

Diffuse X-ray Background Constraints on Models of the Local Interstellar Medium

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Abstract. There is a flux of soft X-rays (0.07-0.284 keV) of diffuse origin observable over the entire sky. As X-rays of this energy are strongly absorbed by the interstellar medium (ISM), one optical depth is $10^{19} - 10^{20} \text{ H cm}^{-2}$, they provide a unique probe of neutral material in the solar vicinity. However, to be an effective probe requires that the distribution of emission be well understood, a requirement that is currently unfulfilled (although progress is being made), with unclear fractions originating in the Galactic halo, Local Hot Bubble, heliosphere, and Earth's magnetosheath. The various available data, their consistency (or lack thereof), and their implications for understanding the very local ISM are briefly discussed.

1. Introduction

The canonical view of the diffuse X-ray background has it comprised of a complicated combination of emission and absorption regions. Working inwards from cosmological distances, there is the extragalactic background dominated by emission from unresolved AGN, external galaxies, groups and clusters of galaxies, and the cosmic web. Closer to the Sun there is emission from the halo and central bulge of the Milky Way. The halo emission likely consists of a hotter extended (large scale height) component (kT~0.25 keV) and a cooler (kT~0.1 keV) clumpy component lying closer to the disk. Within the disk of the Galaxy, sometimes extending into the halo, are supernova remnants, superbubbles, and other regions of X-ray emitting plasma. In the Sun's backyard, the heliosphere is surrounded by the Local Cloud (LCI), which in turn is located within a bubble of hot (kT~0.1 keV) plasma called the Local Hot Bubble (LHB). Within the heliosphere there is extensive X-ray emission from solar wind charge exchange with interstellar neutrals passing through the solar system, as well as with exospheric hydrogen in Earth's magnetosheath. In addition, all of the emission originating beyond the LHB is moderated by absorption by the foreground neutral or molecular material in the ISM. Nearly all diffuse emission in the 0.07-1.5 keV band is thermal or charge exchange in origin, and therefore dominated by line emission, for the most part the same lines. However, observation technology is insufficient for the use of velocity information to constrain the distance to the emission, or to examine the difference between thermal and charge exchange emission. To further complicate the issue, the thermal emission regions have a variety of temperatures and absorption is strongly energy dependent.

Figure 1 shows images of the $\frac{1}{4}$ keV and $\frac{3}{4}$ keV sky. The structure of the X-ray sky appears quite different in the two energy bands due both to different absorption cross sections as well as the differences in the distributions of the emitting plasma at different temperatures. However, the $\frac{1}{4}$ keV



band serves as better probe of the local ISM as absorption reaches one optical depth at $\sim 10^{20}$ H I cm^{-2} , a better match with nearby column densities.

