Part X

Conference Summary

Relaxed atmosphere during the conference dinner.

Joachim Trümper closes the conference: what have we learnt?

The Local Bubble and Beyond: Summary

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1 Introduction

Lyman Spitzer, Jr, the founder of modern studies of the interstellar medium (ISM), passed away March 31, 1997. This conference occurred shortly thereafter and is dedicated to his memory. While many of his contributions underlie the work that was discussed at this meeting, one paper stands out in particular: his theoretical "discovery" of the hot gaseous halo of the Galaxy based on the need to confine the clouds of H I observed above the Galactic plane (Spitzer 1956). We now know that much of the ISM within about 100 pc of the Sun is largely filled by very low density gas, which is generally inferred to be hot, and as a result this region is termed the Local Bubble (Cox and Reynolds 1987). This conference was convened to establish the current state of our knowledge of the Local Bubble, both observational and theoretical, and its relation to the rest of the ISM. Because it is nearby, the Local Bubble is a laboratory for interstellar astrophysics, making the dedication to Spitzer's memory particularly appropriate.

Everyone I have talked to agrees that this conference was a great success. That success is due to two individuals. One is an experimentalist who has realized his dream of making a high resolution map of the entire X-ray sky. After enormous effort, the *ROSAT* All-Sky Survey is nearing completion. When it is released, it will become an invaluable resource for all astronomers, just as the *IRAS* infrared survey did over a decade ago. This person is Joachim Trümper. The second is a theorist who has developed a highly original model for the Local Bubble. Don Cox and I both refereed the paper describing this model for *Nature*. Although we rarely agree (I like to think of our approaches as lying along the real and imaginary axes–I'll let you decide which is which), we both felt that the paper was so original that it should be published there. This person is Dieter Breitschwerdt. Dieter had not only the vision to create the conference, but also the energy to ensure that everything worked perfectly. We owe both Joachim and Dieter a debt of gratitude.

It is impossible to adequately summarize such a large conference with so many threads of thought. The community is attempting to weave these threads into a coherent tapestry, but our work is far from done and the final image unclear. To bring some order to my discussion, I shall largely follow the outline suggested by Cox and Reynolds (1987) in their review:

1. What is the local interstellar medium (LISM) like?
2. Why is it like that?
3. Is the LISM typical of the ISM as a whole?

Additional comprehensive reviews of the Local Bubble are to be found in Bochkarev (1987) and Frisch (1995).

2 What Is the LISM Like?

2.1 The Very Local ISM–Interaction with the Heliosphere

It is traditional to distinguish space physics, which relies on in situ observations, from astrophysics, which relies on remote observation. The two fields converge in the study of the very local ISM that is streaming through the solar system. The exciting recent developments in this field were described by Lallement*.[1] Theoretically, one expects the solar wind to expand until its ram pressure becomes comparable to the pressure of the ambient medium, at which point the solar wind undergoes a termination shock. Because of the motion of the Sun relative to the surrounding medium, the shocked solar wind is swept backwards. The interstellar medium also undergoes a shock (the bow shock) when it interacts with the solar wind. The interface between the shocked solar wind and shocked ISM is termed the heliopause. The bow shock occurs primarily in the ionized component of the ISM. Interstellar H^0 interacts with the ionized gas through charge exchange, creating a "wall" of hot hydrogen. On the other hand, the charge exchange cross section for He^0 is small; interstellar He^0 readily penetrates the heliosphere, enabling direct measurement of its properties by the *Ulysses* spacecraft (Witte et al., 1992). Lallement* reported that the Sun's velocity relative to the local ISM is found to be 26 $\mathrm{km\,s^{-1}}$, the densities are in the range $n(\mathrm{H}^0) = 0.1 - 0.15\ \mathrm{cm}^{-3}$ and $n_e = 0.15 - 0.05\ \mathrm{cm}^{-3}$, the temperature is $T \sim 7000$ K, and the thermal pressure is in the range $P/k = 2700 - 1700\ \mathrm{K\ cm}^{-3}$. The sun is thus embedded in a cloud of warm gas (the Local Cloud, sometimes termed the "Local Fluff"), which in turn is embedded in the Local Bubble.

