et al. 1995; Almaini et al. 1996; Hasinger et al. 1998; McHardy et al. 1998). Many of these sources appear to be associated with faint active galaxies with implied X-ray luminosities 100 times higher than normal field galaxies. Furthermore, a promising population of sources with hard X-ray spectra has been discovered by ASCA and BeppoSAX in the 2–10 keV band (Ueda et al. 1998; Giommi et al. 1998). These findings indicate the presence of a population which could significantly contribute to the XRB (resolving $\sim 30$ per cent of the 2–10 keV XRB). Although it seems plausible that a fraction of the observed hard-spectrum sources

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might simply be heavily obscured AGN, in the majority of cases the true nature of the emission remains unclear. In addition, most models predict that the bulk of the hard XRB originates at redshifts $z \sim 2$ which are currently largely unexplored in X-rays.

Continuing on the lines of Di Matteo & Fabian (1997; hereafter DF), in this paper we further examine the possibility that the sources contributing to the XRB have intrinsically hard X-ray spectra, such as are naturally produced in the context of advection–dominated accretion models.

In an advection-dominated accretion flow (ADAF) most of the energy released by viscous dissipation is stored within the gas and advected inward with the accreted plasma; only a small fraction is radiated away (see Narayan, Mahadevan & Quataret 1998 for a recent review). Recent work on ADAFs has concentrated on low-$M$ solutions (Ichimaru 1977; Rees et al. 1982; Narayan & Yi 1994, 1995; Abramowicz et al. 1995) which exist when the accretion rate is lower then a critical value, $\dot{m}_{\text{crit}} \sim 1.3 \times 10^2$ K, in Eddington units. This optically–thin branch is based on two critical assumptions: (1) viscous energy is deposited into the ions and only a small fraction of energy goes directly into the electrons; and (2) the energy transfer between the ions and electrons occurs only via Coulomb collisions. Because Coulomb transfer in the the low-density ADAF is inefficient, as a result of these assumptions, the accreting gas takes the form of a two-temperature plasma, in which the ions are at nearly virial temperature $T_i \sim 10^{12}/r \text{ K}$ and the electron temperature saturates at around $10^9 - 10^{10} \text{ K}$.

The spectrum from an optically–thin ADAF is very different from that of a standard thin disk. The high electron and ion temperatures and the presence of an equipartition magnetic field allow a variety of radiation processes to contribute to the emitted spectrum from radio to gamma rays. The radio to X-ray emission is produced by the electrons whereas the gamma-ray emission is produced by the ions via pion production. Here, we restrict the discussion to electron emission which comprises synchrotron, inverse Compton, and bremsstrahlung processes and in particular to those processes which contribute to the X–ray emission.

In this Letter, we consider whether a significant fraction of the hard XRB can be due to the integrated emission from a population of galaxies undergoing advection–dominated accretion with $\dot{m} \sim \dot{m}_{\text{crit}}$. When the accretion rate $\dot{m}$ is substantially lower than $\dot{m}_{\text{crit}}$, the X-ray emission from an ADAF is dominated by bremsstrahlung radiation. As the accretion rate approaches $\dot{m}_{\text{crit}}$, Comptonized emission dominates and contributes more significantly to the high energy spectrum. In previous paper DF have analyzed the contribution to the XRB from ADAFs in the bremsstrahlung–dominated regime. Here we show that for sources undergoing accretion close to $\dot{m} \sim \dot{m}_{\text{crit}}$, thermal Comptonization is highly saturated, and produces hard spectra which can easily account for the XRB (this condition then resembles that proposed on ad hoc basis by Zdziarski, 1988).

In §2 of this paper, we compute the detailed spectrum of an ADAF in the high–$\dot{m}$ regime using the model described by Narayan, Barret & McClintock (1997) and Esin, McClintock & Narayan (1997). In §3, we use an appropriate cosmological model to derive the contribution to the XRB intensity from these sources and compare the resulting spectrum with the data. We discuss possible implications of our model and summarize our results in §4.

