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Some Observations Related to the Origin and Evolution of the Local Bubble/Local ISM

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Abstract I discuss some recent observations of the Local Interstellar medium (ISM) that are related to its history and temperature structure. I focus on three topics: (i) the abundance pattern of interstellar deuterium and metals, (ii) highly charged ion data, (iii) soft X-ray data.

Deuterium has been unambiguously shown to correlate almost linearly with refractory metals, confirming that interstellar grains are a “reservoir” of deuterium, and release it into the gaseous phase jointly with metals when the gas is shocked and heated. By interpreting the observed level of deuterium with respect to the abundance patterns of metals and oxygen, these data give some clues to the event, which gave rise to the expanding Gould belt. As a matter of fact abundance data seem to be linked to the belt, and the observed trends suggest an explosive origin, rather than a collision with an external cloud made of unastrated material.

X-rays and high ions trace hot gas and interfaces between hot and cool gas. However absorption lines of high ions show highly complex characteristics and no relationships have been established yet between their detected columns and the existence of hot-cool gas interfaces. Adding to the complexity, the X-ray emission through charge-exchange reactions between highly charged solar wind ions and neutrals plays a significant role, calling for modifications of the global picture of the LISM. In addition to the ubiquitous contamination of background data by locally emitted X-rays, there are also potential distant charge transfer (CX) X-ray emissions from clouds-hot gas interfaces.

There is a strong need for high quality, high spectral resolution X-ray data, because X-ray lines emitted after charge-transfer neutralization of helium-like ions bear a clear signature of the charge transfer process, if present, and allow to disentangle thermal and CX emission. More precise density and velocity distributions of the local ISM are also needed to take full advantage of the X-ray and high ion data and build a consistent picture of the Local Cavity (LC) and its surroundings. As an example of these requirements I discuss the case of the North Polar Spur for which there may be some evidence for CX emission.

Keywords ISM · X-ray background

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1 Introduction

Understanding the detailed structure of the Local Interstellar Medium (ISM) in our galactic neighborhood is becoming increasingly important. Firstly, it is a foreground that contaminates extragalactic diffuse background emission. A precise description of the gas distribution, resulting radiation field and dust emission is a mandatory tool for foreground corrections to the Cosmic Microwave Background (ESA Planck, Herschel forthcoming space missions). Second, the distribution of gas and dust influences the local gamma-ray radiation field, which will be the focus of the NASA GLAST mission. Third, it provides foregrounds and also helpful insights on the environment of a number of nearby galactic objects, and subsequently on potential interactions between these objects and the ambient medium. Examples are the astrospheres around cool stars detected in absorption at Lyman-alpha (Wood et al. 2008) or the cometary-shape envelopes recently discovered around evolved giant stars (e.g. Liebert et al. 2007). An extreme case is the spectacular trail around Mira which has been used to infer the date of entry of the star in the Local Bubble (Wareing et al. 2007). Last but not least, it provides a way to study and better understand the multi-phase structure of the local galactic ISM (LISM).

During this meeting, all of the local ISM aspects have been presented and debated by the best experts. A global picture emerges from these contributions that is at first sight consistent. The distribution of clouds and blown up, often reheated cavities as they come out from the simulations of stellar winds and supernovae (De Avillez and Breitschwerdt 2005; De Avillez 2008; Fuchs 2008) seems to represent very well the observations of dense and diffuse gas (Redfield 2008) and X-ray or radio data (Snowden et al. 2000). Intermediate ions (Shelton 2008) also roughly correspond to the theoretical interfaces between million degree gas and cool clouds and the estimated radiation field roughly explains the ionization states of the clouds (Slavin and Frisch 2002; Frisch 2008).

Still, a few contradictions remain, suggesting that the structure is still not entirely understood. Why are there very cold clouds and ultra-small scale structures within the hot gas of the Local Cavity (LC) (see Stanimirovic 2008), which should not happen in an old and repeatedly heated bubble? Why is the O VI distribution that traces interfaces between the hot gas and the clouds (inside and at the boundary) still defying a consistent picture, with many line-of-sight (LOS) devoid of O VI while other angularly close LOS have significant column densities? How to explain that warm (i.e. with thermally broadened lines) C IV and Si IV are absent along LOS going through the LC and nearby cavities (see Sect. 2)? Tangled magnetic fields around the clouds inhibiting the conduction can hardly be the unique solution. Finally, as stated by Jenkins (2008), the origin of the strong ionization of helium may be a problem if the properties of the local hot gas are going to be strongly revised due to the solar wind contamination of the X-ray background. New "ingredients" may be missing in the present picture. I discuss some observations potentially related to these "ingredients".

