Keynote Lecture: Galactic and Extragalactic Bubbles

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The observational and theoretical state of Galactic and extragalactic bubbles are reviewed. Observations of superbubbles are discussed, with some emphasis on nearby bubbles such as the Local Bubble (LB) and the Loop I superbubble (LI). Analytical bubble theory is revisited, and similarity solutions, including the time-dependent energy input by supernova explosions according to a Galactic initial mass function (IMF), are studied. Since the agreement with observations is not convincing in case of the LB, we present high resolution 3D AMR simulations of the LB and LI in an inhomogeneous background medium. It is demonstrated that both the morphology and recently published FUSE data on O\text{vi} absorption line column densities can be well understood, if the LB is the result of about 20 supernova explosions from a moving group, and the LB age is about 14.7 Myrs.

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1 Introduction

The term “bubble” in science is not well defined. A convenient operational definition could be that of a closed two-dimensional surface in three-space, separating two media of different (physical) properties, with lower density inside than outside. Consequently there exists a vast range of topics in the literature from electron bubbles in superfluid helium to bubbles in avalanches. In astrophysics, interstellar bubbles are an already classical subject in ISM research, and seem to have experienced a renaissance each time a new process for significant energy injection has been found. After the discovery of the Stroemgren (1939) sphere, generated by stellar Lyman continuum photons, it became clear that the rise in temperature in the H\text{II} region, $T_{\text{II}}$, with respect to the neutral ambient medium, $T_1$, would imply a strong pressure imbalance of the order $\sim T_{\text{II}}/T_1$, and thus a shock wave would be driven outwards (Oort 1954). The major effect is the growth of the H\text{II} region in size due to the decrease in electron density $n_e$ inside and hence in recombination rate ($\propto n_e^2$), allowing stellar photons to propagate further out. The net result is a bubble filled with low density ionized gas. Another, even more powerful energy injection mechanism emerged after the discovery of P Cygni profiles in stellar spectra (Morton 1967), revealing the existence of hypersonic stellar winds smashing into the ISM at speeds of $\sim 2000$ km/s and a canonical mass loss rate of $10^{-6} M_\odot/\text{yr}$, or even higher for Wolf-Rayet stars. Like in the case of the solar wind this leads to a two-shock structure, separated by a contact discontinuity that isolates the wind from the ISM material, but is in reality unstable to perturbations and allows mixing and mass loading of the stellar wind flow. Observationally, these bubbles can be detected in X-rays, since the temperature behind the inner termination shock rises according
to mass and momentum conservation (energy conservation for a monatomic gas does not give any new information) to \( T \approx \frac{3}{2} \frac{1}{m_{\text{w}}} \frac{V_{\text{w}}^2}{k_B} = 5.4 \times 10^7 \text{K} \), neglecting ambient thermal pressure with respect to ram pressure. Under these conditions radiative cooling of the bubble is negligible, and the bubbles are in their so-called energy driven phase. Adiabatic cooling due to \( p - d\mathbf{V} \) work on the surrounding medium, however, is significant. Sweeping up and compressing ISM gas slows down the outer shock, which can eventually suffer severe radiative losses, as the downstream density is considerably higher than behind the stellar wind termination shock. Moreover the dense outer shell (or part of it) is photoionized and thus well observable in the optical. Diffuse soft X-ray emission from stellar wind bubbles has been observed from NGC 6888 with ASCA SIS (Wrigge et al. 1998) and from S 308 with XMM-Newton EPIC pn (Chu et al. 2003), revealing temperatures of \( 1.5 \times 10^6 \text{K} \) and \( 8 \times 10^6 \text{K} \) for NGC 6888, and \( 1.1 \times 10^6 \text{K} \), for S 308. As we shall see, mass loading must play an important rôle for decreasing the temperature thereby enhancing the cooling and thus the X-ray emissivity.

Already 70 years ago, Baade & Zwicky (1934) suggested that stellar core collapse resulting in a neutron star could release a sufficient amount of gravitational energy to power a supernova (SN) explosion. The effect of the kinetic energy of \( 10^{51} \text{erg} \), which is only \( \sim 1\% \) of the released neutrino energy, is dramatic. After a free expansion phase, in which a shell with mass similar to the ejecta mass is swept up, the pressure difference between shocked ISM and ejecta drives a reverse shock into the supernova remnant (SNR), reheating the ejecta as it propagates inwards. The transfer of energy to the ISM is now determined by the adiabatic Sedov-Taylor phase, lasting several ten thousands of years until the cooling time of the outer shock becomes less than the dynamical time scale, and the SNR enters the radiative phase before eventually merging with the ISM. The widespread O\text{vi} line in the ISM is thought to be the signature of old SNRs.

