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Observations of the darkest regions in the sky: X-ray shadowing by the Bok globule Barnard 68

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Abstract. The densest and closest absorbers of the soft X-ray background (SXRB) in the Milky Way are Bok globules, located just outside the Local Bubble in the Pipe Nebula at a distance of 125 pc. With column densities of up to $N_{\rm H} \sim 10^{23}\,{\rm cm}^{-2}$, they are ideal targets for shadowing the SXRB in the energy range 0.1 − 2 keV, thus giving important information on the spatial and spectral variation of the foreground X-ray intensity on small scales. Preliminary analysis of a recent *XMM-Newton* EPIC observation of the Bok globule Barnard 68 has revealed a deep X-ray shadow cast by the globule. The shadow is deepest at an energy of ∼ 800 eV. Oxygen line emission at ∼ 560 and ∼ 660 eV seems to originate at least partially in the foreground.

Key words. *XMM-Newton* – interstellar medium – soft X-ray background – X-ray shadowing – Local Bubble

1. Background

Since its discovery in 1968 (Bowyer et al. 1968) the soft X-ray background (SXRB) below 2 keV has been understood only rudimentarily due to its complexity. The following major components have been identified: (i) unresolved Galactic point sources (e.g. stars, accreting compact objects), (ii) unresolved extragalactic point sources, comprising about 80% of the total emission (e.g. AGNs), (iii) diffuse *local* emission (Local Bubble, Loop I), (iv) diffuse *distant Galactic* emission (hot ISM and Galactic halo), (v) a recently proposed (Cen & Ostriker 1999) diffuse warm-hot *intergalactic* medium (WHIM), and perhaps, (vi) a yet unquantified very local emission component due to charge exchange reaction of solar wind ions with heliospheric gas (Lallement, private communication).

Since any observation of diffuse soft X-ray emission will always be "contaminated" by the Local Bubble (and possibly ISM and/or halo), it is extremely important to have a 3D emissivity profile as well as detailed spectral information of the Local Bubble emission. One of the most promising techniques to extract *morphological* and *spectral* information of diffuse emission regions, which has been successfully applied with the ROSAT PSPC instrument, was the shadowing of nearby clouds (Snowden et al. 1991, Burrows & Mendenhall 1991). This method allows to disentangle foreground from background emission, if the distance to the absorbing cloud and its column density

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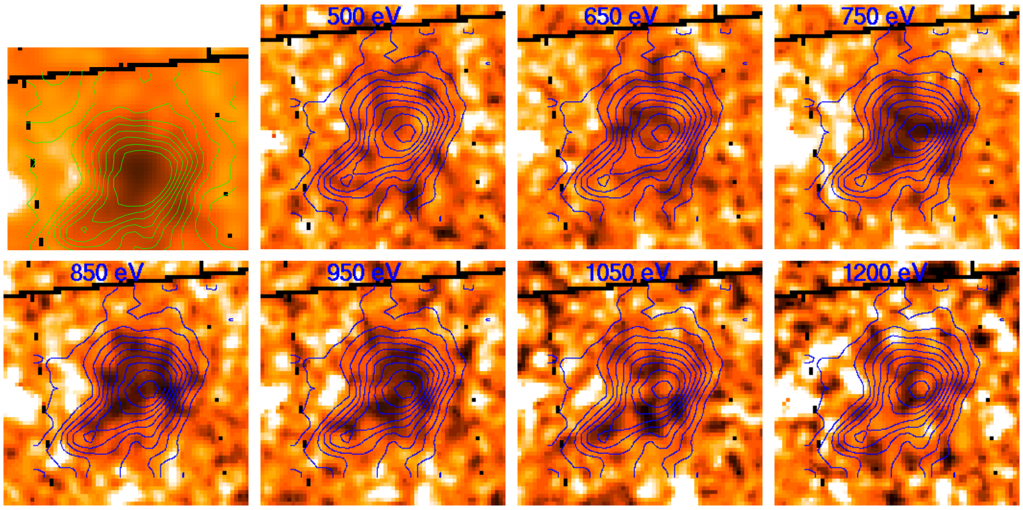

