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The extragalactic X-ray background at 0.25 keV

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We review recent results from shadowing experiments relating to the intensity of the extragalactic X-ray background at 0.25 keV. The measurements appear to be converging on a value in the range 20 → 35 keV cm^{-2} s^{-1} sr^{-1} keV^{-1}. The implication is that over 80% of the background signal at 0.25 keV may have been resolved into discrete sources in the deepest pointed observations carried out by ROSAT.

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1. Introduction

Although more than 30 years have passed since the discovery of the cosmic X-ray background (XRB), the origin of this phenomenon is still keenly debated. The observed isotropy of the background at energies above 3 keV establishes an extragalactic origin for this hard radiation. The current view is that the bulk of the X-ray through to gamma-ray background, which encompasses roughly 7 decades of the electromagnetic spectrum, is produced by discrete sources (see Hasinger 1996 and references therein).

In the soft X-ray regime the XRB exhibits a more complex spatial distribution. The onset of anisotropy is consistent with the emergence of one or more local components of the background with relatively soft spectral forms. In the 0.1–0.4 keV (hereafter 0.25 keV) band the average XRB intensity exceeds the extrapolated hard XRB spectrum by a factor ≥ 3, with regions at high Galactic latitude being generally brighter than the Galactic plane. There is good evidence that much of the emission is due to a $T \approx 10^6$ K plasma situated within the local low density cavity in the interstellar medium. However, based largely on ROSAT observations of shadows cast by discrete HI and molecular clouds, it has been possible, albeit for a restricted number of directions, to separate the very local soft X-ray emission from that arising in a much more extensive Galactic component. In this soft X-ray band, line-of-sight interstellar material gives rise to significant absorption[1] and the extragalactic signal is all but swamped by the Galactic emission.

Undoubtedly the best way of sorting out the various contributions to the soft XRB is through shadowing experiments. For example, if the shadow of an extragalactic object, say the disk of a spiral galaxy, can be detected against the 0.25 keV XRB then, provided the characteristics of the absorbing screen are reasonably well determined, the depth of the shadow provides a direct measurement of the intensity of extragalactic component at this energy. In the present paper we review recent results from ROSAT which now set quite tight constraints on the intensity of the extragalactic background at 0.25 keV.

2. Measurements and constraints

2.1. The pre-ROSAT situation

Prior to the launch of ROSAT the best measurements of the extragalactic 0.25 keV XRB intensity were obtained by the Wisconsin group. McCammon & Sanders (1990) quote an up-dated result from an earlier study of the SMC, namely that the 95% confidence upper limit for a flux originating beyond the SMC is 30 keV cm^{-2} s^{-1} sr^{-1} keV^{-1} at 0.25 keV. McCammon & Sanders also note that such measurements are strongly dependent on the assumed *line-of-sight absorption* through our Galaxy. Specifically, there may (at least in some directions) be additional

[1]At 0.25 keV unity optical depth corresponds to a column density of cold solar abundance gas of $\sim 10^{20}$ cm^{-2}.

opacity in the 0.25 keV band, over and above that implied by HI measurements, due to He I or HeII associated with an ionized component of the ISM (hereafter we refer to this as the Reynolds Layer, see Reynolds 1991). A plausible (but nevertheless very uncertain) estimate of the extra absorption due the putative Reynolds Layer leads to an increase in the McCammon & Sanders upper limit on the 0.25 keV extragalactic XRB flux by a factor of ~ 1.5.