Young star clusters, like the four million years old NGC 2244 exciting the Rosette Nebula, can blow holes into the emission nebulae by the combined action of several stellar winds. Since the discoveries of huge H\text{i} shells, so-called supershells, either in the Milky Way (e.g. Heiles 1979, 1980) or in M 31 (Brinks & Shane 1984), or by direct observation of huge X-ray emitting cavities (e.g. Cash et al. 1980) in the Orion, Eridanus or Cygnus regions, it is understood that O- and B-stars in concert can create superbubbles (SBs). Although stellar winds are the initial contributors over the first few million years, it is obvious that SN explosions dwarf their energy input over the SB life time of a few tens of million years. The SBs range in sizes from a few tens to a few hundreds of parsecs. The most prominent ones are undoubtedly the Local Bubble (LB), in which our solar system is immersed, and which is still not well understood, and the adjacent Loop I SB (LI); both will be discussed in some detail in this review. Extreme examples of bubbles with respect to their energy input on galactic scales are those driven by (nuclear) starbursts - often called superwinds -, which in case of NGC 3079 (Cecil et al. 2002) show clear signatures of an outflowing bubble both with Chandra and HST. Although driven by star formation processes, but for lack of space, we will discuss neither planetary nebulae, which exhibit a prominent white dwarf blown wind bubble, nor pulsar wind bubbles driven by energetic particles, nor bipolar outflows and jets, which show some additional features such as Mach disks. Why is it important to study bubbles? Apart from being interesting astrophysical objects, they are part of the interstellar matter cycle, enriching the ISM with metals, and, most importantly, they are the major energy sources of the ISM, controlling its structure and evolution, with SNRs and SBs being the major contributors.

In Section 2 we present some recent observations of the LB and the LI SB, taken in X-rays and in H\text{i}. Then, in Section 3 some analytical work, mainly similarity solutions, and their limitations are discussed, and in Section 4 numerical high resolution simulations of the LB and LI are shown, finishing off with our conclusions in Section 5.
Since we want to describe bubbles in the *young local universe*, the closest examples are undoubtedly the LB, in which our solar system is immersed, and the neighbouring LI SB, whose outer shell is most likely in contact with the LB shell (cf. Egger & Aschenbach 1995). The centre of the LI bubble is approximately 250 pc away, and the bubble radius is about 170 pc. Its proximity is most impressively seen in a ROSAT All Sky Survey (RASS) multispectral image (Freyberg & Egger 1999), which shows it as the largest coherent X-ray structure in the sky (see Fig. 1), centred roughly on the Galactic Centre direction and covering a solid angle of $7/6 \pi$ (Breitschwerdt et al. 1996). Although the existence of local X-ray emission was realized already soon after the observation of the diffuse soft X-ray background (SXRB) (Bowyer et al. 1968), the idea received considerable support by HI observations, revealing a local cavity (e.g. Frisch & York, 1983). The simplest explanation is given by the so-called “displacement” or Local Hot Bubble model (Sanders et al., 1977; Tanaka & Bleeker, 1977), in which it is assumed that the solar system is immersed in a bubble of diffuse hot plasma in collisional ionization equilibrium, that displaces HI, and has an average radius of 100 pc. More recent observations of the Local Cavity (see Fig. 2), using NaI as a sensitive tracer of HI (Lallement et al. 2003), show a more complex 3D structure of the hydrogen deficient hole in the Galactic disk, as well as a clear indication of opening up into the halo like a chimney. As a natural result, also the X-ray brightness of the bubble will vary with direction, especially if entrained clouds are shocked and