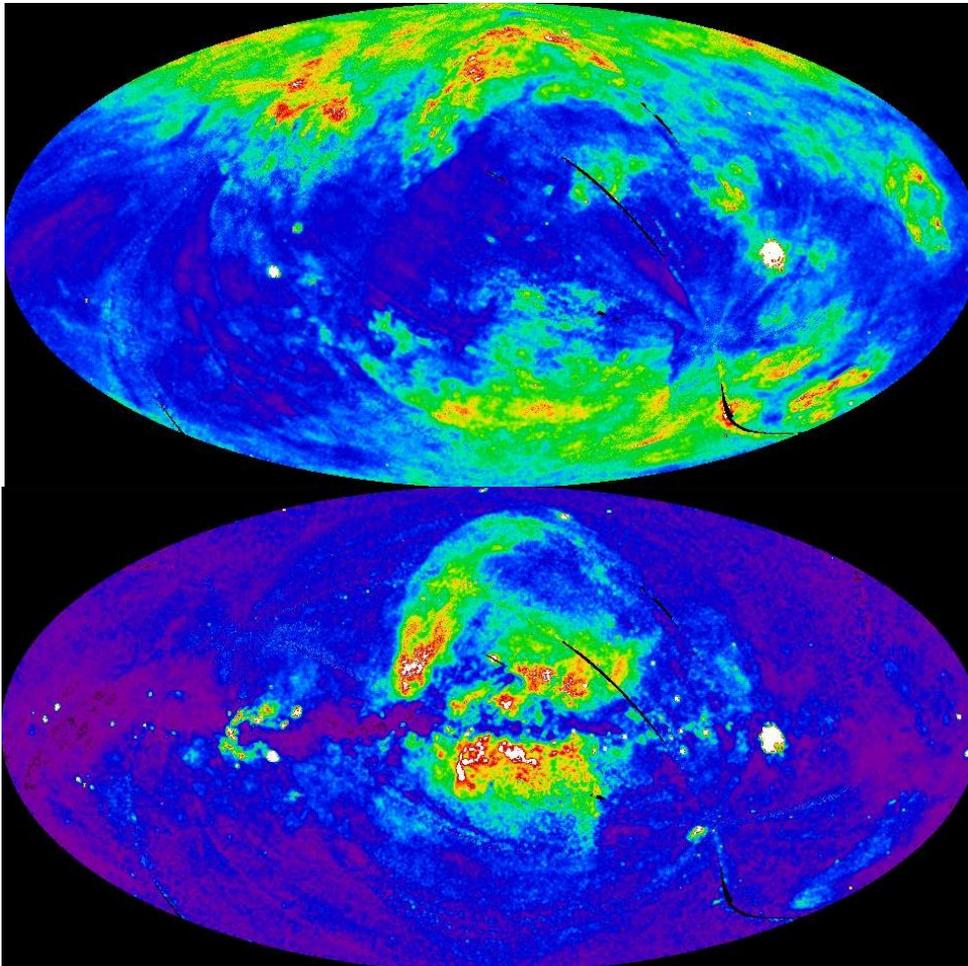


Figure 1. ROSAT All-Sky Survey maps of the $\frac{1}{4}$ keV (upper) and $\frac{3}{4}$ keV (lower) diffuse X-ray background. The images are in Aitoff-Hammer equal-area projections in Galactic coordinates, centred on the Galactic centre, with longitude increasing to the left and the north Galactic pole at the top. The false colour images show dim areas as purple and bright areas as red/white [1].

2. Setting the stage – the cool part of the local ISM

There is a deficiency of H I in the local ISM that is easily seen in plots of the average column density as a function of Galactic latitude (e.g., [2], see Figure 2). Studies using interstellar absorption lines [3][4][5] have shown that the deficiency is due to a cavity in the H I of the Galactic disk surrounding the Sun (called the Local Cavity, LCa). Recently, extensive absorption line and reddening measurements have been combined to provide a rather good three-dimensional map of the neutral material within the nearest ~ 500 pc from the Sun [6]. From [6] it is clear that the H I of the local Galactic disk is in no way distributed smoothly; there are both relatively dense regions as well as extensive voids.

3. Setting the stage – the warm part of the local ISM

Directly surrounding the heliosphere is a region of partially ionized gas which has been called the Local Cloud (LC1), the Very Local ISM (VLISM), or my personal favorite, the Local Fluff (LF, e.g., [8]). The LF was identified by interstellar absorption line measurements of nearby stars and has an

extent of up to ~ 15 pc from the Sun (placing it well inside the LCa). It has a temperature of $T \sim 10^3 - 10^4$ K and an H I density of $\sim 0.1 \text{ cm}^{-3}$. (See other papers in these proceedings for much more extended discussions of the LF.) Because there are a variety of distinct velocity components observed in the absorption lines it has been thought that the LF is made up of ~ 15 cloudlets [8]. As there is some relative motion between the LF and the Sun, the neutral part of the LF penetrates through the heliospheric magnetic field and flows through the heliosphere with a speed of $\sim 25 \text{ km s}^{-1}$. From [9] there is no indication of expansion or contraction implying pressure equilibrium between the LF and its surroundings. Note, however, that there is a new interpretation of the absorption line data by [10] which suggests that the LF may actually be a single monolithic cloud which is experiencing some compression along the flow direction and expansion in the cross direction.

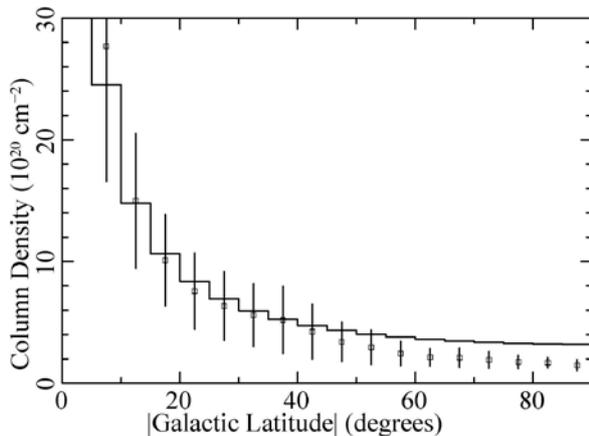


Figure 2. The average column density of Galactic H I in 5° latitude annuli as a function of Galactic latitude. The vertical error bars show the RMS range of values in each latitude bin while the model curve shows a $\text{csc}|b|$ approximation to the data with the scaling roughly set by intermediate-latitude data.