The *Voyager* spacecraft, which have yet to reach the termination shock, have detected electromagnetic radiation with a lower cutoff at 1.8 kHz (Kurth et al., 1984). According to Lallement*, this radiation is now believed to originate beyond the heliopause, which suggests that the interstellar electron density is $n_e \simeq 0.04\ \mathrm{cm}^{-3}$, just below the lower limit inferred from *Ulysses* data. The termination shock is inferred to be more than 75 AU from the Sun, and this limits the total pressure of the incoming ISM, including the magnetic pressure. Knowing the density and the velocity of the local ISM, it is then possible to place an upper limit on $B_\perp$, the component of the interstellar magnetic field that is normal to the relative velocity: $B_\perp < 4.4\ \mu$G

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[1] References to talks and posters at this conference are denoted by an asterisk.

(Lallement*). Once the *Voyager* spacecraft penetrate the heliopause, it will be possible to make a direct measurement of the shocked interstellar field.

The most surprising recent result on the very local ISM is described in a poster by Landgraf*: the dust size distribution measured by the *Ulysses* and *Galileo* spacecraft is inconsistent with that inferred from analysis of interstellar extinction (e.g., Kim, Martin, and Hendry 1994; Kim and Martin 1996). Whereas the mass distribution of interstellar grains is inferred to peak at about 0.2 μm, the in situ observations imply a mass distribution that peaks at about 0.4 μm. Although large grains are less efficient at causing extinction than small grains, it does not appear possible that the extinction observations have simply missed the large grains: virtually all the silicon in the ISM is needed to make the grain size distribution inferred by Kim et al. (1994), so there is none left to make the large grains observed by *Ulysses* and *Galileo*. Furthermore, the astrophysical model for interstellar grains has passed a major test with *ISO* observations, which show that the infrared emission spectrum of interstellar grains is just what was predicted (Reach and Boulanger*). The convergence of space physics and astrophysics appears to have produced a real puzzle in this case.

2.2 Hot Gas in the Local Bubble

There have been two recent major discoveries about the hot gas in the Local Bubble. First, as discussed by Snowden*, the observation of X-ray shadows by *ROSAT* has demonstrated that a significant fraction of the observed emission comes from the halo of the Galaxy, not the Local Bubble. He infers that the hot gas in the Local Bubble has a size of 40 – 130 pc, a temperature $T \simeq 10^{6.07}$ K and a pressure $P/k \simeq 1.4 \times 10^4$ K cm^{-3}. The hot gas in the halo is not uniform; on average, its emission measure is comparable to that in the Local Bubble, and its temperature is about the same ($T \simeq 10^{6.02}$ K). After allowing for the halo emission, it is still possible to describe the hot gas in the Local Bubble by a modified displacement model in which the X-ray brightness is proportional to the radius of the Local Bubble. There is little, if any, hard X-ray (M-band) emission from the Local Bubble. The hot gas in the Local Bubble appears to be approximately isobaric: analysis of the emission toward Eridanus gives $P/k \simeq 1.2 \times 10^4$ K cm^{-3} (Burrows and Guo*), similar to the value inferred by Snowden* for the entire Local Bubble. Historically, Bochkarev (1987) appears to have been the first to use X-ray shadows to establish the existence of Galactic X-ray emission from beyond the Local Bubble, although the data available at that time did not permit him to derive any quantitative conclusions. It should be noted that there is also spectroscopic evidence for two components of thermal X-ray emission, a local one with no evidence for absorption, and a distant one with evidence for absorption by the gaseous disk of the Galaxy that is consistent with a halo origin (Garmire et al., 1992).