![Figure 1: Multispectral X-ray view of the soft X-ray background as seen by the ROSAT PSPC. The RGB image covers three energy bands (1/4, 3/4 and 1.5 keV, respectively), and is shown in galactic coordinates in Aitoff-Hammer projection. The Galactic Centre is at $l = 0^\circ$ with longitudes increasing to the left. The Loop I bubble lies in the direction of the Galactic Centre and is the largest coherent X-ray structure in the sky. The North Polar Spur stretching from $(l, b) = (30^\circ, 15^\circ)$ to $(300^\circ, 80^\circ)$ is clearly visible. Since we are located inside the Local Bubble, we can observe its X-ray emission from all directions. The picture is taken from Freyberg & Egger (1999).](image-url)
Figure 2: Projection of the Local Cavity onto the Galactic plane inferred from Na\textsc{i} absorption line studies by Lallement et al. (2003), using sightlines to 1005 stars with known Hipparcos parallaxes. The grey scale represents the density contrast with white being low and dark high densities. The dashed lines give the contours of Na\textsc{i} equivalent widths of 20 and 50 m\text{Å}, respectively, with 20 m\text{Å} corresponding to log(Na\textsc{i}) = 11.0 or $N_{\text{H}} \approx 2 \times 10^{19}$ cm$^{-2}$. The existence of a shell in most directions is clearly seen, since the small difference between the contours indicates a steep gradient.

evaporated. Indeed, observations of the SXRB exhibit a distinct patchiness in emission, as has been reported from ROSAT PSPC observations (Snowden et al. 2000), and more recently by a mosaic of observations of the Ophiuchus cloud (Mendes et al. 2005), which was used to shadow the SXRB and thus allow to disentangle cloud fore- and background emission. The absorbing column density in direction to the Ophiuchus cloud, which is a well-known star forming region at a distance of 150 pc in direction of the Galactic Centre, contains up to $10^{22}$ cm$^{-2}$ H atoms, efficiently blocking out background radiation up to 1 keV. This is demonstrated nicely by a deep shadow in diffuse X-rays, which correlates very well with the IRAS 100 $\mu$m contours (s. Fig. 3).

Our analysis of the spectral composition of the fore- and background radiation (s. Fig. 4) shows convincingly that the major fraction of the emission below 0.3 keV (most likely unresolved carbon lines) is generated in the foreground. In addition we observe a significant local fraction of oxygen lines (O\textsc{vii} and O\textsc{viii}) between 0.5 and 0.7 keV, as well as lines between 0.7-0.9 keV (probably iron). These results give strong observational evidence that the gas inside the LB is not in collisional ionization equilibrium, in disagreement with the classical Local Hot Bubble model. A small fraction of the foreground emission stems also from LI. However, Fig. 4 shows that the off-cloud spectrum contains iron lines, which are absent in the on-cloud spectrum. Therefore the excitation temperature in the LI SB must be significantly higher than in the LB, allowing to disentangle spectrally the respective contributions. This is not surprising as LI is still an active SB in contrast to the LB, as we shall see in section 4.

The spectral interpretation of the SXRB is far from trivial. First of all it is at present unclear to what extent different sources contribute. These are: (i) diffuse local emission from the LB (and possibly the LI SB, although its major component has a distinctly higher temperature), (ii) diffuse Galactic emission from the hot ISM (and other SBs) and unresolved point sources (e.g. X-ray binaries), (iii) a diffuse Galactic halo component (presumably from the Galactic...
Figure 3: Three individual pointings of the Ophiuchus molecular cloud merged into one EPIC-pn image, showing the first X-ray shadow detected with XMM-Newton, in the energy range 0.5 – 0.9 keV. There is an excellent anticorrelation between soft X-ray emission and the overlaid IRAS 100 µ contours (green). The color coding represents the X-ray intensity with white being the maximum.

fountain/wind), (iv) a diffuse extragalactic component (thought to consist of the WHIM = Warm Hot Intergalactic Medium and unresolved point sources). Shadowing the darkest regions of the Milky Way, i.e. nearby Bok globules with extinctions of $A_V \sim 30 – 50$ mag, give unmistakably in case of Barnard 68 two temperature components of the local emission (and thus inconsistent with the standard Local Hot Bubble model): $kT_1 \approx 0.14 \pm 0.04$ keV, and $T_2 \approx 0.20 \pm 0.06$ keV (Freyberg et al. 2004). How is this possible? Several (not mutually exclusive) explanations have to be further investigated: (i) the LB is an old SB emitting X-rays from a gas not in ionization equilibrium (cf. Breitschwerdt & Schmutzler 1994) thus mimicking a multi-temperature plasma, (ii) there is a significant contribution from heliospheric plasma which undergoes charge exchange reactions with highly ionized solar wind atoms (Lallement 2004). At present it is unclear what the quantitative contribution of the latter process is (values $\leq 75\%$ in the disk and $\leq 50\%$ in the halo have been advocated). Such a very local emission should in principle exhibit seasonal variations. We have obtained two exposures of the Ophiuchus cloud, which partially overlap and are 6 months apart. The differences in emission measure and the spectrum are within the noise level. Although this is no counterargument it does not support the hypothesis of a substantial time-dependent variation of the heliospheric contribution. Further studies are needed to pin down this crucial component.