4. Setting the stage – the hot part of the local ISM

The sky has been at least partially mapped at $\frac{1}{4}$ keV by four surveys (Figure 3) with different observation geometries and at different times during the solar cycle. The Wisconsin [11] and ROSAT [1] surveys are in good agreement while there is a minor zero-level offset between them and the SAS-3 [12] and HEAO-1 A2 [13] maps. The offset is likely due to an unremoved background contamination from solar wind charge exchange X-ray emission either in the heliosphere or Earth’s magnetosheath. However, the angular structure of the surface brightness variations is consistent between the various maps, limited only by the statistical significance and angular resolution of the different surveys and instruments.

The $\frac{1}{4}$ keV and lower energy bands are those most relevant for studies of the local ISM. One optical depth for their band-averaged cross sections are $N_H \sim 10^{20} \text{ cm}^{-2}$ for the C band (0.1-0.284 keV, historically named for the carbon filter used in early proportional counter observations of the SXR), $N_H \sim 0.5 \times 10^{20} \text{ cm}^{-2}$ for the B band (0.1-0.188 keV, defined by the use of a boron filter), and $N_H \sim 0.1 \times 10^{20} \text{ cm}^{-2}$ for the Be band (0.07-0.111 keV, defined by the use of a beryllium filter). The B and C bands are primarily sensitive to emission in front of the nearest walls of the LCa (although the C band can “see” beyond the thinner walls and into the Galactic halo) and the Be band is sensitive to neutral material within the LCa.

The $\frac{1}{4}$ keV X-ray maps show a non-zero flux from the Galactic plane. With the short mean free path of these X-rays in the nominal ISM, the emission must originate locally, and as the LCa was a convenient place to confine a hot plasma, the Local Hot Bubble (LHB) [14] was born. As the plasma is confined within the LCa, it surrounds the Sun with an extent of ~ 50 to ~ 150 pc, and emits X-rays characteristic of a temperature $kT \sim 0.1$ keV. The LHB, and the requirements indicating its existence, can be considered the first constraint on the local ISM.

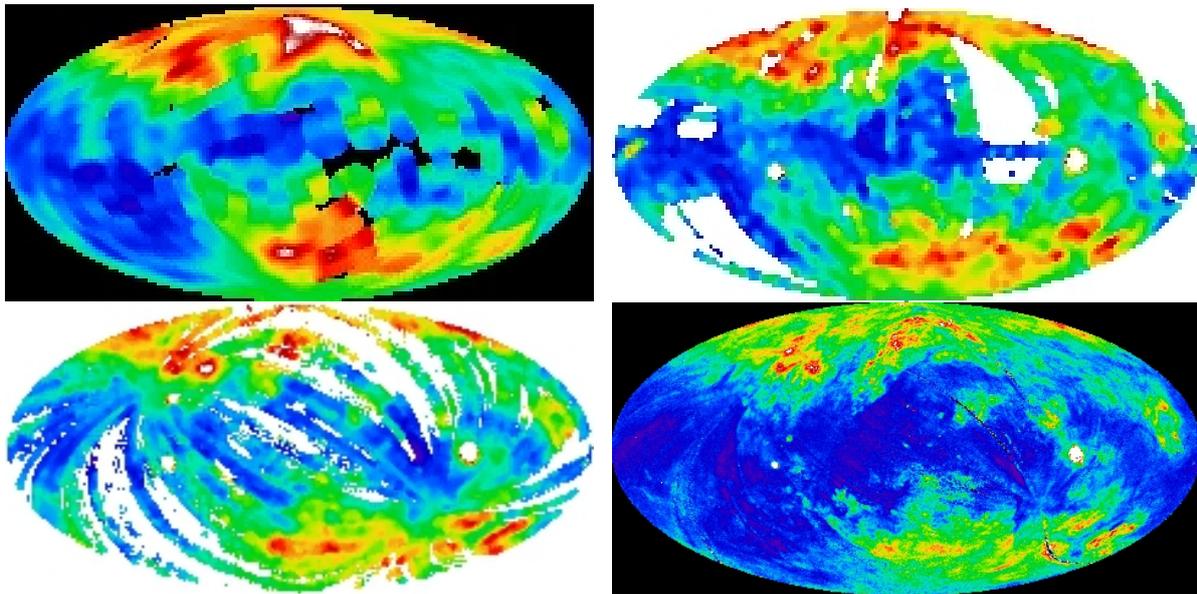


Figure 3. Maps of the $\frac{1}{4}$ keV diffuse X-ray background from the Wisconsin [11] (upper left, published in 1983), SAS-3 [12] (upper right, published in 1984), HEAO-1 A-2 [13] (lower left, published in 1992), and ROSAT [1] (lower right, published in 1995) surveys. Note that while the statistics and angular resolution improved over time, the basic structure of the $\frac{1}{4}$ keV SXRb remained unchanged.