Fig. 1. X-ray images of the Bok globule Barnard 68: in the upper left the total intensity in the 0.4 – 1.3 keV band is displayed (with contours indicating the absorption due to the cloud); the other images show narrow bands (±100 eV around the indicated energies), from left to right at 500, 650, 750 (top panel), 850, 950, 1050, and 1200 eV (bottom panel), respectively. The X-ray shadow is clearly evident in the 0.5 – 1.0 keV range. Most of the Fe-L emission at ~ 850 eV originates in the background, and the shadow is much weaker at the oxygen line energies (< 700 eV).

along the line of sight are known. Moreover, if there exists a density gradient across the cloud surface, this will act as an energy dependent filter of soft photons, and will give important spectral information on the SXRB. Such an endeavour relies heavily on the existence of absorbers with *high* column densities at *known* distances, both of which are hard to find. There is at present only one molecular cloud – MBM12 – which is most likely located *inside* the Local Bubble at a distance d of $58 \pm 5 < d < 90 \pm 12$ pc (Hearty et al. 2000). Snowden et al. (1993) have detected a soft shadow in the 1/4 keV PSPC band and an uncertain amount of 3/4 keV foreground emission up to 20%, but with large error bars, since with a column density of only $2.4 - 5.5 \times 10^{21}$ cm^{-2} the cloud becomes transparent above 0.7 keV. Thus it gets increasingly difficult to disentangle foreground and background emission at higher energies. By fitting an absorption model to only the 1/4 keV emission it was concluded that the Local Bubble spectrum is consistent with no flux in the 3/4 keV band. However, including all energy channels in the spectral fit and therefore accounting also for background contributions, we were able to show by reanalyzing the PSPC data as well as using *XMM-Newton* EPIC-pn data, that the best fit model shows indeed a significant amount of 3/4 keV band foreground emission (Freyberg & Breitschwerdt 2004). However, the existence of a higher energy thermal emission component in the Local Bubble would be in conflict with standard models based on pure collisional ionization equilibrium (CIE) (Snowden et al. 1990), but is naturally explained by non-equilibrium (NEI) models (Breitschwerdt & Schmutzler 1994, Breitschwerdt 2001). Observations with instruments of higher spectral resolution, such as the Diffuse X-ray Spectrometer (DXS) (Sanders et al. 2001) and more recently, from a suborbital flight of a microcalorimeter array (McCammon et al. 2002), have shown that the obtained spectra are inconsistent with standard CIE fits of optically thin plasmas (however, the