The second major discovery, albeit an expected one, is the demonstration that the soft X-ray background is dominated by line emission, as expected for emission from a hot plasma (Sanders*). These results, which were obtained with the DXS experiment, were initially very puzzling, since at first thermal emission models did not fit the data. However, inclusion of better atomic physics in the models and allowance for depletion of Si, S, and Fe results in a significantly better fit for collisional ionization equilibrium (CIE) models, albeit with a χ^2 greater than 2. In fact, gas at a temperature of about 10^6 K is almost certainly not in ionization equilibrium (Böhringer*), so the data should prove to be consistent with thermal emission models. Significantly greater spectral resolution will be needed in order to determine just how the ionization deviates from that expected in equilibrium.

EUV observations reported at the conference also shed light on the nature and distribution of the hot gas in the Local Bubble. In what is possibly the longest single observation in the history of astronomy, 2×10^7 s of data from the Extreme Ultraviolet Explorer *(EUVE)* have been searched for line emission without success (Vallerga and Slavin*). *EUVE* was not designed for observations of diffuse emission, however, so this negative result is consistent with thermal emission from hot gas if iron is depleted.

EUV shadowing observations reported by Berghöfer et al* show that the pressure of the hot gas in the Local Bubble is consistent with that inferred from X-ray observations and is the same along several different lines of sight. X-ray data have given a consistent value of the pressure of the local hot gas over the years: McKee and Ostriker (1977) inferred $P/k \simeq 1.0 \times 10^4$ K cm^{-3} from the data available 20 years ago, whereas the current estimate from *ROSAT* is 1.4×10^4 K cm^{-3} (Snowden*). After correcting for the background, *EUVE* data give a value of 1.3×10^4 K cm^{-3}. Both the X-ray and EUV estimates are based on the assumption of CIE and use the atomic physics in the Raymond and Smith code; if the gas is far from ionization equilibrium, as in the model of Breitschwerdt and Schmutzler (1994), then the pressure of the hot gas could be much different. Provided the CIE estimates are even approximately correct, however, there is a major conundrum: why is the thermal pressure of the hot gas so much greater than that of the Local Cloud? It is not that the Local Cloud is anomalous, since its thermal pressure is similar to that of another cloud in the Local Bubble (Jenkins*).

It is also possible to study hot gas through UV absorption lines of highly ionized species. Gry and Dupin* presented a tantalizing result, a 2σ detection of C IV absorption at the velocity of the Local Cloud. Confirmation of this possible detection is important. C IV and Si IV absorption lines have also been detected in the spectra of stars located in Loop I (Freire Ferrero*).

2.3 Warm and Cold Gas in the Local Bubble

Although most of the volume in the Local Bubble appears to be filled with hot gas, most of the mass is either warm and partially ionized or cold and neutral. The ionization of helium in the warm gas seems comparable to that of hydrogen: Bowyer* reported values of the column density ratios for helium and hydrogen as $N(\mathrm{He}^+)/N(\mathrm{He}^0) \simeq 0.3 - 0.4$ and $N(\mathrm{H}^+)/N(\mathrm{H}^0) \lesssim 0.25$; Barstow et al* found values of 0.27 and 0.35 for these ratios. The relatively high ionization of helium is quite different from that in most of the ISM: optical (Reynolds and Tufte 1995) and radio (Heiles et al., 1996) observations of gas beyond the Local Bubble show that He II recombination lines are quite weak, indicating a low level of ionization compared to that of hydrogen. However, Slavin and Frisch* have shown that emission from evaporating clouds has an ionizing spectrum that can account for the observed ionization.

21 cm observations show that the Local Bubble corresponds to a cavity in the distribution of H I (Mebold*). For a disk of uniform column density $N_\perp$, one expects the column density observed at Galactic latitude b to satisfy the relation $N \sin b = N_\perp$ =const. Instead, observations show that $N \sin b$ increases away from the poles, reaching a constant value only for $b < 45°$. The column density at negative latitudes is somewhat greater than that at positive latitudes, as expected for the Sun's position above the Galactic plane.