While the LHB accounted for much of the observed emission at $\frac{1}{4}$ keV, there was clear evidence for a flux of a more distant origin (significantly above the relatively minor extrapolation of the extragalactic power law observed at higher energies) as soon as ROSAT began operations in 1990. The first clear “shadowing” feature (the absorption of a flux of distant origin by a distinct foreground object) was by the Draco Nebula [15]. Figure 4 shows the IRAS $100\ \mu\text{m}$ and ROSAT All-Sky Survey (RASS) images of the Draco region where the negative correlation between the two images is rather spectacular.

5. Limits on neutral material within the LHB

The Be band data were used in the 1980’s to place strong limits on the amount of diffuse neutral material similar to the LF present within the LHB [16]. Because the cross sections are a factor of 5 different between the Be and B bands, their hardness ratio is a strong function of an absorbing column density. However, the sample directions, which were scattered over the northern Galactic hemisphere (but away from the Loop I/Galactic center region), showed essentially no variation of the Be band to B band ratio although the intensities varied by more than a factor of three. This leads to constraint number 2 on the LISM: there is very little material (2σ upper limit of $< 10^{19}\ \text{cm}^{-2}$) in the LHB similar to the LF (at least in the northern hemisphere).

6. Things get complicated by magnetosheath SWCX

Although the attribution to solar wind charge exchange (SWCX) came several years later, it was clear from the RASS raw data that we had a problem with contamination in our measurements of the SXRb. Long-term background enhancements (LTEs) lasting from hours to days left a strong signature in the data. The emission was clearly diffuse in origin, and with the duration of the episodes it was assumed to originate in the near-Earth environment.

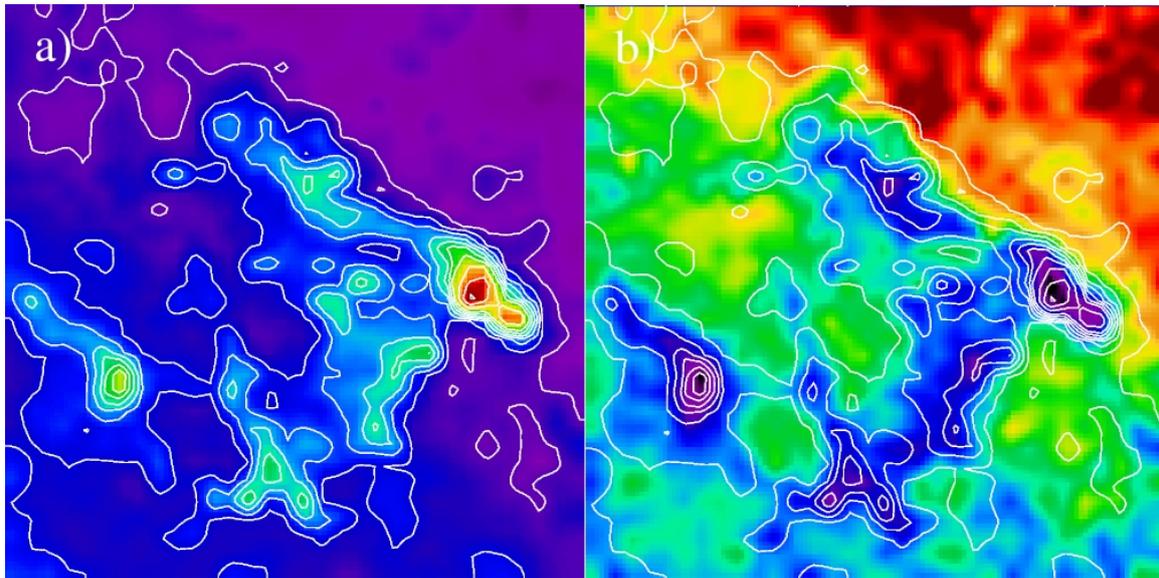


Figure 4. Maps of the IRAS 100 μm (left) and RASS $\frac{1}{4}$ keV (right) data of the Draco Nebula. In both cases purple indicates low intensity while red indicates high intensity. The contours in both images are those of the 100 μm data. The negative correlation between the two images is obvious indicating shadowing by the Draco Nebula of an X-ray flux of more distant origin. Considering the Galactic latitude of the nebula and its distance, the distant emission must originate in at least the lower halo.

