Soft X-rays from High-Velocity Clouds

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Abstract. The ROSAT mission gave us the unique possibility to study the galactic interstellar medium by “shadowing” observations on arcmin angular resolution level. The high sensitivity of the ROSAT PSPC in combination with the large field of view allows the detailed study of individual clouds, while the ROSAT all-sky survey is the main source for studies of the large-scale intensity distribution of the diffuse soft X-ray emission.

We show that neutral hydrogen clouds are associated with soft X-ray emission, \( E_{\text{X-ray}} \leq \frac{1}{4}\text{keV} \). These neutral hydrogen clouds, known as high-velocity clouds (HVCs), are located partly within the galactic halo, and partly in intergalactic space. The ROSAT detection of soft X-ray emission from some of these HVCs is the first detection of HVCs in emission other than H\textsubscript{i} 21-cm line radiation.

1. Introduction

The standard method for the analysis of an individual X-ray source is the subtraction of the background from the observed total count rate. This approach overcomes the main uncertainties introduced by the so-called non-cosmic X-ray background radiation as well as residual contamination by scattered solar X-rays. However, if the background radiation itself is the main interest, one needs excellent detectors and a clear understanding of the residual contamination of the data, which is not automatically rejected by the detector electronics or the raw-data processing.

The ROSAT PSPC was a superb detector to investigate the background emission, especially for the analysis of the soft X-ray emission within the \( \frac{1}{4}\text{keV} \) band. Towards the high galactic latitude sky, the product of the neutral hydrogen column density and the interstellar photoelectric absorption cross section reaches at least unity within the \( \frac{1}{4}\text{keV} \) energy band. Accordingly, \( \frac{1}{4}\text{keV} \) soft X-ray shadows of individual clouds are expected for clouds located in front of an extended X-ray source.

The first maps of the diffuse soft X-ray background (McCammon et al. 1983) did not resolve individual cloud shadows, but confirmed the general negative correlation between the soft X-ray background intensity distribution and the galactic neutral hydrogen distribution (Bowyer, Field and Mack 1968). Moreover, the Wisconsin survey established the existence of a \( T \approx 10^6\text{K} \) plasma in the local void of neutral matter, the so-called local hot bubble (LHB, Cox & Reynolds 1987).

One of the first major discoveries of the ROSAT mission was the detection of the “Draco shadow” by Snowden et al. (1991). The \( \frac{1}{4}\text{keV} \) shadow of this cloud, which is located outside the LHB, gave evidence for an X-ray emitting plasma beyond the LHB. This X-ray emitting plasma within the galactic halo was attributed to an individual hot spot (Burrows & Mendenhall 1993). During the course of the ROSAT mission, more \( \frac{1}{4}\text{keV} \) X-ray shadows of neutral clouds were discovered (i.e. Kerp et al. 1993, Snowden et al. 1993, Herbstmeier et al. 1994).

There has been a lot of discussion about whether the distant X-ray emission is associated with a smoothly distributed X-ray emitting plasma within the galactic halo (Kerp et al. 1999, Pietz et al. 1998, Freyberg 1997) or whether it is the superposition of individual scattered hot spots (Snowden et al. 1998, Shelton 1998).

In this paper we will demonstrate that a smooth, constant intensity distribution of the halo X-ray plasma, quantitatively fits the observed soft X-ray background (SXRB) intensity distribution (Sect. 2) very well. This modelling of the SXRB intensity distribution allows us to disclose sky areas of too faint or too bright soft X-ray emission. This approach provides evidence that some HVCs are associated with \( \frac{1}{4}\text{keV} \) soft X-ray emission (Sect. 3).

2. Modelling the SXRB

Figure 1 shows the application of our model to the SXRB intensity distribution, step-by-step. The intensity profiles (Fig. 1 left) are extracted from the corresponding maps (Fig. 1 right). The arrows mark the (constant) galactic latitude position of the slices, while the intensity profiles are a function of the galactic longitude. Fig. 1(c) shows the assumed constant intensity distribution of the X-ray halo.

The unabsorbed intensity level seen on the y-axis of the intensity profile is \( I_{\text{halo}} = 25 \cdot 10^{-4}\text{cts}\text{s}^{-1}\text{arcmin}^{-2} \).
In panel b), the soft X-ray attenuating column density distribution of $N_{\text{HI}}$ is shown. Black indicates low column densities, and white high column densities. On the left the corresponding slice at $b = 40^\circ$ shows that the column density, $N_{\text{HI}}$, varies between 1 to $5 \cdot 10^{20}$ cm$^{-2}$.

