THE LOCAL BUBBLE

Current state of observations and models

DIETER BREITSCHWERDT *
Max-Planck-Institut für extraterrestrische Physik, Postfach 1603, D-85740 Garching, Germany
Email: breitsch@rosat.mpe-garching.mpg.de

Abstract. Recently, observations with the ROSAT PSPC instrument and the spectrometers onboard the EUVE satellite have given new detailed information on the structure and physical conditions of the Local Bubble. From the early rocket experiments, and in particular from the WISCONSIN Survey, the existence of a diffuse hot gas in the vicinity of the solar system, extending out to about 100 pc, has been inferred in order to explain the emission below 0.3 keV. The higher angular resolution and sensitivity of ROSAT made it possible to use diffuse neutral clouds as targets for shadowing the soft X-ray background. Thus, in some directions, more than half of the flux in the 0.25 keV band appears to come from outside the Local Bubble. Further, measurements of the diffuse EUV in the LISM, show surprisingly few emission lines. These findings are in conflict with the standard LHB model, which assumes a local hot ($T \sim 10^6\ K$) plasma in CIE. Model calculations, based on the non-equilibrium cooling of an expanding plasma, show a promising way of reconciling all available observations. Thus the present temperature within the LB may be as low as $4 \times 10^4\ K$ and its number density as large as $2 \times 10^{-2}\ cm^{-3}$, giving a total pressure that is roughly in agreement with the Local Cloud.

Key words: Local Interstellar Medium, Soft X-ray Background, diffuse emission, non-equilibrium plasma models

Abbreviations: CIE – collisional ionization equilibrium; ISM – Interstellar Medium; LHB – Local Hot Bubble; LB – Local Bubble; LISM – Local ISM; SB – superbubble; SXR – soft X-ray; SXRB – SXR Background; VLISM – Very Local ISM

1. Introduction

Generally, our intuitive concept of a background radiation is that of a diffuse emission from a more or less homogeneous distribution of very distant sources. This is certainly true for the first background radiation ever observed, which was in X-rays above 2 keV (Giacconi *et al.* , 1962), as well as for the Cosmic Microwave background. However, for a softer X-ray component below 2 keV (Bowyer *et al.* , 1968), due to photoelectric absorption by neutral hydrogen, the mean free path of the photons becomes less than the radius of the Galaxy. This emission extends down to less than 100 eV, and thus a local Galactic origin for the ultrasoft (0.08 - 0.3 keV) component seems compelling. In any case, a pure extragalactic origin was questionable, because the absolute intensity of the measured flux exceeded the downward

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* Heisenberg Fellow

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extrapolation of the spectrum above 2 keV (Henry *et al.*, 1968). After brightness distributions of SXRs for most of the sky were available in the early 70's, and with the recognition of a wide spread hot phase (Cox & Smith, 1974; McKee & Ostriker, 1977) of the ISM from ubiquitous OVI absorption lines (Jenkins & Meloy, 1974), the nexus between the soft X-ray emission and a supernova origin became suggestive.

However, it has been pointed out (McCammon & Sanders, 1990) that the hot intercloud medium, with a typical temperature of $\sim 5 \times 10^5\,K$ (McKee & Ostriker, 1977), fails to reproduce the correct ratios (c.f. McCammon & Sanders, 1990) of the WISCONSIN C-band (160 - 284 eV), B-band (130 - 188 eV) and Be-band (77 - 111 eV). Although the origin of the SXRB is still under debate, there is agreement that our LISM is a highly ionized region with low HI column density, i.e. $N_H \leq 10^{20}\,cm^{-2}$ within a radius of less than 100 pc. For this and other reasons that will be discussed in some detail in the next Section, the region is called the Local Bubble (LB).

Why is the LB, apart from its not yet fully understood relation to the SXRB, an interesting subject of investigation?

Firstly, there is a wealth of observational data available in different wave bands, which allow us to test current ISM models. Indeed, this may be the reason that too simple models are in conflict with some of the observations, and thus one is forced to give up convenient assumptions of a zero order model. In this spirit, that a model should be as simple as possible, but not simpler, I will present in Section 3 a first order model, in which the assumption of ionization equilibrium has been rejected in favour of a self-consistent dynamical and thermal evolution of the LB. It is shown that the results are consistent with all present data, but owing to the complexity of the ISM, it is clear that further modifications will be necessary as observations are progressing.

Secondly, if one would be able to explain the LISM observations by a more general model that is also appropriate, though with different boundary conditions, for other ISM regions, one could answer the question whether the LISM is really so distinctly unusual as it has been claimed (Cox & Reynolds, 1987).