2 MODELING THE X–RAY EMISSION FROM AN ADAF

The hot, two–temperature, advection–dominated solution on which our model is based is known to exist only for accretion rates below the critical value $\dot{m}_{\text{crit}}$ (e.g. Narayan & Yi 1995; Abramowicz et al. 1995). For $\dot{m} > \dot{m}_{\text{crit}}$, Coulomb coupling becomes very efficient, allowing the protons to cool rapidly and causing the hot flow to collapse into a standard cooling–dominated thin disk. In this paper we consider a regime of accretion close to $\dot{m}_{\text{crit}}$. In our model, the accretion flow is composed of two separate zones: an inner ADAF and an outer thin disk. The boundary between the two zones lies at the transition radius, $r_{\text{tr}}$ (hereafter all radii are in Schwarzschild units). Since we are interested in the high $\dot{m}$ regime, we adopt a rather low value of the transition radius in our calculations, setting $r_{\text{tr}} = 10^2$ km. It is worth noting, however, that the ADAF spectrum in the X-ray band is practically independent of our choice of the transition radius, as long as it lies outside $\sim 100$ Schwarzschild radii (see Esin, McClintock & Narayan 1997).

We compute the ADAF spectra using the numerical procedure described in detail by Esin, McClintock & Narayan (1997) and Narayan, Barret & McClintock (1997). This procedure combines a fairly sophisticated treatment of radiative transfer (Poutanen & Svensson 1996) with global dynamical accretion flow solutions (Narayan, Kato, & Honma 1997), while solving for the thermal balance of the ions and electrons. In our calculations, we take the black
hole mass to be \( m = 10^7 \) (in solar mass units), and set the viscosity parameter to \( \alpha = 0.25 \). We also assume that the magnetic field in equipartition with thermal pressure, so that the ratio between the thermal and total pressure, denoted by \( \beta \), is equal to 0.5.

Spectra produced from such an accretion flow, for a series of \( \dot{m} \) in the vicinity of \( \dot{m}_{\text{crit}} \), are shown in Fig. 1. The low energy (radio-IR) end of the spectrum is due to self-absorbed synchrotron emission from hot electrons in the equipartition magnetic field. The quasi-thermal emission from the outer thin disk peaks in the NIR/optical band. The soft synchrotron and blackbody photons inverse Compton scatter off the hot thermal electrons in the ADAF and produce the hard power law spectrum with a spectral cut-off at \( \sim 2 - 3kT_e \). X-rays scattering off the outer thin disk produce a reflection bump at a characteristic energy \( \sim 30 \) keV. We also include bremsstrahlung emission which peaks at \( h\nu \approx kT_e \).

The relative importance of Comptonization increases very rapidly with increasing \( \dot{m} \) (see Fig. 2). In the high \( \dot{m} \) regime considered here, the characteristic electron scattering optical depth \( \tau \) of the ADAF becomes of order unity, since \( \tau \propto \dot{m} \). This implies that the value of the Compton y−parameter is close to unity as well. As a consequence, inverse Compton scattering becomes the most important cooling mechanism, and the Comptonized tail dominates the X-ray spectrum, as shown by the models plotted in Fig. 1.

The energy boost experienced by a photon in each scattering is proportional to the electron temperature. Although, with increasing \( \dot{m} \) more energy is transferred to the electrons by Coulomb coupling, inverse Compton cooling also becomes more efficient, with the result that \( T_e \) saturates at around a few times 10^7 K. Since the synchrotron radiation (the main source of seed photons) is very soft (see Fig. 1), the photons will be scattered many times before reaching the Wien saturation limit, giving rise to a smooth power law spectrum. The slope \( (\alpha_x) \) of the power law is proportional to \( \log \tau \), so that the X-ray spectrum becomes flatter (in \( L_x \)) as \( \dot{m} \) increases.