Panel c) shows the modelled $1/2$ keV intensity distribution of $I_{\text{halo}}$ (panel a) absorbed by the galactic interstellar matter (NIC: panel b). The longitude profile on the left $I_{\text{halo}}$ is attenuated by a factor of 3 to 5. The minimum X-ray intensity level of $I_{X-\text{ray}} = 5 \cdot 10^{-4}$ cts s$^{-1}$ arcmin$^{-2}$ is a superposition of the attenuated $I_{\text{halo}}$ and the foreground $I_{\text{LHB}} = 3 \cdot 10^{-4}$ cts s$^{-1}$ arcmin$^{-2}$. Thus, towards high $N_{\text{HI}}$ regions, only 40% of the detected X-ray photons have their origin in the galactic halo plasma; the rest originates from the LHB. The unabsorbed intensities are $I_{\text{halo}} / I_{\text{LHB}} \geq 8$.

Finally, in panel d), we present the ROSAT all-sky survey data for this $25^\circ \times 25^\circ$ region. The left panel shows a superposition of the observed intensity-profile at $b = 40^\circ$ from the ROSAT all-sky survey data and the modelled intensity profile (thick line). Considering the uncertainties in the ROSAT all-sky survey data of about $\Delta I_{X-\text{ray}} \approx 0.8 \cdot 10^{-4}$ cts s$^{-1}$ arcmin$^{-2}$, the observed and modelled intensity profiles agree very well.

Using this method, Kerp et al. (1999) analysed four large areas of the X-ray sky to search for signatures of HVCs. They proved statistically that the modelled and observed map intensity distributions match perfectly.

3. X-rays from HVCs

Kerp et al. (1999) analysed four large fields using the method described above, to search for signatures of HVCs in the ROSAT all-sky survey data. In Fig. 3, we show a mosaic of the ROSAT all-sky survey data towards the HVC complex C. The ROSAT all-sky survey field described in Fig. 1 is the lower right area of the mosaic. Because of the well modelled intensity distribution of the “normal” SXRB (Fig. 4), we can now examine areas of excess soft X-ray emission by subtracting the model from the observed SXRB intensity distribution. Excess SXRB emission is defined here more significant as residuals $> 5\sigma$ (Fig. 2). Most of the SXRB emission is modelled well, and no large-scale excess emission is found. The distribution of the soft X-ray excess is patchy, with the most prominent one located close to the position of the Draco cloud ($l \sim 90^\circ$, $b \sim 39^\circ$). Overall, the galactic X-ray halo has a smooth large-scale-intensity distribution, while close to some of the HVCs bright excess soft X-ray patches are located.

Superimposed on the excess soft X-ray emission (grey-scale in Fig. 3) as contours, is the $^{1}$H$^{\text{I}}$ column density distribution of HVC complex C. Although there is no one-to-one positional correlation between the excess X-ray emitting areas and the HVCs, the places where SXRB excesses are seen do coincide with the locations of HVCs.

Kerp et al. (1999) found a total of 12 excess X-ray emitting areas. Integrated over the whole excess area, the detected excess $1/2$ keV energy is about $E_{\text{det}} = 1 \cdot 10^{-10}$ erg s$^{-1}$ cm$^{-2}$. Accordingly, the unabsorbed $1/2$ keV X-ray flux is about $E_{\text{rad}} = 5 \cdot 10^{34}$ erg s$^{-1}$ ($E_{\text{rad}} \propto \frac{N_{\text{HI}}}{D^{2}}$). The maximum in the ROSAT $1/2$ keV data is $E_{\text{rad}} \sim 10^{36}$ erg s$^{-1}$, which is only a tiny fraction of the available kinetic energy of HVC complex C ($E_{\text{kin}} \sim 10^{53}$ erg).