2 The Local ISM Deuterium Abundance Variability and its Link with the Local Bubble/Gould Belt Structure

2.1 The Deuterium Abundance within 500 pc

The analysis of the FUSE far UV spectra and the inferred D/H ratios have given rise to a strong debate. The situation is illustrated in Fig. 1, from Linsky et al. (2006). Within uncertainties the D/H ratio is about constant along lines-of-sight having a H column-density

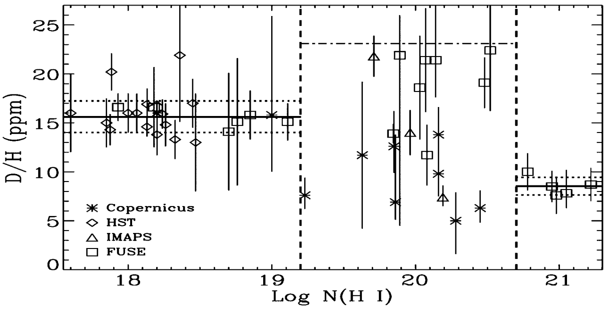

Fig. 1 Combined D/H measurements as a function of the total H I column-density to the target star. From Linsky et al. (2006)

less than 2×10^{19} cm^{-2}, which corresponds to distances of 50 to 150 pc according to the direction sampled. Then, beyond this value, the ratio is highly variable (by more than a factor of 4), while for columns above 10^{21} cm^{-2} it becomes significantly smaller and seems again about constant. Such a variability has been interpreted in two different ways. Linsky et al. (2006) attribute it to the effect of the preferential adsorption of deuterium at the surface of dust grains, and identify the low columns homogenous volume as the Local Cavity. Extreme deuteration of dust grains has been first proposed by Jura (1982), and the associated release of deuterium from grains into the gas following grain destruction has been suggested by Draine (2004) as the source of the strong variability of the D/H ratio in the local interstellar medium. Grain destruction and subsequent gas phase deuteration should in principle occur at shocks and in heated matter, i.e. especially within stellar wind cavities and supernovae remnants. Observational support to this scenario is brought by the observed correlations between deuterium and singly ionized titanium on one hand (Ellison et al. 2007), singly ionized iron and silicon on the other (Linsky et al. 2006). Grains are a “reservoir” of metals, and as a consequence such correlations naturally arise if they are a also “reservoir” of deuterium. Additional evidence comes from the apparent correlation between D/H and the excitation temperature of molecular hydrogen (Linsky et al. 2006).

At variance with this interpretation, Hébrard et al. (2005) invoked the very large uncertainties on the H I measurements as the source of the “apparent” abundance correlations. If one uses abundances relative to H for both D and the metal M, they are evidently both influenced by measurements errors on H. If the measured column NH_{obs} is in error by some factor X, both abundances are under- or over-estimated by the same factor X and the resulting set of data points for different lines-of-sight (and different X) is mimicking a linear correlation between the two abundances. Another argument used against the “depletion hypothesis” is the fact that the D/O ratio seemed to vary in a significantly less extent compared to D/H. Because the D and O absorption lines are less saturated than the H lines, O-related abundances are more reliable. Hébrard et al. (2005) suggest that D is locally overabundant due to some mixing processes, i.e. the gas within the first hundred parsecs is less processed than the gas at larger distance. This would be in agreement with Geiss et al. (2002) who suggest that the local gas is a mixture of “fresh” gas fallen from the halo down to the disk and processed galactic gas.

