IBEX, SWCX and a Consistent Model for the Local ISM

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Abstract. The Local Interstellar Medium (LISM) makes its presence felt in the heliosphere in a number of ways including inflowing neutral atoms and dust and shaping of the heliosphere via its ram pressure and magnetic field. Modelers of the heliosphere need to know the ISM density and magnetic field as boundary conditions while ISM modelers would like to use the data and models of the heliosphere to constrain the nature of the LISM. An important data set on the LISM is the diffuse soft X-ray background (SXRB), which is thought to originate in hot gas that surrounds the local interstellar cloud (LIC) in which the heliosphere resides. However, in the past decade or so it has become clear that there is a significant X-ray foreground due to emission within the heliosphere generated when solar wind ions charge exchange with inflowing neutrals. The existence of this SWCX emission complicates the interpretation of the SXRB. We discuss how data from IBEX and models for the Ribbon in particular provide the possibility of tying together heliosphere models with models for the LISM, providing a consistent picture for the pressure in the LISM, the ionization in the LIC and the size and shape of the heliosphere.

1. Introduction

The Local Interstellar Medium (LISM) is dominated by the large, ~ 100 pc radius, very low density region known as the Local Bubble or Local Cavity. This region is irregularly shaped and its extent has been mapped out via a few different methods such as dust extinction and Na\textsc{i} and Ca\textsc{ii} absorption lines (Welsh et al. 2010) which probe the distance at which substantial extinction or absorption begin. Within the bubble are several warm, $T \sim 7000$ K, partially ionized clouds (Redfield & Linsky 2008; Frisch et al. 2011), known as the Complex of Local Interstellar Clouds (CLIC), including the Local Interstellar Cloud (LIC) that surrounds the heliosphere.

2. The Diffuse Soft X-ray Background

Diffuse soft ($<1$ keV) X-rays were first detected more than forty years ago (Williamson et al. 1974, and references therein). Though the brightening of the emission toward the poles suggested emission from a hot Galactic halo (see figure [1]), it was soon determined that the simplest model for the source, radiation from a hot Galactic halo absorbed by Galactic H\textsc{i} (and other accompanying elements), was not adequate. The anti-correlation between the H\textsc{i} column density and the soft X-ray flux was not strong enough to support the absorbed halo model. Other data, such as the lack of variation in the ratio of flux in different energy bands even as the total intensity varied strongly, suggested that
the X-rays are generated nearby with little absorption (Snowden et al. 1990). For the lowest energies (∼100 – 284 eV) especially, the X-ray emission must be from nearby because the photoelectric cross section of H and He at those energies is so large that a small column density of neutral gas causes substantial absorption. However, an only slightly more complicated model did fit the data well, the so-called displacement model. In this model it is assumed that all the emission is generated by a uniform emissivity, single temperature hot plasma contained in the Local Bubble. The emission variations are then explained as variations in the emission path length. Combining this model with estimates of the distance to the edge of the bubble can then yield an estimate for the thermal pressure in the Local Bubble. This model did a fairly good job of explaining the emission morphology, but predicted a relatively high pressure for the Local Bubble of $P/k_B \approx 1 - 2 \times 10^4 \text{ cm}^{-3} \text{ K}$.

![Figure 1. ROSAT all sky map in the R1 and R2 band which peaks in sensitivity at around 1/4 keV. The high intensity of the background at high latitudes led to models that put the emission in the halo, but that model would predict zero emission in the Galactic plane since the X-rays would all be absorbed.](image)

This determination leads to problem no. 1 for Local Hot Bubble (LHB) model, the excess pressure problem. The high thermal pressure predicted by the LHB model does not match the thermal pressure determined for the CLIC and in particular for the LIC. Absorption line and in situ neutral density and temperature data on the LIC gives much lower value, thermal pressure $\sim 2000 - 3000 \text{ cm}^{-3} \text{ K}$. Magnetic pressure could help balance out this discrepancy if the magnetic pressure in the LIC could make up for the difference in thermal pressures. However, as we discuss below, the evidence suggests that the field is not large enough to make up for a difference of $P/k_B \geq 7000 \text{ cm}^{-3} \text{ K}$, which would require $B \geq 5 \mu \text{G}$. Heliosphere models give us our best handle on the field strength in the LIC and most models that are consistent with the size of the solar wind termination shock as determined by the Voyager crossings have a magnetic field strength lower than needed to help balance the derived LHB thermal pressure. We note that without pressure support, cloud would be crushed on dynamical time scale $\sim L/c_s \sim 10^5 \text{ yr}$, where $L$ is the scale of the cloud and $c_s$ is the signal (sound or magnetosonic) speed. In addition, the motion of the LIC relative to the Sun is determined by a large number of absorption line measurements across a large fraction of the sky. These velocity components are consistent with a single LIC velocity vector to high accuracy (Frisch et al. 2011) and there are no indications of significant dynamical motions occurring in the LIC.