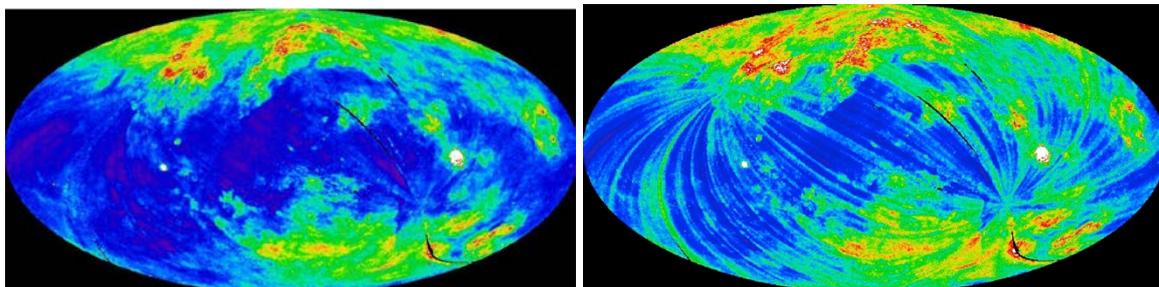


Figure 5. Maps of the cleaned (left) and uncleaned (of the LTE background, right) RASS $\frac{1}{4}$ keV data. The striping in the uncleaned map is due to solar wind charge exchange with exospheric H in Earth's magnetosheath.

When the LTE count rate was compared to the solar wind flux during the ROSAT survey [17], the correlation was obvious, and while the correlation had considerable scatter it adhered to a linear relation. However, while modeling the light curve could address the temporally varying part (on time scales of ~ 1 day or less), any constant contribution would remain. Plotting the relationship as a scatter plot and extrapolating a linear fit to a zero solar wind flux provides an estimate for the residual SWCX contamination from the near-Earth environment of ~ 0.31 counts s^{-1} FOV^{-1} [18]. This provides constraint number 3, while there is considerable temporally variable SWCX emission from Earth's magnetosheath, after "cleaning" it probably accounts for only about 5-15% of the observed surface brightness of the $\frac{1}{4}$ keV band (for dim and bright regions, respectively).

7. Heliospheric SWCX – now life really gets complicated

Heliospheric SWCX emission is produced by solar wind ions charge exchanging with interstellar neutrals flowing through the solar system. As the emission is integrated out to the heliopause, most

temporal variations are smoothed out but there are geometric variations due to perturbed flow of interstellar neutrals and the solar latitude variation of the solar wind.

Given that: 1) The flow of interstellar neutrals through the solar system is reasonably well understood, 2) the average solar wind flux throughout the solar system is reasonably well understood, and 3) the SWCX cross sections relevant to the $\frac{1}{4}$ keV band are understood, it is straight forward to model the heliospheric SWCX flux. While these assumptions get progressively less certain, [19] did put limits on the heliospheric SWCX contribution to the observed X-ray flux. If the model geometric distribution of SWCX emission is scaled so that it accounts for all of the observed flux in the Galactic plane there is “left over” emission above and below the plane but still within the Local Cavity. Given that a picture of the local ISM would look more than a slightly odd with hot bubbles floating above and below the plane in the LCa, heliospheric SWCX probably does not provide all of the $\frac{1}{4}$ keV flux observed in the Galactic plane. Very recently there has been a confirmation of this view [20]. Using a sounding rocket flight to measure the SWCX flux from the heliosphere He focusing cone it was determined that only $40\pm 7\%$ of the observed flux from a direction of minimal SXR flux was due to heliospheric and magnetosheath SWCX emission. This leads to the fourth and final constraint: The heliosphere contributes only a limited amount of flux to the surface brightness of the RASS $\frac{1}{4}$ keV background.

8. Summary

The four constraints that have been presented are: 1) Local emission leads to the idea of the Local Hot Bubble; 2) There is very little absorbing gas within the LHB (the LF may be relatively alone); 3) While there is considerable temporally variable SWCX emission from Earth’s magnetosheath, after “cleaning” it probably accounts for only $\sim 5\%$ of the observed maximum SXR flux and $\sim 15\%$ of the observed minimum SXR flux; 4) The heliosphere contributes a limited flux to the observed SXR, at least at $\frac{1}{4}$ keV, $\sim 40\%$ at low Galactic latitude and $\sim 15\%$ at high Galactic latitudes.

9. References

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