2.2. ROSAT studies of the primary Lockman Hole

The primary Lockman Hole is the region of the sky with the lowest line-of-sight column density through the Galactic HI distribution (Lockman, Jahoda & McCammon 1986) and so affords the clearest view of extragalactic sky at 0.25 keV. As such this region has been studied extensively by ROSAT both via the all-sky survey and in deep pointed observations. Hasinger et al. (1993) found the integrated spectrum of the resolved source population in the deep Lockman Hole survey to be a power-law ($I(E) = 7.8 \times E^{-0.96}$) with an absorption column equivalent to 8.7×10^{19} cm^{-2}. This implies a *lower limit* to the 0.25 keV XRB intensity of 29.5 keV cm^{-2} s^{-1} sr^{-1} keV^{-1} assuming that all the absorption is attributable to our Galaxy (i.e. an HI column of 5.3×10^{19} cm^{-2} plus an additional component of 3.4×10^{19} cm^{-2} due to the Reynolds Layer). An alternative interpretation is that the apparent absorption in excess of the HI column is due to a spectral turnover intrinsic to the source population, in which case the lower limit must be modified to ~ 20.5 keV cm^{-2} s^{-1} sr^{-1} keV^{-1}. Similarly an *upper limit* on the background intensity can be obtained from the results of Snowden et al. (1994), who demonstrate that $\sim 40\%$ of the diffuse 0.25 keV flux measured in the direction of the Lockman Hole must originate beyond the local HI distribution. The derived upper limit to the extragalactic background intensity is either 45 or 65 keV cm^{-2} s^{-1} sr^{-1} keV^{-1} depending on whether the Galactic absorption factor excludes or includes an estimate for the Reynolds Layer component.

2.3. ROSAT measurements of extragalactic shadows

The high sensitivity to low surface brightness features, good spatial resolution and the low instrumental background provided by the combination of the ROSAT XRT/PSPC has lead to a revolution in our knowledge of the soft X-ray background. Many observations with ROSAT have been aimed at exploiting shadowing techniques to unravel the complexity of this background. In attempting to measure the extragalactic XRB at 0.25 keV by shadowing techniques it is desirable that (i) there is a low Galactic HI column density along the line-of-sight to the target; (ii) the object casting the shadow is not a bright source of soft X-rays (so as to avoid the "filling-in" of a putative shadow); (iii) the absorbing screen subtends an adequate solid angle and (iv) a high resolution map of the HI in the target is available. In practice extragalactic shadowing experiments are limited by the fact that there are few, if any, targets which closely match all of these requirements. Types of objects potentially suitable as shadowing targets include High Velocity Clouds (HVCs), interacting galaxies and normal galaxies.

The largest group of HVCs is the Magellanic Stream which probably represents gas tidally stripped from the Magellanic Clouds following their passage close to our own Galaxy. The material of the Magellanic stream is distributed in the sky along a great circle which passes close to the Galactic South Pole. Components of the Magellanic Stream may in the future provide useful shadowing targets but unfortunately no detailed studies have so far been completed relevant to the question of the extragalactic XRB intensity.

Interacting galaxies could, potentially, be excellent targets for shadowing experiments, since the gravitational influence they exert over each other tends to tidally disrupt their HI clouds, often resulting in the trailing of long "plumes" of HI over a considerable distance from the galaxy. Barber & Warwick (1994) utilised this approach in their investigation of the extended HI cloud associated with the NGC 4747/4725 galaxy pair. These authors obtained a 95% upper limit on the XRB intensity of 40 (52) keV cm^{-2} s^{-1} sr^{-1} keV^{-1} (here and below the value given in brackets, if available, refers to the case where extra absorption due to Reynolds Layer gas is included). A note of caution, however, in attempting to exploit interacting galaxies in this way is that the interaction may lead to an increased X-ray luminosity due to the triggering of star-formation activity.

Most recent studies have focussed on individual late-type spiral galaxies in either face-on or edge-on configurations. For example, Snowden and Pietsch (1995) report the detection of an apparent absorption feature coincident with a spiral arm of the supergiant spiral galaxy M 101 and from the deficit in counts derive an intensity of 28 ± 10 keV cm^{-2} s^{-1} sr^{-1} keV^{-1} at 0.25 keV. This was the first published value to be considered as a direct measurement by the authors rather than as a lower limit (the latter is the conservative approach if in-filling of the shadow due to the intrinsic soft X-ray emission of the target is suspected). Cui et al. (1996) considered ROSAT observations of several nearby face-on spiral galaxies; these authors quote a 95% *lower limit* of 26 (32) keV cm^{-2} s^{-1} sr^{-1} keV^{-1} based on a conspicuous shadow observed in NGC 3184. A similar lower limit has also been reported by Vogler, Pietsch & Bertoldi (1997) based on a study of NGC 4559.