Thirdly, knowing the physical conditions of the LB, helps us to provide input parameters for our very local environment, the heliosphere. This touches the problem of the interaction between the LB and the Local Cloud, that surrounds our solar system, extending out to $\sim 5\,pc$ with an average HI column density of $N_{HI} \approx 3 \times 10^{18}\,cm^{-2}$ (Chassefière *et al.*, 1988). This is discussed in detail in the papers by P. Frisch and R. Lallement (this volume).

Finally, we should bear in mind, how lucky we are that our solar system is located in a region of low density, that is transparent to optical photons. If we were sitting deep inside a dark cloud, our concept of the world would certainly be very different, let alone the consequences for astronomy and navigation in the past.

2. Observational constraints

Using atomic absorption edge filters with a narrow bandpass, spectral information in the ultrasoft X-ray components, i.e. Be-, B- and C-band, was obtained in the WISCONSIN Survey (cf. McCammon & Sanders, 1990). For energies between $0.5 - 1.5\,keV$ (M-, I- and J-bands), one had to rely on pulse height distribution. A somewhat surprising result was the approximate constancy of the Be/B band ratio with increasing count rate (Bloch *et al.* , 1986), because a small column density of $N_H = 10^{19}\,cm^{-2}$ represents already unity optical depth for the B-band. Moreover, the effective absorption cross section for the Be-band is a factor of 6 larger than for the B-band. Observations show that most of the nearby Galactic HI is extended and diffuse, with significant clumping being very unlikely (Lockman *et al.* , 1986). Therefore, an obvious interpretation is that our LISM could be a local cavity, filled with hot plasma and devoid of neutral hydrogen. The observed anticorrelation between ultrasoft X-rays and HI is the basis of the so-called *displacement model* (Sanders *et al.* , 1977; Tanaka & Bleeker, 1977; Snowden *et al.* , 1990). Assuming that *all* of the observed background below 0.3 keV originates in the cavity, it was thought that the measured X-ray intensity along a given line of sight was directly proportional to its extension. Since there is an increase of flux by a factor of 2 to 3 with galactic latitude, a Local Hot Bubble (LHB) was conceived, extending about 200 pc perpendicular and 30 pc into the galactic plane. In such a geometrical model, a complicated 3-dimensional shaping of the LHB was obtained from the varying X-ray intensities along different lines of sight (Snowden *et al.* , 1990). A temperature of $10^6\,K$ was assigned by fitting a Raymond and Smith (1977) equilibrium plasma model to the broad band spectrum, i.e. reproducing the observed C/B/Be band ratios in the WISCONSIN Survey. The essential free parameter in this model is the X-ray emissivity or the plasma thermal pressure, respectively; the best-fit model yields $n_e = 4.7 \times 10^{-3}\,cm^{-3}$ for the electron density, and hence $p/k \approx 9000\,cm^{-3}\,K$. For the Local Cloud, $p/k \approx 2600\,cm^{-3}\,K$ (Bertaux *et al.* , 1985) and thus additional components, such as magnetic pressure, are needed for support. On the other hand the existence of a regular magnetic field reduces the mean free path of thermal electrons perpendicular to the field, thereby impeding conduction efficiently.

Now turning to the M-bands (0.5 - 1.0 keV) emission, it was found in the WISCONSIN Survey, and later confirmed by the ROSAT All Sky Survey (RASS), that the emission is fairly isotropic, if some prominent sources (Loop I, Cygnus SB, Eridanus cavity etc.) are subtracted. This is not easily explained, because both discrete disk and extragalactic sources would certainly exhibit latitudinal intensity variations, the latter due to photoelectric absorption, the former because of their Galactic scale height distribution.

It is certainly fair to state that recent satellite missions like EUVE, DXS and, in particular, ROSAT have fundamentally changed our concept of the LISM and the LB.