2.2 End of the Debate about Dust Release of Deuterium?

High resolution spectra of target stars whose D/H is known were recorded with the UVES spectrograph at the ESO Paranal Very Large Telescope and have been used to extend and reinforce the correlations with titanium. Figure 2 shows the data and the fitted linear relationship. For the first time titanium (and also iron) abundances relative to H have been

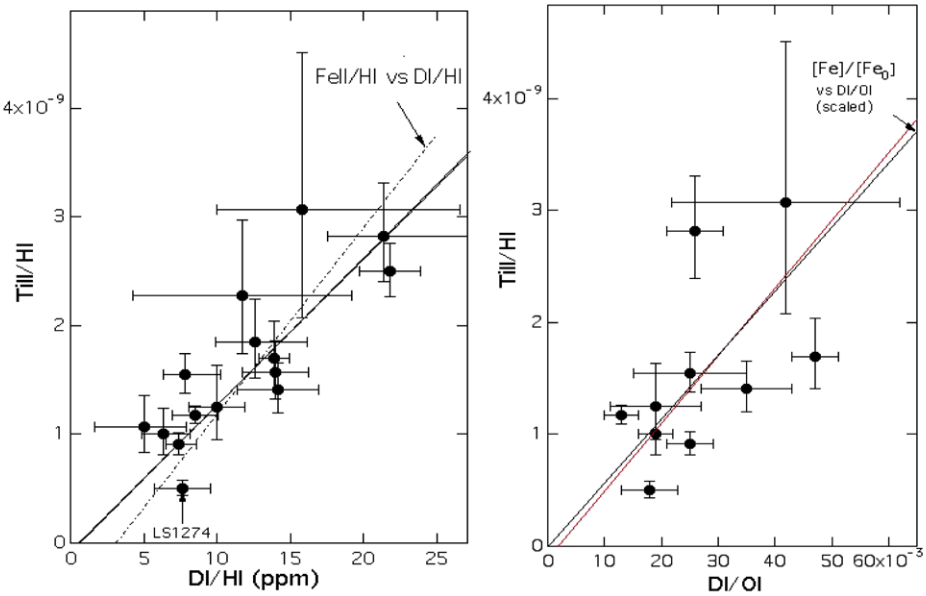

Fig. 2 Singly ionized titanium abundance and deuterium abundance. The data are consistent with linear relationships for Ti II/H vs both D/H and D/O (Lallement et al. 2008)

also correlated with D/O (in addition to D/H), convincingly revealing a new relationship and demonstrating that the uncertainty on H is definitely ruled out as the unique source of the deuterium-metals correlations (Lallement et al. 2008). Surprisingly, the deuterium abundance seems to vary linearly with the titanium abundance.

2.3 The Gould Belt

The deuterium depletion has some important consequences on its abundance and galactic evolutionary models, but it also opens a new perspective: deuterium can be used as a tracer of the ISM history. In particular it may bring some information on the local ISM, i.e. the local pattern shown in Fig. 1 must be related to past events having heated the dust.

Already noticed by Herschel in 1847, the peculiar distribution of the bright early-type stars in the solar neighborhood known as the Gould belt is still a subject of debate (for a review see Pöppel 1997). Hipparcos-based maps of early-type stars show the belt as a wavy band with a maximum at about −20 deg of galactic latitude in the direction close to the anticenter and another maximum at +20 deg in the opposite direction. The belt is close to an inclined plane made of stars, H I and H II regions as well as molecular clouds. The system is in expansion and rotation and is mainly composed of stars younger than 20–40 Myrs. The supernova rate is believed to be enhanced along the belt by comparison with the galactic average and has reached 20–27 SNe per million years within the belt (Grenier 2000). A representation of the associations along the belt is shown in Fig. 3 from Perrot and Grenier (2003). Potential sources of the belt include the impact of a giant cloud (Comerón and Torra 1994), which helps to explain the inclination, a strong explosion followed by a circular shock wave (Olano 1982) which helps to explain the expansion but not very well the inclination. Olano (2001) invokes the interaction between a super-cloud and the spiral arm. A gamma burst origin has also been proposed by Perrot and Grenier (2003), in parallel

