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Reflection-dominated hard X-ray sources and the X-ray background

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SUMMARY

The spectrum of the X-ray background is flat in the 2–10 keV range and has a break at about 30 keV. We show here that the spectrum of hard X-rays scattered by Thomson-thick material gives a good fit to the background above 10 keV when redshifted to $z \sim 1.5$. An evolutionary model covering a range of redshifts explains the background spectrum over a wider energy band. The necessary reflection-dominated sources may occur when massive black holes grow by accretion. A large fraction of the power generated by the sources must emerge as thermal radiation in the EUV and may be the intergalactic ionizing flux required to explain the properties of QSO absorption lines.

1 INTRODUCTION

The spectrum of the X-ray background (XRB) is well characterized by thermal bremsstrahlung from gas at $kT \sim 40$ keV (Marshall *et al.* 1980). This means that it has an approximate power-law energy index of $\alpha = 0.4$ in the energy range of 2–10 keV and that it breaks to an index of $\alpha \sim 1.4$ above ~ 60 keV. At photon energies above 100 keV, the spectrum gradually flattens out to form the 'MeV bump' (see Gruber *et al.* 1984 and references therein). Although hot gas provides an explanation for the spectrum of the XRB (see e.g. Guilbert & Fabian 1987), to be successful it requires large amounts of both energy and baryonic matter density. This has meant that many alternative models for the origin of the XRB have been, and are still being, proposed. Most of these models involve the unresolved emission from many point sources.

There are two major problems to be solved; the first is that no known class of source has exactly the same spectrum as the XRB and the second is that the 30-keV break in the XRB spectrum is relatively sharp. Schwartz & Tucker (1988) have proposed that the (poorly measured) high-energy spectra of Active Galactic Nuclei (AGN) do have the spectral shape of the XRB when redshift is taken into account. Others (Grindlay, private communication; Setti & Woltjer 1989) invoke a class of highly absorbed source. The sharpness of the spectral break is important. It must involve some process common to all sources, otherwise, with a range of break energies and redshifts, the observed break would be much less distinct. This suggests that the break is due to a physical limit or process, not just a variable parameter having some particular value. One energy which could be associated with the break is $m_e c^2$, the electron rest-mass energy. Pair production, for example, could cause spectra to be cut off at about 511 keV. A model involving this has been proposed by Fabian, Done & Ghisellini (1988) but it creates a new problem in that the sources must be at a mean redshift of ~ 20 in order to fit the observed XRB spectrum. Here we identify another physical process, the spectrum of a hard radiation reflected off a semi-infinite slab, which gives a good fit to the XRB over the energy range 10–300 keV from sources at the modest redshift of $\bar{z} \sim 1.5$.

The physical motivation for our model derives from the observations of 'soft excess' X-ray emission in many Seyfert 1 galaxies (e.g. Arnaud *et al.* 1985; Turner & Pounds 1989). This is interpreted as quasi-blackbody emission from around the central engine in the AGN which peaks in the EUV. The dense gas giving rise to this emission is either in an accretion disc, or may be in many clouds surrounding the central hard source. Such 'cold' ($< 10^6$ K) gas reprocesses the harder X-ray spectrum by Compton scattering and photoelectric absorption (Guilbert & Rees 1988; Lightman & White 1988). A characteristic fluorescent emission feature due to iron appears at about 6 keV in the spectra of Cyg X-1 and in some Seyfert 1 galaxies which otherwise show no evidence for strong absorption (Nandra *et al.* 1989a; Matsuoka *et al.* 1989; Nandra, Pounds & Stewart 1989b). A 'reflection hump' appears at higher energies, peaking at 30–50 keV. It is this hump and its higher energy tail which provide a good model for the spectrum of the XRB.

2 THE REFLECTION SPECTRUM

X-rays with a hard power-law spectrum incident on a slab of cold matter are reflected with a spectrum of characteristic shape (Bai 1980). The X-rays below 10 keV are predominantly absorbed and the albedo is low. Compton scattering decreases the energy of incident photons by a significant amount above 50 keV leading to a low apparent albedo at high energies. This leads to a hump appearing in the reprocessed spectrum. An emission line due to fluorescent iron occurs at 6.4 keV. The detailed shape of the 'reflected hump' above 10 keV has been studied by Lightman & White (1988). Their work includes the Klein-Nishina cross-section and a relativistic treatment of the Compton scattering process (White, Lightman & Zdziarski 1988).