3 Analytical treatment of superbubble (SB) evolution

The dynamics of SBs has been worked out analytically by McCray & Kafatos (1987), based on earlier work by Pikel’ner (1968), Dyson & deVries (1972), Weaver et al. (1977) on stellar winds. A basic principle, which is used in aerodynamics for constructing models in the wind channel,
Figure 4: Spectrum of the soft X-ray background towards the Ophiuchus cloud. We have analyzed XMM-Newton EPIC pn data from two pointings of 20 ksec exposure each. Emission line complexes are clearly distinguishable at $0.5 - 0.7, \sim 0.9$ keV, and to a minor extent at $\sim 0.3$ keV. The on-cloud pointing (red) contains mainly contributions from the Local Bubble, while the off-cloud observation has significant contributions from the ambient Loop I superbubble, as can be seen from the substantial amount of emission at $0.8 - 0.9$ keV. This can be attributed to iron line complexes, indicating a higher plasma temperature in Loop I than in the Local Bubble.

is the scaling of hydrodynamic flows if there are no specific length or time scales entering the problem. Strictly speaking this is never fulfilled, because there are always boundary layers or time-dependent changes in the flow, but for studying the large-scale asymptotic behaviour of the flow this ansatz works remarkably well. If we e.g. neglect the initial switch-on phase of a SB, if we assume that the stellar source region is much smaller than the bubble, and if the discontinuous energy supply during the SN explosion phase can be approximated by a continuous injection of mass, momentum and energy, then similarity solutions are reasonably well applicable.

Mathematically speaking, the transformation to a similarity variable $\xi = (r/A) t^{-\alpha}$, projects the family of solutions of a PDE system to a one-dimensional family, with all hydrodynamic variables depending only on the dimensionless similarity variable $\xi$. A flow is said to be self-similar if its properties at any point $x_1$ and instance of time $t_1$ can be recovered by a similarity transformation at some other point in spacetime $(x_0, t_0)$. The exponent $\alpha$ can already be derived from dimensional analysis. The physical quantities determining the SB dynamics are the energy injection rate, $L_{SB}$ (with mass and momentum injection being negligible with respect to the shell mass and momentum during the energy driven phase) and the ambient density, $\rho_0$. Note that it is implicitly assumed that the pressure of the ambient medium can be neglected with respect to the interior pressure of the bubble. This is certainly valid until the shock becomes weak, in which case counterpressure has to be included. Then, $\xi = (L_{SB}/\rho_0)^{-1/5} rt^{-3/5}$, is the only possibility to form a dimensionless quantity. Using this similarity variable, it is now possible to construct the complete flow solutions in terms of variables $u'(\xi), \rho'(\xi)$ and $P'(\xi)$, obeying matching conditions for boundaries in the flow at which these variables change discontinuously, like at the termination shock (where the “wind” ejecta are decelerated), the contact discontinuity (separating the wind from the ISM flow), and the outer shock (propagating into the ISM). The integration of the resulting ODE system is a straightforward but tedious exercise that can be
carried out with the help of an integral, representing the conservation of the total energy of the system. We can simplify the procedure considerably by making a few additional, but well justified, assumptions about the flow in the different regions. Firstly, the ejecta gas, having a high kinetic energy, is compressed and heated by the strong termination shock, converting 3/4 of its initial bulk motion into heat. Therefore the temperature and the speed of sound in this bubble region are so high, that radiative cooling can be neglected and the pressure remains uniform for long time. On the other hand the pressure in the swept-up shell is also uniform due to its thinness, or in more physical terms, because the sound crossing time is much less than the dynamical time scale. This is because the outer shock can cool efficiently, as the ISM density is orders of magnitude higher than the ejecta gas density, if the latter one is assumed to be smoothly distributed. In essence, we are allowed to assume spatially constant density and pressure in the wind bubble and the shell, respectively.