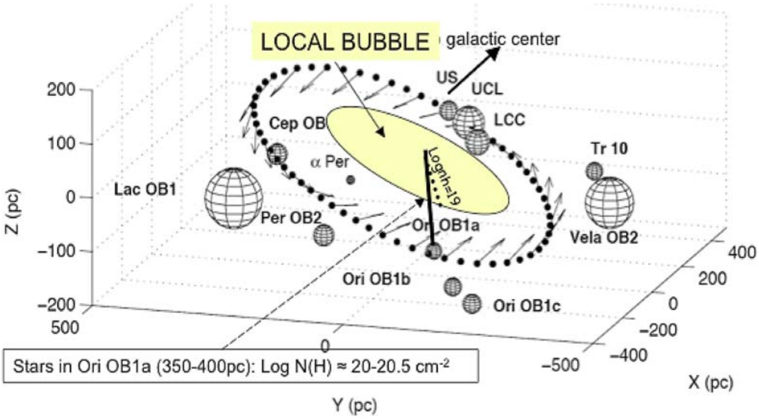

Fig. 3 A schematic view of the expanding belt, as modeled by Perrot and Grenier (2003). Despite the visual impression the longitude of the ascending order of the belt is here 296 deg (highest positive galactic latitudes at $l = 26$ deg). The LC (*solid oval*) corresponds to small H I columns, while the columns towards the OB associations defining the belt correspond to the high variability of D/H. The Sun is between the center of the belt and the Scorpius, Centaurus, Lupus associations. The "chimneys" of the LC opening to the southern and northern galactic halos are roughly perpendicular to the belt. The belt corresponds to the region of high variability of D/H

with the suggestion by Lallement et al. (2003) of a GRB origin for the Local Cavity and its inclined "chimneys" connecting the LC to the halo (Welsh et al. 1999). Both structures, the LC and the belt, may be related, and the inclination of the "chimney" axis at right angle to the may not be fortuitous belt (Sfeir et al. 1999).

2.4 A Link between the LC, the Gould Belt and the D/H Pattern?

As shown in Fig. 4, the LC, if defined by $N_H < 10^{19.3}$ cm^{-2}, is interior to the belt. This is also the region of almost constant D/H (see Fig. 1). On the other hand, belt associations like the Ori OBIa correspond to $N_H \approx 10^{20-20.5}$ cm^{-2}, a column that corresponds to the transition value between D/H constancy and high variability. In the light of the deuterium release by heated dust, the high variability transition region could be associated with the expanding front of the GB, where shocked and unshocked gas and dust do coexist (Lallement 2007).

Both a cloud impact and an explosive event can produce the Gould belt expansion and its associated stellar births and deaths, and the associated D/H variability. In the first case however two cumulative sources of deuterium enrichment are at work within the belt: dust evaporation on one hand, and mixing of galactic gas with D-rich extra-galactic gas on the second hand. Dust evaporation is accompanied by an equivalent increase of metals (Fig. 2) and a negligible or very small oxygen increase, while mixing with unastrated gas produces a strong decrease of metal and oxygen, which precludes simple proportionalities between metal abundances and both D/H and D/O. Thus, the observed linear relationships favor the first process more than the second. This is reinforced by the absence of significant O/H variations within the first 400 parsecs (Meyer et al. 1998; André et al. 2003; Oliveira et al. 2006)

3 Highly Charged Ions

The intermediate ions C IV and Si IV are preferentially found in photoionized gas within the ISM. N V and O VI are present in collisionally ionized gas found in interfaces between hot and cool gas (Slavin 2008), and are formed at temperatures of the order of 150,000–3,000,000 K. C IV and Si IV are also present in interfaces, but are formed at lower temperatures (around 80,000 K). These four ions will be found within blown up “bubbles” at locations where the gas has moderately cooled down.

The O VI ion has been detected with FUSE along a large number of target stars (Savage and Lehner 2006; Oegerle et al. 2005). The overall spatial distribution of local interstellar O VI absorption is found to be quite patchy, with both detections or non-detections for LOS of the same length or angularly close, which has been interpreted as being due to the presence of tangled or tangential magnetic fields which can quench the thermally conductive interfaces of cloud surfaces on which the O VI is thought to form (Cox and Helenius 2003). However, since there are numerous clouds around the Sun, one would expect the resulting columns to make a more homogeneous set.