ROSAT observations have also been used to search for a shadow in the 0.25 keV X-ray background cast by the disk of the nearby spiral galaxy NGC 55 (Barber, Roberts & Warwick 1996). Several factors including the

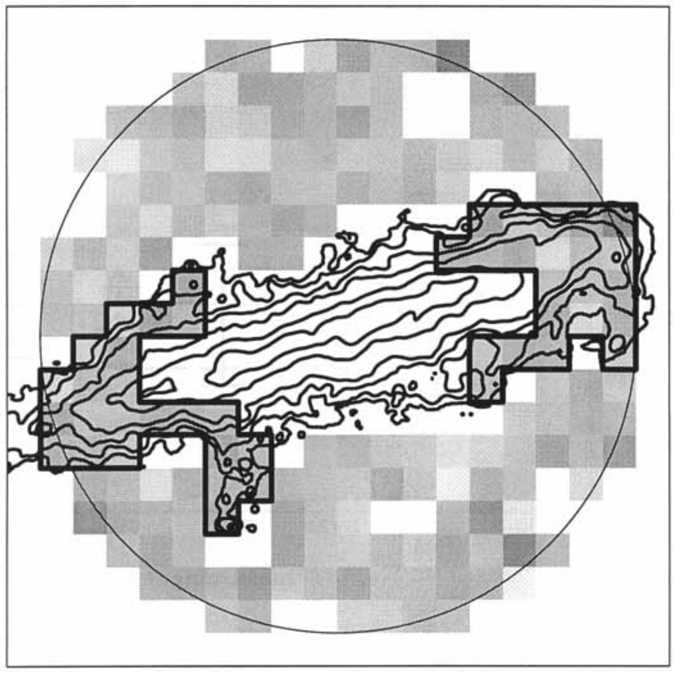

Fig. 1: The ROSAT PSPC observation of the nearby galaxy NGC 55 in the 0.25 keV band. The circle corresponds to the inner (18′ radius) region of the PSPC field of view. The background measurements have been binned into pixels of 2 × 2 arcmin^2. The contour levels corresponding to HI column densities of 0.5, 2, 5, 10, 30 and 60 × 10^{20} cm^{-2}. The "on-source" pixels used in the shadowing measurements are enclosed by the thick lines

close to edge-on aspect and the extensive HI disk make NGC 55 an excellent target in which to search for such effects. The ROSAT PSPC image reveals a deficit of 0.25 keV counts coincident with the outer disk of NGC 55 (see Figure 1). From the depth of the shadow Barber et al. estimate the total extragalactic background signal at 0.25 keV to be 29.4 ± 7.2 (35.7 ± 10.2) keV cm^{-2} s^{-1} sr^{-1} keV^{-1}. More recently Roberts & Warwick (1997) have reanalysed the ROSAT PSPC observation of NGC 55, NGC 3184 and three other late-type spirals in a consistent and rigorous fashion and obtain the best constrained measurements so far available of the 0.25 keV XRB intensity, namely 24.8 ± 4.9 (26.9 ± 6.8) keV cm^{-2} s^{-1} sr^{-1} keV^{-1}.

3. Discussion

The recent measurements of the 0.25 keV XRB intensity from shadowing experiments appear to be converging towards a definitive value in the range 20 → 35 keV cm^{-2} s^{-1} sr^{-1} keV^{-1} (see Figure 2). The recent work of Roberts & Warwick (1997) suggests that the underlying systematic uncertainty due to the absence or presence of a Reynolds Layer component may have been overestimated in some previous studies, with the difference now amounting to only a 10% effect. It seems likely we are approaching the limit of what is possible with the ROSAT PSPC, with the statistical errors on the measurements now comparable to the likely residual systematic uncertainty.