We compare the shape of the reflected spectrum with the XRB spectrum in Fig. 1. The reflected spectrum (dotted line) has been redshifted to an equivalent $z=1.5$. It appears to give a good fit to the shape of the XRB above 10 keV. In order to see the effect of a range of redshifts, we have summed the reflected spectrum over $0<z<z_{max}$, where $z_{max}>2$, an with a volume emissivity of emitters (i.e. reflectors) evolving as $(1+z)^{\beta}$ for a range of values of β. The resulting spectrum for $z_{max}=5$ and $\beta=4$ is also shown in Fig. 1 (solid line). We see that the fit remains very good and now only deviates below 10 keV, requiring about 20 per cent of the intensity at 5 keV to be supplied from some other source. A 7 per cent contribution from direct emission has been added to the reflected spectrum. Steeper spectrum AGN, clusters of galaxies and starburst galaxies may easily provide the residual flux below 10 keV. The fit is not particularly sensitive to z_{max}, provided that it exceeds 2 (although a greater contribution from other sources is required below 10 keV if z_{max} is low) or to β in the range 3–5. We have assumed an energy index for the direct power-law spectrum of 0.7; acceptable fits are found if the energy index lies between 0.5 and 1 provided that β is changed appropriately. Our evolutionary model is of a similar form to those commonly used for QSO.

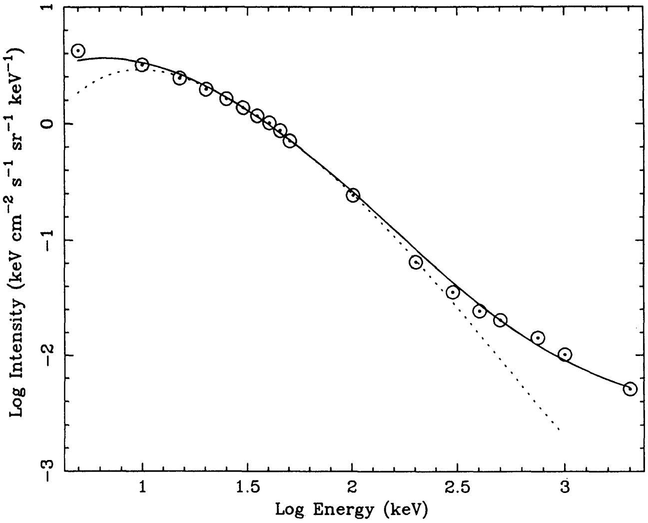

Figure 1. The spectrum of the XRB compared with the reflected spectrum from a population of sources evolving such that the volume emissivity varies as $(1+z)^4$ over the redshift range $0<z<5$. The observed spectrum is approximated by the ⊙ symbols; error bars on the intensity are very small below 40 keV and increase at higher energies. The reflection spectrum of a source at $z=1.5$, normalized to match the XRB at 30 keV, is shown by the dotted line. Acceptable fits are obtained if the maximum redshift is reduced, provided that the other parameters are changed appropriately. A 7 per cent contribution from the direct power-law continuum, of energy index 0.7, is included.

3 DISCUSSION

The reflected spectrum, redshifted to $z\sim1.5$, appears to provide good agreement with the XRB spectrum above 10 keV. The semi-infinite slab approximation is adequate provided that $\tau_T>3$, and the scattering material can be treated as cold provided its temperature is $<10^6$ K. The source parameters do not therefore have to be specific or standard. We do, however, have to specify the geometry, which must allow only 10 per cent at most of the direct hard emission to emerge. This confronts the question of what are the objects that create the spectrum.

We suggest that powerful AGN are responsible. Perhaps all AGN pass through an 'XRB producing phase' as they grow a central black hole by accretion at the Eddington limit. (Leiter & Boldt 1982 have made a similar suggestion but with a very different emission mechanism.) We picture that the accreting matter is either in an accretion disc which has puffed up to form a radiation torus around the central black hole, or that there are large numbers of dense blobs swarming around the central engine. (A hybrid version of these possibilities may be more realistic.) In both cases, most lines-of-sight to the core of the object, where the hard direct continuum originates, are obscured. Only 10 per cent, or less, of the lines-of-sight are unobscured. We do not speculate on the non-thermal emission processes responsible for the formation of the direct flux, but note that there is good empirical evidence for it in nearby AGN, where the reflection spectra are not dominant.