C IV, Si IV, N V have been detected along numerous sight-lines >100 pc (e.g. Sembach et al. 1994; Savage et al. 2001; Gry and Jenkins 2001) with IUE and HST spectrographs, however often with too low resolution or with too many blends to allow accurate measurements of the line-widths. When there is enough resolution and the absorptions are well separated, some high ion lines are narrower than what one would expect for gas at 10^5 K or more (e.g. Knauth et al. 2003), and are likely to be due to photo-ionization.

Figure 4 shows part of HST/STIS measurements of C IV, Si IV and NV along two lines-of-sight that are known to cross both the near and far neutral interface boundaries to the Loop I cavity, in addition to intersecting the fragmented shell of neutral and partially ionized gas that defines the boundary to the Local Bubble. The LOS studied are superimposed on the low resolution dense gas distribution deduced from absorption studies (Lallement et al. 2003). While for one sampled direction there is no C IV detection in association with the distant dense gas (at heliocentric velocity around 0 km/s), for the second direction there is a clear detection, but the narrow line profile-widths, corresponding to temperatures of a few 10^4 K at maximum are found to be incompatible with theoretical models that predict high ion absorption due to the presence of evaporating cloud conduction interfaces (Welsh and Lallement 2005). Either the gas is very far from equilibrium, or these ions are produced by photo-ionization, as in the case of the Knauth et al. data. In any case, there is clearly a lack of “warm” ions from the expected interfaces dense gas and the Loop 1 cavity. On the other hand, the gas located between the LC and Loop 1 (at negative velocities) has some C IV counterpart for the 2 stars, but again when there is no blend (direction A) the line width is too narrow for a classical warm-hot interface. As a conclusion, the picture drawn from the high ions is still far from well understood and must be studied in details for each different context.

4 Charge eXchange (CX) X-Ray Emission

4.1 The Heliospheric CX Emission and its Impact on LC and Halo Hot Gas

Snowden et al. (1998, 2000) have used a large number of ROSAT 1/4 keV shadows, to derive and map the unabsorbed fraction of the soft X-ray diffuse background, i.e. supposedly hot gas filling the LC. It is now clear that a non negligible fraction of this locally emitted soft

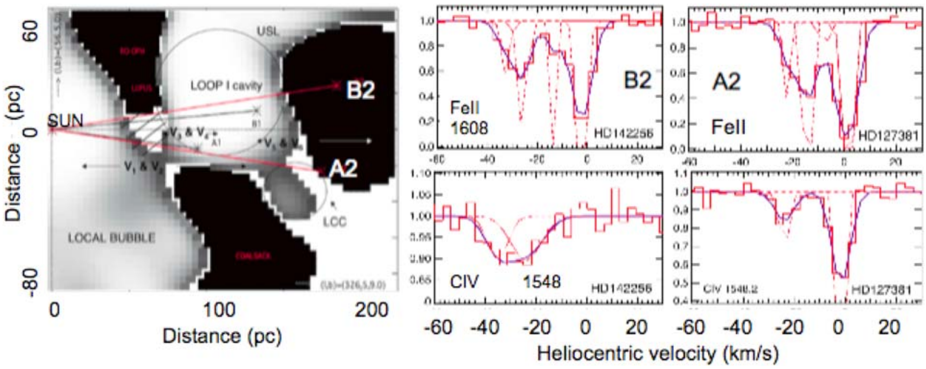

Fig. 4 High resolution HST/STIS spectra towards two target stars (*A2* (HD142256), *B2* (HD127381) on the *left graph*) within dense gas beyond Loop 1. This dense gas is at heliocentric velocity ≈0 km/s and is detected with Fe II (*top right*) for both *A2* and *B2*. Towards *B2* there is no corresponding C IV (nor Si IV) at the dense gas velocity. Towards *A2* C IV is detected, but the line-width is narrow and precludes collisional equilibrium at $T \approx 10^5$ K gas. Similarly, the negative velocity C IV detected towards target *A2*, which corresponds to the gas between the LC and Loop 1 is too narrow