Combining the Roberts & Warwick (1997) measurement of the 0.25 keV XRB intensity with an estimate of the normalisation of the extragalactic background at 1 keV (i.e. 10 ± 1.5 keV cm^{-2} s^{-1} sr^{-1} keV^{-1}) yields an effective slope for the XRB in the 0.25 – 1 keV energy range of $\alpha = 0.66^{+0.24}_{-0.27}$ ($\alpha = 0.71^{+0.28}_{-0.31}$). Since a significant fraction of the 1 keV XRB has been resolved into sources which have steeper spectra than this, the implication is that an even higher fraction of the 0.25 keV background has been resolved. Specifically, the resolved fraction is 83^{+17}_{-14}% (100^{+0}_{-12}%). Thus the observed XRB intensity at 0.25 keV is largely accounted for by known source populations. This is also consistent with the observation that source spectra get harder (on average) as the flux density decreases (e.g. Vikhlinin et al. 1995), a trend which if continued implies little contribution to the 0.25 keV band by sources below the survey limit of current deep ROSAT observations.

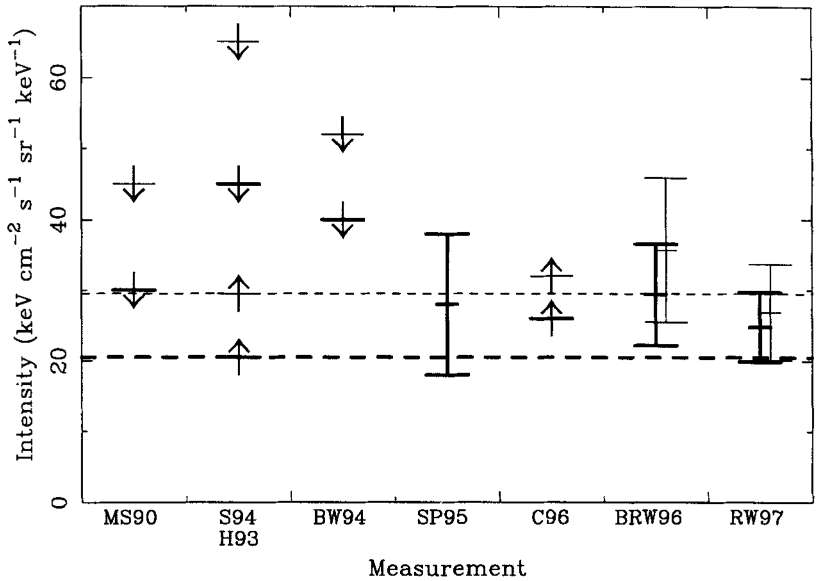

Fig. 2: Recent limits on the 0.25 keV XRB intensity. The measurements, shown in chronological order, are: MS90 - McCammon & Sanders (1990); H93, S94 - Hasinger et al. (1993), Snowden et al. (1994); BW94 - Barber & Warwick (1994); SP95 - Snowden & Pietsch (1995); C96 - Cui et al. (1996); BRW96 - Barber, Roberts & Warwick (1996); RW97 - Roberts & Warwick (1997). Measurements are shown without (thick lines) and with (thin lines) the inclusion of a Reynolds Layer component, which in most cases is assumed to be equivalent to 5×10^{19} cm^{-2}. The dotted lines show the minimum calculated contributions of the resolved sources.

4. Conclusions

Shadowing measurements appear to be converging on a value for the 0.25 keV extragalactic XRB intensity in the range 20 → 35 keV cm^{-2} s^{-1} sr^{-1} keV^{-1}. The 0.25 keV background intensity is an important input for discrete source models of the XRB, and constrains both the form of the intergalactic ionizing continuum at z=0 and the possible contribution to the soft XRB of a putative "not-so-hot" intergalactic medium (e.g. Cen et al. 1995). It is also an important parameter for global models of the soft X-ray background and when mapping the extent of the soft X-ray emission associated with spiral galaxies.

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