As it turns out, the assumption of constant energy injection rate $L_{SB}$ can be relaxed without violating the similarity argument. In reality we are dealing with an OB association, in which the stars are distributed according to some initial mass function (IMF) given by $\Gamma = \frac{d\log \xi(\log m)}{d\log m}$; $\xi$ denotes the number of stars per unit logarithmic mass interval per unit area with $\Gamma = -1.1 \pm 0.1$ for stars in Galactic OB associations with masses in excess of $7 M_\odot$ (Massey et al. 1995). This translates into a number $N(m)dm$ of stars in the mass interval $(m, m + dm)$ (calibrated for some mass interval $N_0 = N(m_0)$), i.e. $N(m)dm = N_0 \left( \frac{m}{m_0} \right)^{\Gamma - 1} dm$. It can be transformed into a time sequence, if we express the stellar mass by its main sequence lifetime, $\tau_{ms}$. For stars within the mass range $7 M_\odot \leq m \leq 30 M_\odot$ this can be empirically approximated by $\tau_{ms} = 3 \times 10^7 \left( m/10 M_\odot \right)^{-\eta} \text{yr}$ (Stothers 1972), with $\eta = 1.6$. Since this defines $m$ as a function of time $\tau$, implicitly assuming that the energy input can be described as a continuous process, we obtain $m(\tau) = M_0 \left( \frac{\tau}{\tau_0} \right)^{-1/\eta}$, with $C = 3.762 \times 10^{16} \text{s}$.

Let then $L_{SB}(t)$ be the energy input per unit time due to a number of successive SN explosions with a constant energy input of $E_{SN} = 10^{51} \text{erg}$ each, so that the cumulative number of SNe between stellar masses $m$ and $m_{\text{max}}$ reads

$$\tilde{N}_{SN}(m) = \int_{m}^{m_{\text{max}}} N(m') dm' = \frac{N_0 m_0}{\Gamma} \left[ \frac{m'}{m_0} \right]^{\Gamma - 1} .$$

Then we have

$$L_{SB} = \frac{d}{dt} \left( \tilde{N}_{SN} E_{SN} \right) = E_{SN} \frac{d\tilde{N}_{SN}}{dt} = E_{SN} \frac{d\tilde{N}_{SN}}{dm} \frac{dm}{d\tau} \frac{d\tau}{dt}$$

$$= \frac{N_0 E_{SN} M_\odot}{\eta C} K^{1-\Gamma} \left( \frac{\tau_0 + t}{C} \right)^{-(\Gamma/\eta + 1)} ,$$

using the previous equations, and putting $m_0 = K M_\odot$. Since $\tau = t + \tau_0$, where $t$ is the time elapsed since the first explosion, i.e. $\tau_0 = \tau_{MS}(m_{\text{max}})$, we have $d\tau/ dt = 1$. With the above values for $\Gamma$ and $\eta$, we obtain the useful formula $L_{SB} = L_0 t_7^\delta$, where $\delta = - (\Gamma/\eta + 1) = -0.3125$ and $t_7 = t/10^7 \text{yr}$. $L_0$ depends on the richness of the stellar cluster. Thus we see that, depending on the stellar IMF, the energy input rate by SN explosions is a mildly decreasing function of time. Although the number of core collapse SNe increases as the higher masses of the cluster become depopulated, the increasing time interval between explosions more than compensates this effect.

If the ambient medium is further assumed to have a constant ambient density, or one which varies with distance like $\rho \propto r^{-\beta}$, in which case the similarity variable has to be transformed to $\alpha = 3/(5 - \beta)$, the system can be cast into the following form:

$$M_{sh}(r) = \int_0^r \rho(r') d^3r' , \quad E_{th}(r) = 1/(\gamma - 1) \int_0^r p(r') d^3r' .$$
and the energy input is shared between kinetic and thermal energy. Using $\gamma = 5/3$ for the ratio of specific heats, observing that the bubble pressure $P_b$ remains uniform, and applying spherical symmetry, conservation of momentum and energy

\[
\frac{d}{dt}(M_{sh} \dot{R}_b) = 4\pi R_b^2 P_b, \quad \frac{dE_{th}}{dt} = L_{SB}(t) - 4\pi R_b^2 \dot{R}_b P_b,
\]

yields the solution

\[
R_b = At^\alpha; \quad \alpha = \frac{\delta + 3}{5 - \beta},
\]

\[
A = \left\{ \frac{(5 - \beta)^3(3 - \beta)}{(7\delta - \beta - \delta\beta + 11)(4\delta + 7 - \delta\beta - 2\beta)} \right\}^{1/5} \times \left\{ \frac{L_0}{2\pi(\delta + 3)\rho_0} \right\}^{1/5}. \tag{7}
\]