X-ray emission is solar wind charge-exchange emission (or SWCX) (Cox 1998; Cravens et al. 2001; Lallement 2004; Snowden et al. 2004). From updated calculations using the best available atomic data, Koutroumpa et al. (2008) show that, while at high galactic latitude the major part of the measured brightness is definitely not from the heliosphere, at low galactic latitudes the emission generated throughout the heliosphere is potentially large enough to explain the observed signal. The whole picture of the hot gas distribution in the LC is thus to be revised, in the light of this strong CX contamination. In case the low galactic latitude emission is entirely solar, the existence of hot gas at small distances from the disk is no longer required, nor the pressure equilibrium between the local clouds and the pressure of the high latitude, because in this case the X-ray emitting hot gas and the disk gas would be physically disconnected. The actual location and characteristics of this high latitude hot gas would have to be revisited. Is this hot gas falling down towards the disk, as do the high velocity clouds (HVCs)? Is this infall a result of the large explosion having given rise to the Gould belt and created a low pressure region in the Sun vicinity? It is tempting to imagine such scenarios, but they are far too speculative at this stage and before new analyses of the hot gas and of the interfaces are performed.

4.2 Non-Solar Charge Transfer X-Ray Emission? The North Polar Spur?

The CX X-ray/EUV emission mechanism, which is extremely efficient, may be at work in other astrophysical situations, and in particular at interfaces between hot gas and cool clouds. In the same way neutral interstellar atoms enter the solar wind, while the ionized fraction is deviated and excluded from the heliosphere, neutral gas from partially ionized clouds may penetrate hot gas of stellar winds or SNR cavities. For an H atom entering a hot plasma, the mean free path against charge transfer is of the same order as the mean free path against collisional ionization for a large number of hot gas temperatures and neutral/hot gas relative velocities. The X-ray emission arising from charge transfer between neutrals and highly charged ions of the hot plasma occurs only within a very narrow layer of the order of this mean free path. However, despite this narrowness, the CX emission may be significant w.r.t. the thermal emission of hot gas, generated along large distances (Lallement 2004).

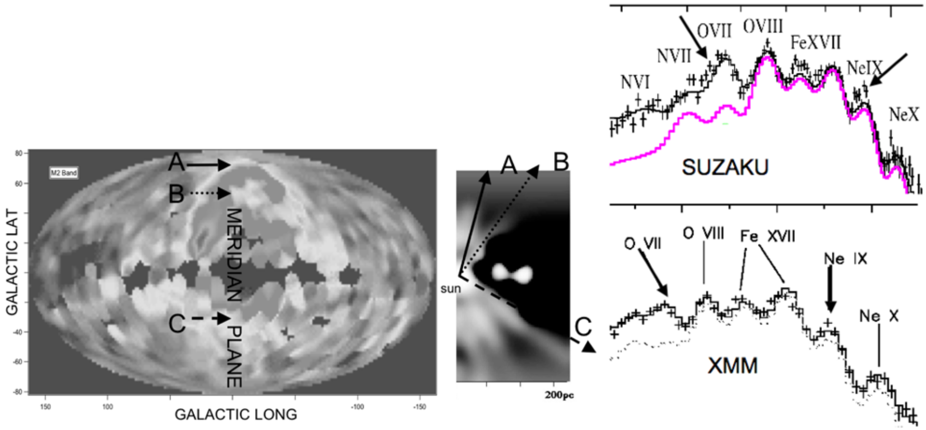

Fig. 5 (*Left*) The ROSAT 3/4 keV map reveals the conspicuous North Polar Spur (NPS) and Loop 1 emission (*grey* area between *A* and *C*). The emission discontinuities *A*, *B*, *C* correspond to lines-of-sight that are tangential to the dense gas, here shown in the meridian plane containing the galactic center (Lallement et al. 2003). (*Right*) XMM and Suzaku spectra of very bright NPS regions (Willingale et al. 2003; Miller et al. 2008). The O VIII and Ne IX emission lines seem in both cases to be shifted to lower energies, while O VIII or Ne X are not. A signature of charge-transfer emission?

Interestingly, crude estimates of the CX emission from high velocity clouds in a hot halo is of the same order as the emission detected with ROSAT (e.g. Kerp et al. 1998) towards some HVCs. In the case of stellar winds expanding within dense media, there may be CX emission lines from ion stages corresponding to the ionization degree within the shocked wind.