One of the first deep pointed ROSAT observations were the so-called shadowing experiments. Due to the fast optics of the XRT (Trümper, 1983) and the sensitivity of the PSPC instrument, it was found (Snowden *et al.* , 1991) that the X-ray intensity, I_x, of a line of sight passing through the Draco nebula was substantially attenuated. Specifically, a satisfactory fit for the C-band count rate was obtained by a simple extinction law, $I_x = I_f + I_b \exp[-\sigma(N_H)N_H]$, with I_f and I_b denoting the foreground and the background intensity and $\sigma(N_H)$ the HI absorption cross section, respectively. Accordingly, roughly 50% of the emission is from beyond the Draco cloud; with distance limits between 300 - 1500 pc, this was clearly *outside* the LHB, and thus in contradiction with the standard assumption of the displacement model. Furthermore, this was direct evidence for the *diffuse* nature of the emission. In order to obtain a limit for I_f, a line of sight that passes through a heavy absorber, like the molecular cloud MBM 12 (distance $\sim 65\,pc$), was chosen. Since almost no C-band shadow was observed ($I_f \approx 0.8\,I_x$), this places a lower limit for C-band emission from the LB. On the other hand, an M-bands shadow was detected, giving a 2-σ upper limit of 30% of the emission in these energy bands (Snowden *et al.* , 1993) originating *inside* the LB. This is interesting, because a $10^6\,K$-LHB-plasma in equilibrium would only produce typically a few percent of the M-bands emission. Thus one may conclude, that a spatial separation of low and high energy SXR bands is dubious. If however some fraction of the M-bands emission originates *inside* the LB, the problem of isotropy becomes less severe.

The Local Cloud is not the only "cool" ($T \approx 7000\,K$) diffuse HI region, embedded in the LB. Kerp *et al.* (1993) found a C-band shadow cast by an HI filament located at a known distance of 60±20 pc. An upper limit for the temperature from the 21-cm line width gives $T \approx 150\,K$. Assuming a similar extension along the l.o.s than perpendicular to it, a density of $n_{HI} \approx 75\,cm^{-3}$ is obtained, giving a pressure in agreement with the LHB model. However, due to the large temperature gradient, conduction should play a rôle, since the pressure contribution of the magnetic field should be negligibly small, and hence observable EUV line emission should be detected.

Due to the short mean free path of EUV photons, shadows are much deeper than for SXRs; they are therefore an excellent probe of the VLISM. Recent observations by the EUVE satellite have given upper limits on the diffuse EUV flux (Jelinsky *et al.* , 1995). Moreover, the high spectral resolution of the instruments in the 70 – 760 Å range allows the detection of emission lines, which should be vastly abundant in a plasma in CIE around $10^6\,K$ (cf. Fig. 2). However, the only lines detected were HeI and HeII, with intensities consistent with local geocoronal and/or interplanetary scattering of solar radiation. Also the limits for the plasma emission measure are a factor of 5 to 10 below of what is expected from the B- and C-band emission from a plasma between $10^{5.7} - 10^{6.4}\,K$, using a Landini and Monsignori-Fossi (1990) plasma code with normal abundances. In addition, the emission spectrum predicted by a conductive interface model (Slavin, 1989) can apparently be rejected at the 99.7% confidence level.

Preliminary results from the DXS Bragg crystal spectrometers (Sanders *et al.* , 1993) ($0.15 \leq E \leq 0.284\,keV$), with high spectral resolution show the existence of emission lines, thus confirming the thermal origin of the diffuse emission. They also indicate that CIE model fits, cannot reproduce the observed spectrum satisfactorily.

There are two peculiar lines of sight (l.o.s.) that cut right through the LB. They may cause severe problems for any hot plasma model, if they were typical for the LB: (i) The l.o.s towards β CMa (distance roughly 200 pc), which is largely filled with HII and shows $\langle n_e \rangle \sim 2 \times 10^{-2}\,cm^{-3}$ and a very low temperature $T \leq 5 \times 10^4\,K$ (Gry *et al.* , 1985) and (ii) the dispersion measure of the nearby pulsar P0950+08 ($D \approx 130\,pc$ from parallax), giving $\langle n_e \rangle \sim 2.3 \times 10^{-2}\,cm^{-3}$ (Reynolds, 1990). However, it may be possible that (i) is not typical and (ii) may refer to a pulsar that is already beyond the LB.

Also considerable effort has been put into modelling the LB as the result of a single massive blast wave. This is certainly the most physical way of understanding the origin of the LB, and the results are valuable as a zero order approach. Basically, the models come in two flavours: a young ($\leq 10^5\,yrs$ active remnant, which produces SXR emitting plasma right behind a strong shock (e.g. Cox & Anderson, 1982), or a very old remnant, in which the hot interior radiates in SXRs (e.g. Innes & Hartquist, 1984; Edgar & Cox, 1993). The problems arise, because reproducing both the intensity and the observed spectrum puts tight constraints on the evolution of the remnant and the boundary conditions. For example, the models of Edgar & Cox (1993) require a rather large ambient magnetic field ($\sim 11\,\mu$G), in order to reproduce a sufficiently large intensity.