Since the swept-up shell is usually thin, the bubble and shell radius can be treated as equal during the energy driven phase and are denoted by $R_b$. The similarity variable in the case considered here is given by $\alpha = (2 - \Gamma/\eta)/(5 - \beta)$. For simplicity, the ambient density is assumed to be constant ($\beta = 0$), although, as we shall see in our numerical simulations, this assumption becomes increasingly worse with time. On scales of ten parsec, the ISM cannot be assumed to be homogeneous any more. As the cold and warm neutral media are observed to be rather filamentary in structure, high pressure flows will be channelled through regions of low density and pressure. It should be mentioned here, that it is not only the pressure difference between the bubble and the ambient medium that determines the expansion, as it is sometimes argued, but also the inertia of the shell is a crucial factor (see Eq. 5). Therefore mass loading of the flow is an important factor. Unfortunately, some convenient assumptions, like e.g. the bubble behaves isobaric, do not hold any more. Pittard et al. (2001a,b) have shown that similarity flow can be maintained provided the mass loading rate scales as $\dot{\rho} \propto r^{(5-\beta)/3}$ in case of conductive evaporation or $\dot{\rho} \propto r^{(-2\beta-5)/3}$ for hydrodynamic mixing according to the Bernoulli effect. It was assumed that in the former case clumps passed through the outer shock as it expanded into a clumpy medium and evaporated in the hot bubble, whereas in the latter case the clumps were thought to be ejected by the central source itself. Here it is possible for strong mass loading that the wind flow is slowed down considerably due to mass pick-up, and in the extreme case even a termination shock transition can be avoided.

Berghöfer & Breitschwerdt (2002) have studied the evolution of the LB under the assumption that 20 SNe from the Pleiades moving subgroup B1 exploded according to their main sequence life times with masses between 20 and 10 M\(_\odot\). Using the above similarity solutions, the radius and the expansion velocity of the bubble evolve as

\[
R_b = 251 \left( \frac{2 \times 10^{-24} g/cm^3}{\rho_0} \right)^{1/5} t_7^{0.5375} \text{ pc}, \quad \dot{R}_b = 13.22 \left( \frac{2 \times 10^{-24} g/cm^3}{\rho_0} \right)^{1/5} t_7^{-0.4625} \text{ km/s}. \tag{8}
\]

As a result of a decreasing energy input rate the exponent in the expansion law of the radius, $\alpha = 43/80 = 0.5375$, in Eq. 8 is between a Sedov ($\mu = 0.4$) and a stellar wind ($\mu = 0.6$) type solution. Thus the present radius of the LB will be 289 pc and 158 pc and its velocity is 11.7 km/s and 6.4 km/s, if the ambient density is $\rho_0 = 2 \times 10^{-24} g/cm^3$ and $\rho_0 = 4 \times 10^{-23} g/cm^3$, respectively (for details see Berghöfer & Breitschwerdt 2002). In the latter case the value of the ambient density would correspond roughly to that of the cold neutral medium. There are several reasons why we may have overestimated the size of the LB in the similarity solutions above. Firstly, the mass inside the bubble is significantly higher than the pure ejecta mass, as can be inferred from the ROSAT X-ray emission measures; when assuming bubble parameters of $R_b = 100$ pc and $n_b = 5 \times 10^{-3}$ cm\(^{-3}\) (e.g. Snowden et al. 1990) a mass of at least 600 M\(_\odot\) is derived, and using non-equilibrium ionization plasma models (Breitschwerdt & Schmutzler 1994)
it is even more than a factor of five higher. The contribution of ejecta is only of the order of 100 $M_\odot$, and the bulk of the bubble mass is therefore due to hydrodynamic mixing of shell material, heat conduction between shell and bubble and evaporation of entrained clouds; hence the flow must be mass-loaded. The net effect is to reduce the amount of specific energy per unit mass, because the material mixed in is essentially cold, thus increasing the rate of radiative cooling. Secondly, the stellar association has probably been surrounded by a molecular cloud with a density in excess of $n_0 = 100\,\text{cm}^{-3}$ with subsequent break-out of the bubble and dispersal of the parent cloud (Breitschwerdt et al. 1996). Thirdly, the number of SN explosions could be less; here we have assumed that all 20 SNe have occurred inside the LB. This need not be the case as the subgroup B1 does not move through the centre of the LB. ROSAT PSPC observations have revealed an annular shadow centered toward the direction ($l_{\text{II}} = 335^\circ, b_{\text{II}} = 0^\circ$), which has been interpreted as an interaction between the LB and the neighbouring LI SB (Egger & Aschenbach 1995). The trajectory of the cluster B1 may have partly crossed the LI region. Alternatively and more likely, part of the thermal energy might have been liberated into the Galactic halo, since there is some evidence that the LB is open toward the North Galactic Pole (see Lallement et al. 2003). It should also be mentioned that due to small number statistics the true number of SNe can vary by a factor of 2. Finally, although there is no stringent evidence, it would be very unusual, if the LB would not be bounded by a magnetic field, whose tension and pressure forces would decrease the size of the LB.