The reflection component producing the XRB in our model contributes little to the XRB below 3 keV, so we are not constrained by the fluctuation limits to the XRB observed there (Hamilton & Helfand 1987; Barcons & Fabian 1989) and just have to keep below the 'excess fluctuation' constraint in the 3–10 keV background of 2 per cent per 25 square degrees (Shafer & Fabian 1983). This requires that there be more than 100 sources per square degree, which means that the mean reflected X-ray luminosity of our sources should be less than $\sim10^{45}$ erg s^{-1} keV^{-1} at 10 keV ($H_0=50$ km s^{-1} Mpc^{-1}, $q_0=0.5$).

Most of the power produced by the central engine in our model is absorbed and re-emitted as thermal radiation by the radiation torus or blobs. The total observed intensity of the XRB is $\sim5\times10^{-8}$ erg cm^{-2} s^{-1} sr^{-1}, so the total reprocessed intensity is $\sim5\times10^{-8}(1-a)/a$ erg cm^{-2} s^{-1} sr^{-1} redshifted to the present epoch, where a is the mean energy albedo of the reprocessing material. This is considerably less than the intensity of the observed EUV and UV background limits of ~3–8×10^{-6} erg cm^{-2} s-1 sr^{-1} (see Holberg 1986 and Paresce 1989) unless $a<0.01$. At the energy where most of the XRB is emitted, ~30 keV, $a\approx0.4$; the effective value for the albedo should also include solid angle considerations, but these are unlikely to reduce a by an order of magnitude. Any contribution from multiple reflections or transmitted flux will be more sharply peaked around 30 keV, but the intensity will be low ($\sim a^2$) and the contribution unimportant unless the geometry is particularly favourable. There will also be some intrinsic thermal emission from the reprocessing material due to its accretion which reduces the *effective* mean albedo (i.e. the ratio of incident hard X-ray to emergent soft thermal power).

A stronger EUV background limit is obtained from estimates of the photo-ionizing flux in the intergalactic medium, of Lyman-α clouds and of galactic haloes. Studies over the past few years of quasar absorption clouds (see Steidel & Sargent 1989 and references therein) have shown that the intensity at the Lyman limit, $J=10^{-21}\,J_0$ erg cm^{-2} s^{-1} sr^{-1} Hz^{-1}, has $J_0>1$ at $1.5<z<3.5$. The direct radiation from QSO is insufficient for this purpose. The reprocessed emission from the sources producing the XRB corresponds to

$$J_0 \approx 1.3\left(\frac{1+z}{3}\right)^4\left(\frac{1-a}{a}\right)$$

if we assume that the emission peaks near the Lyman limit. The source of the XRB therefore appears to provide an intergalactic ionizing flux of adequate intensity as a by-product. Steidel & Sargent (1989) argue that the background cannot be primarily from young stars, because their emission is too soft to account for the relative strength of C IV in absorption line spectra. The actual spectrum of the reprocessed EUV background would be related to the characteristic temperature of the dense material close to the central non-thermal source (e.g. Guilbert & Rees 1988). This temperature would typically be $>10^5$ K, higher than that of OB stars, and therefore is also consistent with the observed excitation conditions in the absorbing clouds. If associated with the growth of QSO, as appears probable, then the ionizing flux from the thermal bump may persist to larger z than direct radiation may be observed.

Our model can be tested by direct measurement of the X-ray spectra of candidate objects such as QSO. We predict a very strong redshifted reflection hump (see Fig. 1) and a reprocessed emission bump in the EUV. A redshifted iron fluorescence line should be detectable below ~ 3 keV. The sources may be relatively weak in the soft X-ray band where most X-ray observations of QSO have so far been made. However, a small hot corona may surround the torus or blobs and Comptonize the EUV radiation into soft X-rays and make some of the sources detectable in that band. This could be responsible for the steep X-ray spectra of radio-quiet QSO (Wilkes & Elvis 1987; Canizares & White 1989). Studies of the influence of the EUV bump in Seyfert 1 galaxies on their emission-line regions suggest that there are no obvious diagnostic effects to be sought at optical wavelengths (Fabian *et al.* 1986; Mathews & Ferland 1987; Binette, Robinson & Courvoisier 1988).

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