The hard X-ray spectrum of an ADAF closely resembles that of the hard X-ray background when the accretion rate is in the vicinity of \( \dot{m}_{\text{crit}} \), but the spectra from sources with lower \( \dot{m} \) become considerably steeper (as illustrated in Fig. 1). However, because the inverse Compton cooling increases as \( \dot{m}^2 \) (see Fig. 1), eventual contributions to the XRB intensity from systems with softer spectra (i.e. smaller \( \dot{m} \)) is not very important, once we assume that a population of sources accreting at \( \dot{m} = \dot{m}_{\text{crit}} \) exists. Since the sources with flat spectra, accreting close to \( \dot{m}_{\text{crit}} \), are more luminous, they contribute more significantly to the XRB intensity. To make this statement more quantitative, the contribution from the lower \( \dot{m} \) regime is negligible, unless the relative fraction of the steep−spectrum sources is greater than that for the hard−spectrum sources by a factor comparable do the difference in their respective hard X-ray luminosities. The latter condition is satisfied only is we draw our sources from a population with number density per logarithmic interval in \( \dot{m} \) described by \( N(\dot{m}) \propto \dot{m}^{-i} \), where \( i \geq 2 \).

In the next section we will consider the integrated emission from sources producing hard Comptonized spectra in the high \( \dot{m} \) regime consistent with a two temperature ADAF, and fold it with the appropriate cosmological model to constrain their potential contribution to the unresolved 3 − 100 keV XRB.

### 3 CONTRIBUTION TO THE XRB

#### 3.1 Cosmological Model

In order to obtain a model for the XRB, we consider the contribution from many unresolved sources accreting at \( \dot{m} \sim \dot{m}_{\text{crit}} \), distributed over a redshift range from the local universe \((z = z_0)\) to the early universe \((z = z_{\text{max}})\). Comoving spectral emissivity from a distribution of such objects can be written as a product \( j[E, z] = n(z) L_E(z) \), where \( n(z) \) is the comoving number density of X-ray sources, and \( L_E(z) \) represents the specific luminosity of individual sources (see §2). In general, both \( n \) and \( L_E \) are functions of redshift, so that neither pure luminosity nor pure number density evolution are very good assumptions. Instead, we adopt the following simple prescription for the redshift evolution of comoving emissivity, \( j[E, z] = j_0(E)(1 + z)^p \), where \( j_0(E) \) is the local (at \( z = z_0 \)) spectral emissivity and \( p \) is the evolution parameter.

The total flux received from such objects, calculated in the framework of the Robertson-Walker metric, is given by

\[
I(E) = \frac{c}{4\pi H_0} \int_{z_0}^{z_{\text{max}}} \frac{(1 + z)^{p-2}}{(1 + 2q_0 z)^{1/2} j_0[E(1 + z)]} dz,
\]

where \( q_0 \) is the deceleration parameter, \( H_0 \) the Hubble constant (we use \( q_0 = 0.5 \) and \( H_0 = 65 \) km s\(^{-1}\) Mpc\(^{-1}\)).

\( I(E) \) represents our computed XRB intensity (in units of keV s\(^{-1}\) cm\(^{-2}\) keV\(^{-1}\)). The only free parameter in Eqn. 1 is the local source number density, \( n(z_0) \), which we determine by comparing \( I(E) \) with the empirical fit to the XRB spectrum.
but with different cosmological evolution parameters: we also plot (thinner solid and dashed line) the spectrum contributing in equal proportion) in each successive redshift shells. As we argued in §2, the contribution from objects with \( \dot{m} \) lower than the values considered here is negligible as long as the relative fraction of sources at a given \( \dot{m} \lesssim \dot{m}_{\text{crit}} \) does not exceed the number of sources close to \( \dot{m}_{\text{crit}} \) by a factor corresponding to \( \sim L_{\dot{m}_{\text{crit}}} / L_{\dot{m}} \). The thinner dashed-line corresponds to a model with \( z_{\text{max}} = 3.5 \) and \( z_{0} = 0 \). In this case, the normalization of the XRB spectrum requires a local comoving number density of \( n(z_{0}) = 0 \sim 10^{-4} \text{Mpc}^{-3} \).