Given these uncertainties and the fact that the simple analytic model discussed above can only be considered as an upper limit, the direct comparison with observations is not convincing. The bubble radius and shell velocity are rather insensitive to the energy input rate and the ambient density (due to the power of $1/5$) and therefore not well constrained, but depend more sensitively on the expansion time scale. Thus we can only assert with some confidence that the age of the LB should be between $1 - 2 \times 10^7$ yr.

The most serious drawback of analytical solutions in general and of similarity solutions in particular, is the assumption of homogeneity of the ambient medium on scales exceeding about 10 pc. To see this, consider the area coverage of the disk by hot gas, which is $\xi_{\text{SN}} \sim \nu_0/2\tau_{\text{SN}} (R_{\text{SN}}/R_{\text{gal}})^2 \approx 0.67$ due to SNe, and $\xi_{\text{SB}} \sim \nu_0/2\tau_{\text{SB}} (R_{\text{SB}}/R_{\text{gal}})^2 \approx 0.9$ due to SBs, respectively, assuming that half of the explosions go off randomly, and half in a clustered fashion within a star forming disk of 10 kpc radius and a disk SN rate of $\nu_0 = 2$ per century. Here we used the final SN radius according to McKee & Ostriker (1977), being $R_{\text{SN}} \approx 55$ pc after $\tau_{\text{SN}} \approx 2.2 \times 10^6$ yr and the SB radius from the paper of McCray & Kafatos (1987) of $R_{\text{SB}} \approx 212$ pc after $\tau_{\text{SB}} \approx 10^7$ yr, for a typical cluster with 50 OB stars. The overturning rate of a typical patch of ISM will then roughly be between $3.4 \times 10^6$ yr and $1.1 \times 10^7$ yr for SNe and SBs, respectively. Since we did not take into account overlapping of remnants and bubbles these values are lower limits. As will be shown in the next section, a roughly constant star formation rate and hence SN rate for a Galactic initial mass function (IMF) will lead to an ISM background medium that is highly irregular in density and temperature (and even pressure variations within an order of magnitude are observed) and it bears a high level of turbulence.

4 Numerical simulations of the Local Bubble (LB) and Loop I (LI) evolution

We have performed high resolution 3D simulations of the Galactic disk and halo (Avillez & Breitschwerdt 2004, 2005; see also this volume) on a grid of 1 kpc $\times$ 1 kpc in the plane and $z = \pm 10$ kpc perpendicular to it. Using AMR technique, we obtained resolution of scales down to 1.25 pc for MHD, and 0.625 pc for pure hydrodynamical (HD) runs. These simulations, which revealed many new features of the ISM, e.g. low volume filling factor of hot gas in the disk, establishment of the fountain flow even in the presence of a disk parallel magnetic field, more than half of the mass in classical thermally unstable regions, serve as a realistic background
medium for the expansion of the LB and the LI SB. We took data cubes of HD runs and picked up a site with enough mass to form the 81 stars, with masses, $M_\ast$, between 7 and 31 $M_\odot$.