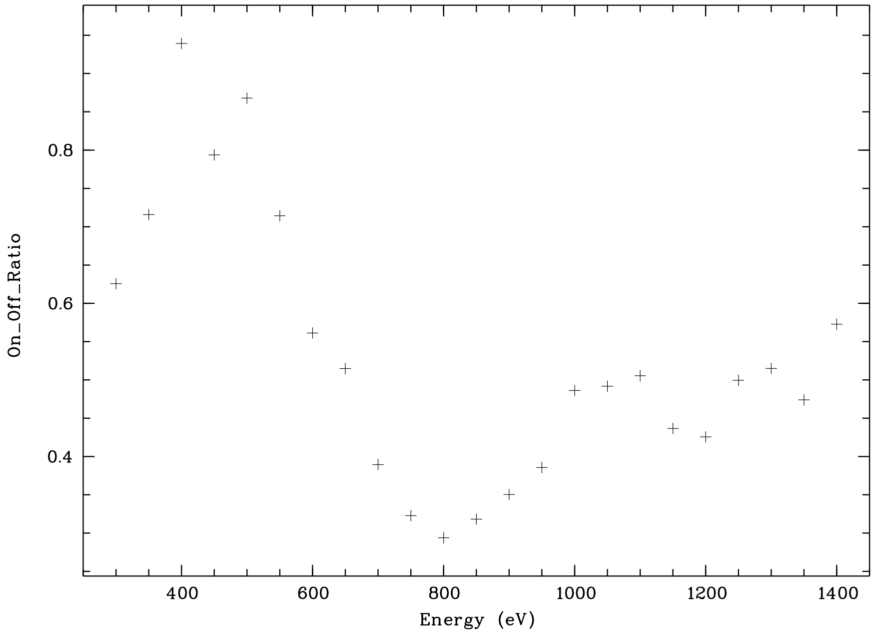

Fig. 2. Depth of the X-ray shadow (ratio of on-cloud to off-cloud intensities) for the Bok globule Barnard 68 as function of energy. This shows that a significant fraction of the emission below 600 eV originates in the foreground of the cloud.

observations sampled large portions of the sky and thus the spectral contributions may come from different regions along the line of sight). In order to perform a detailed comparison, 3-D hydrodynamic simulations were developed including fully time-dependent evolution of non-equilibrium ionization states (Avillez & Breitschwerdt 2003).

2. Results

Advancement in the shadowing technique for detailed spectral studies requires that the ideal absorber should have the following properties: (i) high column density, (ii) well determined distance, (iii) suitable surface area to cover a substantial (but not all) fraction of the detector, and (iv) a strong column density gradient.

Nearby Bok globules fulfill these conditions to a high degree and bear the potential to unambiguously pin down the foreground spectrum. These objects, located in the Pipe Nebula, have largely escaped the attention of observers until very recently (Alves et al. 2001). The extinction values cover a huge dynamic range from 0.5 – 53 mag in A_V. These values correspond to $N_{\rm H} \sim$ few 10^{20} to > $10^{23}\,{\rm cm}^{-2}$. Using a recent *XMM-Newton* observation of the Bok globule Barnard 68 we can analyze the foreground spectrum in an unprecedented energy range from 0.3 – 1 keV, in which all background emission is efficiently blocked off, as can be seen from the deep shadow cast by Barnard 68, in all energy bands from 0.4 – 1.3 keV (cf. Fig. 1).

In addition about 70% of the line of sight passes through the Local Bubble, which extends about 85 pc (cf. NaI contour maps of Sfeir et al. 1999 in this direction). The globules are intrinsically small (~ 20000 AU), but due to their proximity they span several arcminutes in size. A spectroscopic study of the Pipe Nebula (Onishi et al. 1999) revealed that it is indeed one molecular complex without interlopers (background or foreground clouds). Due to the interconnection of the globules, we can then in a straightforward manner exploit the huge range in column density (10^{20} –

$10^{23}\,\mathrm{cm}^{-2}$) and study spatial and spectral variations of the diffuse emission in the Local Bubble. Since the Pipe Nebula is located *inside* the Loop I superbubble, although much closer to the periphery than to the centre, we can also study spatial and spectral variations of the soft X-ray emission in Loop I. The latter should be possible, because we could show by our analysis of the Ophiuchus cloud (which is also inside the Loop I) *XMM-Newton* data that the Local and Loop I plasmas have different *spectral* characteristics (Freyberg & Breitschwerdt 2003), with Loop I showing prominent foreground and background Fe-L line emission, which is absent in sightlines towards other targets, e.g. MBM 12, G133-69. Barnard 68 shows an even deeper shadow than the Ophiuchus cloud. The ratio of off-cloud to on-cloud intensity as a function of energy is shown in Fig. 2. The minimum is at the Fe-L energies while O VIII is more blocked off than O VII though the absorption is less at higher energies, confirming that most of the O VIII is produced in the background. A detailed spectral analysis of the Ophiuchus molecular cloud and of the globule Barnard 68 will be presented elsewhere (Breitschwerdt & Freyberg 2004). In conclusion, the *XMM-Newton* data on Barnard 68 strengthen our previous findings of clear evidence for 3/4 keV emission from the foreground.

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