3. Modelling

In the last Section, I have discussed the most important LB observations and the major problems associated with the interpretation by the standard displacement model. Here I will present a new class of models, in which the assumption of CIE has been dropped. It is well-known, that radiative recom-

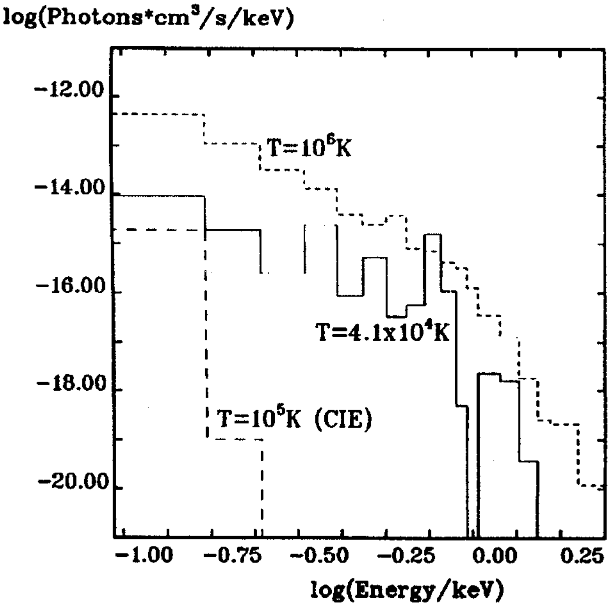

Figure 1. Non-equilibrium emission spectrum (normalized to n_e^2) of a fast adiabatically cooling (initial temperature $T_0 = 2.5 \times 10^6\,K$) plasma (Breitschwerdt and Schmutzler, 1994). The short dashed line shows the spectrum at $T = 10^6\,K$, the solid line at $T = 4.1 \times 10^4\,K$. The long dashed line is a $10^5\,K$ CIE spectrum for comparison.

bination, which is the dominant cooling process in optically thin plasmas, and collisional ionization are not inverse processes, and therefore an external radiation source is needed, in order to maintain equilibrium. Otherwise, if an initially hot plasma ($T \geq 10^6\,K$) in CIE is allowed to cool isochorically or isobarically, substantial deviations from equilibrium occur, increasing with time (Kafatos, 1973; Shapiro & Moore, 1976; Schmutzler & Tscharnuter, 1993). This is even more severe if the gas can expand, and therefore adiabatic cooling can introduce the shortest time scale.

Under these circumstances, the dynamics of the gas cannot be separated from its thermal evolution, and self-consistent calculations have to be performed (Breitschwerdt, 1994; Breitschwerdt & Schmutzler, 1994). As a result, high ionization stages will be "frozen" into the plasma, thus preserving a memory of its origin. The emission spectrum is a superposition of line emission and recombination continuum.

Note the similarity in Fig. 1 between the non-equilibrium X-ray spectrum at $10^6\,K$ and at $4.1 \times 10^4\,K$. The corresponding CIE spectrum would not show any noticeable SXRs. Such a result is of fundamental importance, because it shows that in general the form of the spectrum and the existence of well-known lines do not allow to derive a *unique* temperature of the plasma. Instead its dynamical and thermal history has to be known.

In the following, a model is described that can account for the observations presented in the previous section. It is clear that a successful model of the SXRB requires at least two components: a *local* one (LB), to reproduce the existence of the ultrasoft X-rays and a *distant* one (halo and possibly nearby SBs) to explain the findings of the shadowing experiments. There is observational evidence for a disk-halo connection in spiral galaxies via "chimneys" (Norman & Ikeuchi, 1989), allowing mass, momentum and energy exchange between disk and halo. Such a picture is supported by recent ROSAT observations of the nearby edge-on galaxies NGC 891 (Bregman & Pildis, 1994) and NGC 4631 (Wang *et al.* , 1995), which show the existence of extended X-ray halos in normal spiral galaxies. If the FIR luminosity is taken to be proportional to the star formation rate, these galaxies are comparable to our own (Dettmar, 1992; Table III); in particular NGC 891 is often referred to as a twin of the Galaxy. It has been shown (Breitschwerdt & Schmutzler, 1994) that, with respect to the distant component, a dynamically and thermally self-consistent calculation of a halo outflow towards the North Galactic Pole can reproduce the correct band ratios of count rates from 0.08 - 1.5 keV in the WISCONSIN Survey. Also absorption by an extended HI halo component (Lockman *et al.* , 1986) was included, showing the need for a more local contribution to the ultrasoft component. It is important to note, that a qualitatively new feature of non-equilibrium models is the emission in all of the SXR bands.