Problem no. 2 for the LHB model is that there is another potential nearby source of diffuse soft X-rays. Charge exchange between inflowing interstellar neutrals and highly
ionized solar wind ions (e.g. O$^{+6}$, O$^{+7}$) leads to X-ray emission (SWCX) that is hard to distinguish from hot gas emission at the low spectral resolution of most of the diffuse soft X-ray background observations. Some models for the emission find up to 100% of the diffuse emission observed at low energies by ROSAT in the galactic plane can be explained as SWCX. Lallement (2004) showed that the ROSAT intensity distribution could be explained by a combination of SWCX and LHB emission with a large fraction of the emission coming from SWCX.

SWCX modeling is somewhat complex, however, and the results depend on several factors. Among the requirements of the models are: the solar wind characteristics—speed, density, ionization, heavy element abundances, characteristics of the interstellar inflow—speed, density of H$^0$, He$^0$, and atomic data—cross sections for capture into different energy levels, branching ratios for cascades. The SWCX emission is variable both temporally and spatially and is different in the slow and fast solar wind (Koutouroumpa et al. 2009, 2011). For this reason and because some of the atomic data is uncertain, constraining the emission in the LHB using SWCX alone is not currently feasible.

The soft X-ray background observations over much of the sky were done with low spectral and spatial resolution detectors such as the proportional counter of ROSAT and those of the Wisconsin sounding rocket observations. Higher spectral resolution X-ray observations of diffuse emission have been done, though over more limited regions of the sky. The Chandra X-ray Observatory has excellent spatial resolution, ~ 2 arcsec, and better spectral resolution than proportional counters. The high spatial resolution allows for good point source removal, but unfortunately Chandra’s ACIS detector is not sensitive at energies below ~ 0.4 keV. Nevertheless, we have used the long observations taken in the Chandra Deep Field South to try to extract the diffuse emission in the LHB and SWCX emission simultaneously (Slavin et al. 2013). Our fits to the diffuse emission require significant hot gas emission.

A new analysis of old data also provides insights into the LHB emission. The Diffuse X-ray Spectrometer (DXS) experiment was flown in the 90s (see Sanders et al. 2001, for details). In comparison to the proportional counter instruments it had good spectral resolution though poor spatial resolution. The results were quite interesting, showing a spectrum with several different lines but no acceptable fits were found to the spectrum using standard models. Recently a group at the CfA revisited fitting the data and have new modeling results (R. K. Smith et al. submitted) using a combination of slow and fast solar wind, SWCX and LHB emission that finally give good fits. Using the model results and the estimated distance to the edge of the LHB for the direction observed they derive a thermal pressure in the Local Bubble of $P/k = 5800 \text{ cm}^{-3} \text{ K}$. This value certainly has significant uncertainty attached to it, but nonetheless it is interesting as it is much more in line with our expectations given the pressure in the LIC.

3. The Interaction of LHB Hot Gas and the LIC

Fairly straightforward analysis based on absorption line data toward nearby stars indicates that the LIC is partially ionized, $X(\text{H}^+) \sim 30\%$, $X(\text{He}^+) \sim 40\%$, far more so than would be expected from collisional ionization at the derived temperature of ~ 6500 K. Thus an ionization source is required. There are few main sequence hot stars inside the Local Bubble and a census of them and hot white dwarfs carried out by the Extreme Ultraviolet Explorer (EUVE) satellite found that they do not produce enough ionizing
photons to account for the ionization of the LIC (Vallerga 1998). The only other identified sources of ionizing radiation are the hot gas of the LHB and the interaction region at the boundary of the LIC and the hot gas (Slavin 1989).

Thermal conduction between the surrounding hot gas \( (T \sim 10^6 \text{ K}) \) and the warm LIC leads to evaporation of the cloud. Intermediate temperature gas \( (T \sim 10^5 \text{ K}) \) in the boundary radiates strongly in the EUV and is therefore a good ionization source (Slavin 1989; Slavin & Frisch 2008). The magnetic field support for the cloud drops off in the boundary as the density drops and is insignificant in hot gas, so the model requires that the thermal + magnetic pressure of the cloud equals the thermal pressure of the LHB to maintain pressure equilibrium.

Figure 2. Modeled radiation field incident on the LIC. The black line shows the flux from stars including nearby hot stars and, for wavelengths above 912Å, the flux from many cooler stars. The green line is the modeled emission from the bulk of the volume of the LHB and depends on the thermal pressure in the bubble. The blue line is for emission that comes from the boundary region between the warm cloud and the surrounding hot gas. Ionization thresholds for several ions are shown at top and the wavelength at which optical depth unity is achieved for several H\(_i\) column density values is shown in red. [From Slavin & Frisch (2008).]

As mentioned above, the SWCX contribution to the soft X-ray background reduces the amount that can be attributed to the hot gas emission. In this way the SWCX contribution to soft X-ray background lowers the pressure demand in the LHB – in other words problem no. 1 for the LHB can be solved by problem no. 2. But one can go too far with this. We still need the pressure of the hot gas to confine the cloud – no other gas phase is viable without incurring excessive energy supply or emission problems. This leads to the question: Can the lower pressure hot gas still create enough ionizing flux to ionize the LIC?