Is the diffuse X-ray background contaminated by the CX emission from such interfaces? We discuss here two (although weak) evidences for a positive answer, that call for further investigations.

Figure 5 shows the 3/4 keV ROSAT map, with the spectacular Loop 1/North Polar Spur (NPS) emission. While the NPS has been initially detected in radio, it corresponds to the edge of a very bright X-ray enhancement. We focus on three directions A, B, C defining three edges of the X-ray emission along a meridian line containing the galactic center. The same three directions are superimposed on a dense gas density cut in the corresponding meridian plane containing the Sun, the galactic poles and the galactic center. The density distribution comes from neutral sodium absorption data inversion (Lallement et al. 2003) and shows the shell of dense gas around Loop 1 (the Loop 1 cavity appears as a small white area within the dark region, its small size is due to the very coarse resolution of the distribution). Interestingly, the A, B and C bright edges correspond to directions that are tangential to the dense gas, as one would expect from emission arising at the periphery of the dense gas in potential agreement with a dense/hot gas interface CX emission. However, the limited precision of the density maps precludes a firm conclusion.

There is on the other hand a more direct diagnostic of the CX emission mechanism. After the electron transfer from a neutral to a high ion, and contrary to an electron impact recombination, the electron has a large probability of populating high energy shells, which strongly modifies the subsequent cascades. In the case of electron capture by helium-like ions, the de-excitation of the newly formed excited ions (e.g. N VI, O VIII, Ne IX) generates a resonance/inter-combination/forbidden line triplet considerably different in case of charge-transfer (i.e. if the electron is extracted from a neutral) compared to electron impact (i.e. for a capture of a free electron). E.g., Pepino et al. (2004) predict a 561 eV O VIII forbidden line about 4 times more intense than the 574 eV resonance line in the case of CX, while for electron impact it is twice fainter. Such line ratios, or the triplet wavelength shift in case of unresolved features, bear a clear signature of the charge transfer process, if present. E.g. the O VIII triplet is shifted by about -10 eV and the Ne IX triplet by about -17 eV for XMM and Suzaku spectral resolutions. Unfortunately, such diagnostics are difficult to obtain in case of extended sources and at low resolution.

In the case of the Loop 1, it is interesting to compare the highest quality NPS spectra recorded by XMM (Willingale et al. 2003) and recently Suzaku (Miller et al. 2008) with the model spectra. Figure 5 shows fractions of the recorded spectra at low energy. The O VIII and Ne IX triplets seem indeed to be shifted w.r.t. to the model, by about 10–15 eV, while the O VIII and Ne X lines are well centered. The two Fe XVII lines also seem to be shifted, as it should probably be in case of CX, but there are at present no calculations of the charge transfer shifts for these complex ions. These weak evidences for additional distant CX emission deserve more investigations. If present, interface CX emission should modify the overall picture of the hot gas distribution.

5 Data Need for a Better Global Picture of the LISM

Understanding the history of the local ISM, the origin of the expanding Gould belt, the link between the GB and the LC, the nature of the gas in the LC and the transition to the halo, and finally the ion and X-ray data is a difficult task, presently in progress as shown during this meeting. Is the LC a remnant of an explosive event that gave rise to the Gould belt? Is this region under-pressured, which induces halo gas down-flow, as suggested by high and intermediate velocity clouds negative velocities? Or is it on the contrary a typical, old, reheated SNR bubble? Answering these questions requires:

(i) to disentangle thermal vs. charge-exchange X-ray emission, which requires new generation high-resolution X-ray spectra (McCammon et al. 2002)
(ii) to better characterize the low and high ionization degree ions thanks to high resolution FUV/UV spectra
(iii) to build detailed 3D density and velocity distributions of dense and diffuse gas, thanks to combinations of absorption and emission data. This requires much larger data sets than available ones
(iv) to locate the high ions in the gas and velocity distribution and correlate them with shocks, interfaces, cavities
(iv) to compare abundance variations, such as deuterium, with the same features
(v) to compare the 3D picture with sophisticated models of ISM evolution, including magnetic fields

This is an ambitious program for a research field which is not at high priority, but its achievement would be useful in many ways as discussed in the introduction.

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