The best fit evolutionary parameter is \( p = 3 \) (similar to that inferred for AGN), implying that most of the contribution to the XRB intensity comes from objects at high redshifts. To illustrate this further, we show a model (thicker dashed line) in which all of the emission comes from \( z_{\text{max}} = 3 \) and \( z_{0} = 2 \) and the evolution parameter \( p \) is set to be equal to 0. In this case, the comoving number density of sources, at these redshifts, is consistently higher and of the order of \( n(z_{0}) = 2 \sim 10^{-2} \text{Mpc}^{-3} \). The quality of the two fits (one with strong evolution and the other with a single population of sources between \( z = 2 \) and 3) is very similar. For \( E > 5 \text{keV} \) the computed intensity is within 2\( \sigma \) of the data points, at \( E < 5 \text{keV} \), it significantly overestimates the observed spectrum. However, small amounts of absorption (i.e. a column density \( N_{\text{H}} \lesssim \text{a few } 10^{21} \text{cm}^{-2} \) – much less than that required by Seyfert models of the XRB) would significantly improve the fit at these low energies, where the emission from other extragalactic sources also becomes relevant.

If we only consider the emission from the brightest sources, those with \( \dot{m} \sim \dot{m}_{\text{crit}} \) we find that the fit to the low energy range of the XRB significantly improves: the computed intensity now lies within 1\( \sigma \) of the data points (solid lines in Figs. 3 and 4). The spectra from ADAF sources accreting at these high \( \dot{m} \) values are very hard and give an excellent fit to the XRB when appropriately redshifted. Again, we compute the model intensity considering first, a strongly evolving population \( (p = 3) \) from \( z_{\text{max}} = 3.5 \) to \( z_{0} = 0 \) (thinner solid line) and second, a short lived, non-evolving \( (p = 0) \), population of objects from \( z = 3 \) to \( z_{0} = 2 \) (heavier solid line; this our best fit model plotted in Figs. 3). The normalizations to the XRB yield comoving number densities very similar to those obtained above.

The same set of models described above (for \( z_{\text{max}} = 3.5 \), \( z_{0} = 0 \) and \( p = 3 \)), is also calculated considering a 20 per cent contribution to the \( 2 - 10 \text{keV} \) XRB due to AGN characterized by a canonical power-law spectrum with energy index \( \alpha_{x} = 0.7 \). Such a contribution produces a further steepening of the spectrum and therefore a greater excess at soft energies (\( 3 - 5 \text{keV} \) range; dotted and dashed line in Fig. 3). However, the absorption column density required to suppress such an excess is still much smaller than that required by Seyfert models of the XRB and of the order of \( N_{\text{H}} \lesssim 10^{22} \text{cm}^{-2} \). Note that because of the outstanding issue that the observed AGN spectrum does not match that of the XRB (there is no strong evidence for any hardening of the X-ray spectral slope even for AGN identified in deep ASCA fields; Boyle et al. 1998), we know that there has to be a very significant residual contribution to the 2–10 \text{keV} \ XRB from sources that we have yet to identify (which we suggest might be ADAFs).

In summary, we have directly shown that a significant contribution to the XRB can result from a population of galaxies undergoing advection dominated accretion in their

\[ I_{\text{obs}}(E) = \begin{cases} 7.877E^{-0.20}\exp(-E/41.13 \text{keV}), & 3 \text{keV} < E < 60 \text{keV}; \\ 1652E^{-2.0} + 1.754E^{-0.7}, & 60 \text{keV} < E < 100 \text{keV}. \end{cases} \]
nuclei with $\dot{m} \sim \dot{m}_{\text{crit}}$. In this high-$\dot{m}$ regime an ADAF is luminous enough to satisfy the energy constraints of the XRB (in the $2 - 10\,\text{keV}$ band the ADAF luminosities are in the range of $2 \times 10^{42}$ erg s$^{-1}$ for $0.07 \lesssim \dot{m} \lesssim \dot{m}_{\text{crit}}$, for $m = 10^7$ as shown in Fig. [1]; moreover, an ADAF produces a very hard spectrum, through photon-starved Comptonization, which can explain the observed spectrum of XRB.

4 CONCLUSION AND DISCUSSION

The main results obtained in this paper can be summarized as follows:

(a) In the framework of the ADAF paradigm it is possible to construct a model which reproduces with good accuracy the XRB spectrum in the range $\sim 3 - 100\,\text{keV}$ and meets all the presently known constraints on number density of source population and X-ray spectral characteristics.