Figure 5: Temperature map (cut through Galactic plane) of a 3D Local Bubble simulation, 14.4 Myr after the first explosion; LB is centered at (175, 400) pc and Loop I at (375, 400) pc.

that represent the Sco-Cen cluster inside the LI SB; 39 massive stars with $14 \leq M_\ast \leq 31 M_\odot$ have already exploded, generating the LI cavity. At present the Sco-Cen cluster (arbitrarily located at (375,400) pc has 42 stars to explode within the next 13 Myrs). We followed the trajectory of the moving subgroup B1 of Pleiades (see Berghöfer & Breitschwerdt 2002), whose SNe in the LB went off along a path crossing the solar neighbourhood. As a result, we observe that the locally enhanced SN rates produce coherent LB and LI structures (due to ongoing star formation) within a highly disturbed background medium (see Fig. 5). The successive explosions heat and pressurize the LB, which at first looks smooth, but develops internal temperature and density structure at later stages. After 14 Myr the 20 SNe that occurred inside the LB fill a volume roughly corresponding to the present day size (see Fig. 5 bubbles are labelled by LB and L1). The cavity is still bounded by an outer shell, which exhibits holes due to Rayleigh-Taylor instabilities, as has been predicted analytically by Breitschwerdt et al. (2000), and it will start to fragment in $\sim 3$ Myr from now. It has been argued that a crucial test of any LB model is the column density of the interstellar ion Ovi (Cox 2004), whose discovery back in the 70’s led to the establishment of the hot intercloud medium. So far all models have failed to reproduce the fairly low Ovi-value, most recently measured with FUSE (Oegerle et al. 2004), to be $N_{\text{OVI}} \simeq 7 \times 10^{12}$ cm$^{-2}$. To compare this with our simulations we have calculated the average and maximum
column densities of Ovi, i.e., $\langle N(Ovi) \rangle$ and $N_{\text{max}}(Ovi)$ along 91 lines of sight (LOS) extending from the Sun and crossing LI from an angle of $-45$ deg to $+45$ deg (s. Fig. 5). Within the LB (i.e., for a LOS length $l_{\text{LOS}} \leq 100$ pc) $\langle N(Ovi) \rangle$ and $N_{\text{max}}(Ovi)$ decrease steeply from $5 \times 10^{13}$ to $3 \times 10^{11}$ cm$^{-2}$ and from $1.2 \times 10^{14}$ to $1.5 \times 10^{12}$ cm$^{-2}$, respectively, for $14.1 \leq t \leq 15$ Myr (Fig. 6), because no further SN explosions occur and recombination is taking place. For LOS sampling gas from outside the LB (i.e., $l_{\text{LOS}} > 100$ pc) $\langle N(Ovi) \rangle > 6 \times 10^{12}$ and $N_{\text{max}}(Ovi) > 5 \times 10^{13}$ cm$^{-2}$. We have made histograms of column densities obtained in the 91 LOS for $t = 14.5$ and 14.6 Myr, which show that for $t = 14.6$ Myr all the LOS have column densities smaller than $10^{12.9}$ cm$^{-2}$, while for $t = 14.5$ Myr 67% of the lines have column densities smaller than $10^{13}$ cm$^{-2}$ and in particular 49% of the lines have $N(Ovi) \leq 7.9 \times 10^{12}$ cm$^{-2}$. Noting that in the present model at 14.5 Myr the Ovi column densities are smaller than $1.7 \times 10^{13}$ cm$^{-2}$ and $\langle N(Ovi) \rangle = 8.5 \times 10^{12}$ cm$^{-2}$ (see the respective lines in both panels of Fig. 6), we are thus able to reproduce the measured $\langle N(Ovi) \rangle$ values, provided that the age of the LB is $\sim 14.7^{+0.5}_{-0.2}$ Myrs.

5 Conclusions

Galactic and extragalactic interstellar bubbles are still an active area of research. Despite the widespread belief that HII regions, SNRs, stellar wind bubbles and superbubbles are fully understood in theory, it has to be emphasized that real bubbles, observed in the Galaxy, such as the Local or LI superbubbles, or in external galaxies, such as in the LMC, are often poorly fitted by standard similarity solutions. The reason lies in the inapplicability of major assumptions, e.g., that the ISM is homogeneous, and that the bubbles are either in an energy or momentum conserving phase. High resolution 3D simulations in a highly structured and turbulent background medium offer a much better description and include physical processes such as mass loading and turbulent mixing on a fundamental level. Although this drains heavily on computer resources, the increased precision of observations in the near future will warrant such an effort.

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