As a possible scenario for the origin of the LB, it has been suggested that it is the relic of an old SB, that has been re-energized some 10^6 yrs ago ((Breitschwerdt & Schmutzler, 1994); for details cf. rapporteur paper of the author for Working Group 2). If its further evolution has been dominated by fast adiabatic expansion, the emission spectrum in the SXR bands is characterized by recombination continuum and similar to Fig. 1. Since the plasma kinetic temperature may be as low as $4.2 \times 10^4\,K$, and the density as high as $2.4 \times 10^{-2}\,cm^{-3}$ in order to accommodate to the pulsar dispersion measure, the resulting $p/k \approx 2000$, a value close to the one of the Local Cloud. Temperature gradients between its boundary and the LB are not significant, and therefore conduction should only play a minor rôle. In general, co-existence with HI filaments does not pose a real problem in such a picture.

Since in a non-equilibrium LB model there is simultaneous emission in the B-, C- and M-bands, there seems to be no problem in reproducing the 3/4 keV upper limit intensity towards MBM12. Most interestingly, due to the much lower kinetic temperature, collisional excitation of EUV lines is largely suppressed. Thus the calculations predict a deficiency of EUV lines (s. Fig. 2), in agreement with the EUVE observations, mentioned in the previous Section.

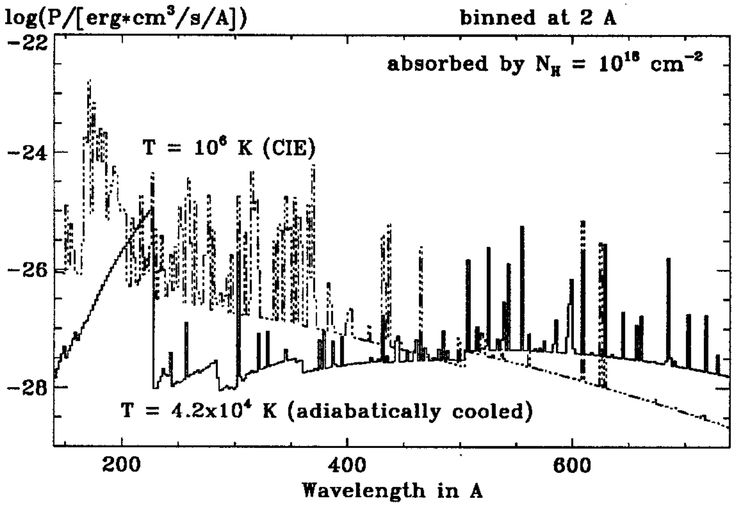

Figure 2. Non-equilibrium EUV emission spectrum (normalized to n_e^2) of the LB in comparison to the CIE spectrum of the LHB; N_H denotes the HI column density of the Local Cloud.

4. Conclusions

Although there are lots of high quality observations, there is still uncertainty about the basic properties of the LB, i.e. the density, temperature (and hence pressure), its extension, amount and distribution of mixed in (partially) neutral material (clouds and HI filaments). Ironically enough, it is just the wealth of information that puts too many constraints on a simple model, from which the LB properties have to be inferred, since none of them can be observed *directly*. These are not only important physical input parameters for modelling the heliosphere, but are also intimately related to the origin of the LB, which still remains a mystery. But the case is not hopeless, because the more detailed information we will obtain in the future by high spatial and spectral resolution in the UV, EUV and SXRs, the more sophisticated modelling we will need. The observational constraints will successively narrow down the number of free parameters. In particular, the observation of individual spectral lines will give us unequivocal information on the excitation conditions, specifically on whether there is still room for CIE models or not.

The model discussed in the previous Section is merely a first step in this direction. No claim is made that it solves the problem of the origin of the LB. Its attractiveness lies in the fact that it connects the fitting of the observations with the origin of the plasma, i.e. its dynamical and thermal history, and that it makes predictions that can be falsified.

If one is willing to accept a "Copernican" view of the LISM, one might get new insight into the physics of the ISM in general. As it appears at present, the LB is just one component of a fairly complex SXRB (including SBs, and a disk-halo outflow component), but it does not seem to be distinctively unusual. The Loop I bubble is a nearby example of a SB, and there is evidence that it is interacting with the LB (cf. rapporteur paper of Working Group 2). A more detailed study of spectral types of the stellar content within the LB, might provide information on whether our LB is also the result of an ancient SB event.

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Address for correspondence: Max-Planck-Institut für extraterrestrische Physik, Postfach 1603, D-85740 Garching, Germany