(b) The key feature of the model is the existence of a population of ADAFs accreting at $\dot{m} \sim \dot{m}_{\text{crit}}$. In this regime thermal Comptonization of cyclo-synchrotron photons gives rise to a typically hard X-spectrum (with $\alpha_x \sim 0.2 - 0.4$) which can naturally fit the $3 - 100\,\text{keV}$ XRB. Also, because of the small solid angle subtended by the cold material, any spectral features due to X-ray irradiation are negligible, and the model is consistent with the observed smoothness of the XRB spectrum.

(c) We compute in detail the typical luminosity and spectra for such sources. The contribution from the Comptonized emission from a population of ADAFs is integrated over redshift to reproduce the XRB intensity. Good fits are obtained for $z_{\text{max}} \sim 3.5$ and values for the evolution parameter $p \sim 3$. Implying that the peak of the XRB production is around $z \sim 3 - 2$ (similar quality of fits are in-fact obtained by considering a single population of ADAFs between $z_{\text{max}} = 3$ and $z_0 = 2$ and assuming $p = 0$). The normalization to the XRB intensity yields a comoving number density of $n_0 \sim 10^{-4}$ Mpc$^{-3}$, similar to that of present day Seyfert galaxies.

The requirement that $z_{\text{max}} \sim 3$ suggests that the XRB is produced before the main quasar phase, which peaks at redshift $z \sim 2$. If a population of massive black holes was assembled very early, by $z \sim 3$, maybe in dwarf galaxies (e.g. M32 contains a black hole of $M_{\text{BH}} \sim 2 \times 10^6 M_\odot$; Van der Marel 1998; Magorrian et al. 1998) it could have undergone advection-dominated accretion between $z \sim 3$ and 2. It is possible that during that time the infall of gas into the central black hole was increasing, e.g. due to galaxy mergers or to star formation, which allowed the sources to accrete close to $\dot{m}_{\text{crit}}$. In this scenario, the end of the ADAF phase would simply be due to the transition to the active QSO phase with $\dot{m} > \dot{m}_{\text{crit}}$. We further speculate that once the accretion fuel was depleted, quasars rapidly dropped again into the low-$\dot{m}$ ADAF state. In this subsequent ADAF phase, $\dot{m}$ is much lower and bremsstrahlung emission can provide a further energy contribution to the hard XRB (as discussed by DF where $z_{\text{max}}$ was determined to be $\sim 2$).

In this paper we have assumed that all systems have black holes with a constant mass, $m = 10^7$. Since the ADAF spectra are rather insensitive to $m$ while X-ray luminosity changes linearly with this parameter, adopting a varying $m$ prescription will simply give a different value for the comoving number density of X-ray sources and will not change any of the other results in this paper.

We must note that decreasing electron temperatures in the accretion flow by a factor of $\sim 2 - 4$ would cause the spectra to have lower cutoff energies, moving the redshift at which the bulk of XRB is produced closer to the QSO deathline at $z \sim 2$. We believe that the present ADAF model is robust enough to make such a decrease in the gas temperature unlikely. However, some physical mechanism currently not included in the model, for example the presence of strong winds from the accretion flow (as suggested by Blandford & Begelman 1998), might produce such an effect (e.g. Di Matteo et al. 1998).

Deep X-ray observations with AXAF and later missions should resolve objects at redshifts beyond the peak of the XRB production, thereby determining the origin and the nature of the hard sources contributing to XRB emission and providing clues for understanding the evolution of the fueling of massive black holes. If ADAFs do contribute significantly, the absence of a strong UV bump in the spectrum means that the objects will not have a normal broad-line region. They will not resemble a standard, broad-line AGN in the optical/UV band.

The main limitation of the high-$\dot{m}$ ADAF model (as it has become apparent in §3), is that it requires most of the objects to be accreting close to $\dot{m}_{\text{crit}}$. Although this might seem a peculiar feature it is worth noticing that models for the galactic black hole candidate Cyg X-1 (Esin et al. 1998), can also be explained by an ADAF which spends most of its time accreting at $\dot{m}_{\text{crit}}$; this might indicate that mechanisms might exist which lock the accretion rate in some systems at values close to their critical rate.

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