The emission measure is about $EM = 0.03$ cm$^{-6}$ pc, which is roughly 6 times higher than the emission measure of the galactic halo plasma ($EM_{\text{halo}}(b = 90^\circ) = 5 \cdot 10^{-3}$ cm$^{-6}$ pc, Pietz et al. 1998). The high excess emission measure implies, that the HVC material itself may be partly ionised and heated up to temperatures of about $T = 10^{6.2}$ K (Kerp et al. 1999). If we compare the volume densities of the electrons and of the neutral hydrogen atoms, we find that $n_{e}/n_{\text{HI}} \approx 0.3 \cdot (b/90^\circ)^{-2}$. If we assume that HVCs are “pure” hydrogen clouds, this ratio is an estimate of the ionisation fraction of the atomic hydrogen ($N_{\text{HII}}/N_{\text{HI}}$). We can invert the electron-to-neutral-hydrogen atom density ratio to calculate the distance for a completely ionised hydrogen HVC to be $D > 11$ kpc. This distance limit is close to the observationally determined upper distance limit (van Woerden et al. 1998) and those based on theoretical considerations (Blitz et al. 1998). We can interpret this high ionisation of HVCs in two ways:

First, the determination of the emission measure may be in error, because the collision equilibrium plasma models do not fit the real situation. Second, a significant fraction of the HVCs hydrogen is not neutral, so the HVCs may have a larger extent and contain more mass than the neutral hydrogen indicates. This might explain the obvious positional offset between the bright soft X-ray enhancements and the neutral hydrogen column density distribution. Also, some of the $^{1}$O$^{\text{II}}$ emission maxima are found to be not positionally coincident with $N_{\text{HI}}$ maxima (i.e. MI-cloud position 6a, Tufte, Reynolds and Haffner 1998).

Further studies of the X-ray emission of HVCs will be carried out by correlating the ROSAT all-sky survey and the Leiden/Dwingeloo survey, as well as through future XMM observations.

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Fig. 1. The soft X-ray radiation transport of 1/2 keV photons through the galactic interstellar medium. **Right:** b) The distribution of the 1/2 keV absorbing interstellar matter, traced by the HI 21-cm column density distribution (Hartmann & Burton 1997). c) The SXRB intensity distribution of the constant HI column density (panel a) after the transition through the absorbing medium (panel b)). d) The ROSAT all-sky survey data of the same region. The comparison of the maps in panels c) and d) shows an excellent agreement between the model and the observations. **Left:** Intensity profiles at b = 40° from the maps on the right. Superimposed on the intensity profile of the ROSAT all-sky survey map in panel d), is the intensity profile from the model in panel e). The maps on the right cover an area of about 25° × 25°. The values of $I_{X-ray}$ and $N_{HI}$ are given by the labelling of the left-hand side panels. The $I_{LHB} = (2.8 \pm 0.5) \times 10^{-4} \text{cts s}^{-1} \text{arcmin}^{-2}$, which is nearly an order of magnitude fainter that $I_{halo}$ (panel a).

Fig. 2. Mosaic showing the 1/2 keV and HI data towards HVC complex C. **Top left:** The ROSAT 1/2 keV map towards HVC complex C. **Top right:** The HI column density map of the same field of view, extracted from the Leiden/Dwingeloo survey within the velocity range $v_{LSR} \in [-100; +100] \text{km s}^{-1}$. **Bottom:** The positional correlation of excess 1/2 keV emission and the HVC (left) and IVC (right) $N_{HI}$ distributions towards the HVC complex C. The images present the areas of excess soft X-ray emission in the significance range $4\sigma$ (black) to $10\sigma$ (white). **Bottom left:** The HVC $N_{HI}$ distribution ($-450 < v_{LSR} < -100 \text{km s}^{-1}$) superposed as contours with $1 \times 10^{19} \text{cm}^{-2} \leq N_{HI} \leq 1 \times 10^{20} \text{cm}^{-2}$ in steps of $\Delta N_{HI} = 1 \times 10^{19} \text{cm}^{-2}$. **Bottom right:** The IVC $N_{HI}$ distribution ($-75 < v_{LSR} < -25 \text{km s}^{-1}$) superposed as contours with $5 \times 10^{19} \text{cm}^{-2} \leq N_{HI} \leq 2 \times 10^{20} \text{cm}^{-2}$ in steps of $\Delta N_{HI} = 2.5 \times 10^{19} \text{cm}^{-2}$. The HVC $N_{HI}$ distribution follows the orientation of the soft X-ray enhancements. The $N_{HI}$ maxima of the IVCs are not positionally coincident with excess X-ray areas, except near $l \sim 102°, b \sim 37°$, close to the Draco nebula, and near $l \sim 118°, b \sim 42°$. Both IVCs are located close to HVCs and perhaps link both cloud populations.

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