Mapping the distribution of the warm and cold gas in and around the Local Bubble is a major undertaking, and several groups reported progress on this problem. Fluctuations in the X-ray background at high latitudes are consistent with absorption by clouds of column density $2 - 3 \times 10^{19}$ cm^{-2} (Warwick et al*), similar to those seen by Spitzer and Fitzpatrick (1993) toward a star in the halo. EUV observations can give a coarse picture of the distribution of gas with no velocity information; observations of over 200 white dwarfs and late-type stars in the EUV showed that the wall of absorbing gas toward Loop I is very nearby (Hutchinson et al*). Optical absorption line observations can provide much higher spatial resolution and offer velocity resolution as well. Beckman et al* have measured optical absorption lines toward a number of stars within 200 pc in order to constrain the three dimensional distribution of the interstellar gas, and they developed a technique to combine these data with 21 cm observations to extract more information about the absorbing clouds. They have found cold atomic clouds, cold clouds with warm ionized envelopes, and warm clouds without any cold cores. The cold atomic clouds have masses up to 2000 $M_\odot$, and the warm clouds have masses up to several hundred $M_\odot$. Some of the clouds appear to be roughly spherical, whereas others are sheet-like. Ultra-high resolution spectroscopy of such clouds indicates a complex structure (Welty*): even at a resolution of 0.3 km s^{-1} , only about half the velocity components appear to have been resolved. The complexity of the velocity structure is apparent even for very nearby stars, with distances less than 30 pc (Welsh et al*). Finally, interstellar scintillation studies are suggestive of turbulent structures in the ionized component of the LISM (Bhat et al*; Bochkarev and Ryabov*).

Spectral line observations also allow the determination of the overall kinematics of the gas. The Local Cloud is moving away from the Scorpius-

Centaurus Association (Frisch*); indeed, the Local Cloud velocity is approximately parallel to the velocity of the H I associated with the center of the North Polar Spur (Heiles*). On the other hand, somewhat more distant gas, which appears to be outside the Local Bubble, is moving in the opposite direction, toward Sco-Cen (Genova et al*).

There is very little molecular gas in the Local Bubble. Studies of the molecular gas at the boundaries of the Local Bubble are quite valuable because of the high spatial resolution that is possible. Observations of CO emission at very high velocity resolution ($\lambda/\Delta\lambda \simeq 2 \times 10^7$) suggest that the gas is in structures only 200 AU in size (Falgarone*). Direct observations of these structures with interferometry would be highly desirable.

2.4 Magnetic Field and Cosmic Rays

Although it is widely recognized that magnetic fields and cosmic rays play a central role in the dynamics of the ISM (e.g., Parker 1969), they are often slighted because it is so difficult to observe them. Heiles*, who has devoted a non-negligible fraction of his scientific life to measuring interstellar magnetic fields, gave a graphic demonstration of this problem: acknowledging that there are very few data on the magnetic field in the Local Bubble (except for the inferred upper limit discussed in §2.1 and the observation of optical polarization in some nearby stars by Tinbergen 1982), he presented an analysis of the structure of the field in radio Loop I, which lies in the North Polar Spur. He argued that the surface brightness of the synchrotron emission is inconsistent with a limb–brightened shell; instead, the field must be concentrated in flux ropes that have been displaced into a spherical shell. Heiles's results suggest that the field inside Loop I is very weak (Kahn*). It appears that interchange instabilities have not acted to bring the flux ropes back into the interior. Furthermore, the lack of limb brightening suggests that the relativistic electrons can escape from the compressed flux ropes, at least in some cases.

Cosmic rays outside the solar system can be observed only indirectly, through the gamma ray emission and, for cosmic ray electrons, the synchrotron emission they produce. It is therefore of some interest that they can also be observed back through time. As discussed by Morfill*, the intensity of the cosmic rays has been remarkably constant over the last 10^3, 10^6, and 10^9 yr. (However, fluctuations in the ^{10}Be concentration in Antarctic ice cores have been interpreted as being due to brief fluctuations in the cosmic ray intensity—Sonett et al., 1987.) The constancy of the mean cosmic ray intensity is somewhat surprising, since the radius of the heliopause varies substantially as the Sun moves into different regions of the Galaxy, leading to variations in the amount of solar modulation (Frisch*).