Our models of the photoionization of the LIC (Slavin & Frisch 2008) include the radiation field from nearby hot stars, emission from the LHB and emission from the boundary region between the hot gas and the LIC where the gas is evaporating off the cloud (see figure 2). It was assumed in the models that all of the soft X-ray background came from the LHB and thus all those photons were available to ionize the LIC. SWCX emission is moderately bright relative to the LHB emission at the Earth because it is
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generated so close to us, but it is insignificant for the ionization of the LIC. Thus a lower fraction of the soft X-ray background that is from the LHB, the less flux of soft X-rays that are available for ionizing the LIC. However, the soft X-rays are fairly inefficient for the ionization of H and He, so it is the associated diffuse EUV radiation, which has not been directly observed, that is responsible for the photoionization. In the model most of that emission originates in the cloud boundary region.

| Model Parameters | Percentage of B band Emission from the Local Bubble |
|------------------|-----------------------------------------------------|
| $N_{\text{HI}}/10^{17}$ | $T_{\text{hot}}$(K) | $B_{\text{LIC}}$(µG) | $n(\text{H}^+)$ (cm$^{-3}$) | $n(\text{H}^0)$ (cm$^{-3}$) | $P_{\text{LB}}$(cm$^{-3}$ K) |
| 3 | 5.9 | 4.63 | 5.60 | 0.077 | 0.082 | 0.186 | 0.177 | 8680 | 11400 |
| 4 | 5.9 | 2.52 | 3.74 | 0.055 | 0.058 | 0.191 | 0.189 | 4080 | 6280 |
| 3 | 6.0 | 4.06 | 5.03 | 0.070 | 0.073 | 0.197 | 0.194 | 7170 | 9750 |
| 4 | 6.0 | 2.05 | 3.47 | 0.051 | 0.054 | 0.193 | 0.192 | 3300 | 5600 |
| 3 | 6.1 | 3.51 | 4.65 | 0.065 | 0.070 | 0.204 | 0.201 | 5710 | 8440 |
| 4 | 6.1 | 0.05 | 3.22 | 0.050 | 0.052 | 0.197 | 0.193 | 2150 | 4920 |

To explore the effects of having a substantial amount of the soft X-ray emission come from SWCX instead of the LHB we have recalculated our photoionization models with 50% of the Wisconsin B band (100 - 284 eV) emission missing. By necessity the pressure in the hot gas is equal to that in cloud and since we control the cloud parameters the hot gas pressures find their own level. The thermal pressure in the boundary sets the emissivity there and other model parameters, e.g. elemental abundances, are set by matching observed column densities (see Slavin & Frisch 2008, for details). Less emission from the LHB requires more from cloud boundary and thus we find that our new models need a somewhat higher magnetic fields than our old models. Results for these models are listed in table 1. We find that a subset of the models are consistent with LHB thermal pressure of $\sim 5800$ cm$^{-3}$ K as determined for the DXS data, which given the LIC thermal pressure implies $B_{\text{LIC}} = 3.4 - 3.6$ µG.

| Heliosphere model parameters |
|-----------------------------|
| $B_{\text{LIC}}$(µG) | $n(\text{H}^+)$ (cm$^{-3}$) | $n(\text{H}^0)$ (cm$^{-3}$) |
| 2 | 0.13 | 0.22 |
| 3 | 0.095 | 0.195 |
| 4 | 0.048 | 0.16 |

The magnetic field is best constrained by heliosphere models and data. Schwadron et al. (2011) used IBEX ENA and other data and a semi-analytic model and estimated the interstellar magnetic field to be $\sim 3$ µG. The IBEX Ribbon location and strength depends on $B_{\text{LIC}}$, the magnetic field in the LIC, and the proton and neutral H density and velocity at the heliosphere. Recent results by Heerikuisen (in preparation) finds good fits to the heliosphere shape with the parameters in table 2. The 4 µG case leads to a ribbon that does not fit the data well. Zank et al. (2013) also find a $B_{\text{LIC}} \sim 3$ µG fits observations of the H wall and 4 µG does not.
4. Conclusions

With the combination of the soft X-ray diffuse background observations, data from IBEX, especially the ribbon, and absorption line data toward nearby stars the constraints on the nature of the LIC are becoming ever tighter. The links between the photoionization of the LIC and the heliosphere are also getting stronger because, if the ionizing radiation field includes a substantial contribution from the emission generated at the cloud edge, then the ionization of the cloud depends on the strength of the interstellar magnetic field as does the shape of the heliosphere. Charge exchange reactions between inflowing interstellar neutrals and solar wind ions play important roles in shaping the heliosphere and in generating emission that makes up part of the soft X-ray diffuse background. The new interpretation of the DXS data by R. Smith et al. lends additional credence to the idea that the background is generated both by SWCX and by hot gas in the Local Bubble and that there is a consistent pressure for the hot gas and the LIC, which is partially supported by the magnetic field. This pressure is lower than previous estimates that did not include the SWCX emission, but hot gas is still required to fill the Local Bubble. Further modeling of the SWCX emission, the heliosphere and photoionization of the LIC needs to be pursued to fully realize the goal of a consistent model for the LISM, heliosphere and LHB, but we are closer than ever to achieving that goal.

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