2.5 Relation to the Sco-Cen Association

The Scorpius-Centaurus Association is the nearest OB association to the Sun, at a distance of about 170 pc. Berkhuijsen et al. (1971) identified the origin of the Loop I radio source with a "super-supernova" in Sco-Cen. Subsequently, Weaver (1979) pointed out that the stellar winds from the OB stars in Sco-Cen would create a large bubble surrounded by an H I shell. He identified the H I filaments associated with the Loop I radio source as the shell produced by Sco-Cen, and pointed out that the near side of the bubble must be very close to the Sun since the filaments subtend an angle of 170°. At about that time, Heiles (1979) showed that H I shells and supershells are quite common in the Galaxy. Weaver identified Radio Loop I as a supernova remnant that exploded in the Sco-Cen Bubble relatively recently. Weaver's picture of the interstellar structures associated with Sco-Cen is quite close to the one we have today, except that it is now known that the supernovae dominate stellar winds after several million years (Bruhweiler et al., 1980).

Egger* presented evidence for the interaction of the Sco-Cen Bubble with the Local Bubble. He identified an elliptical ring of H I in the Sco-Cen shell with the ring of dense gas formed by the collision of two bubbles (Yoshioka and Ikeuchi 1990). Absorption line data indicate that this H I ring is about 70 pc away. Soft X-rays are absorbed by this gas. However, there is also a lack of hard X-ray emission on the western side of Loop I, and he attributed this to cooling of the X-ray emitting gas by the H I ring. The pressure of the X-ray emitting gas within the Sco-Cen Bubble was estimated to be $P/k \simeq 2 \times 10^4$ K cm^{-3}, somewhat greater than that of the Local Bubble.

As remarked above, the very local ISM is moving away from Sco-Cen, just as if it were part of the Sco-Cen shell. How can this be consistent with the geometry inferred by Weaver and by Egger*, in which the shell has yet to reach us? In the discussion following Egger's talk, Kahn* pointed out that the shell of shocked gas between the Local Bubble and the Sco-Cen Bubble would be accelerated by the greater pressure in the latter, leading to a Rayleigh-Taylor instability. In addition, the colliding shells would be subject to a bending mode instability (Vishniac 1994). Hydrodynamic instabilities such as these could account for the complex structure of the H I in the LISM.

Frisch's* view of the Local Bubble is somewhat different from Egger's: she associates the creation of a separate bubble and shell with each of the three subassociations in Sco-Cen. The first two shells have already swept past us; we are now in the third shell. The low density of the Local Bubble is due in part to our location in an interarm region; it was not created by local supernova explosions. The question yet to be quantitatively addressed by this model is how the bubbles and shells created by the successive subassociations in Sco-Cen could avoid merging into a single large superbubble and supershell.

3 Why Is the Local Bubble Like That?

3.1 Models of the Local Bubble

In the beginning was Cox and Smith (1974). They were the first to show that the supernova rate in the Galaxy is large enough that supernova remnants (SNRs) should occupy a significant fraction of the volume of the ISM. They envisioned old SNRs forming a network of tunnels in the ISM. To determine the importance of the interaction among old SNRs, they introduced the porosity

$$Q = S \int V(t)\, dt, \tag{1}$$

where S is the SN rate per unit volume and $V(t)$ is the volume of an SNR of age t. If the porosity Q is small, then it is just the filling factor of SNRs; for large values of Q, interactions among SNRs will be important. Q is proportional to the four-volume of the SNR in space-time (McKee 1990), and it gives the filling factor of the SNRs in space when the ISM is in a steady state.

Next, McKee and Ostriker (1977) showed that simple estimates of the porosity suggest that it was large, and that this required a revision of our picture of the ISM. Instead of H I filling most of space, with isolated H II regions and SNRs, it is the hot gas in old SNRs that fills space. H I is in the form of clouds embedded in this hot gas; ionizing radiation propagating through the hot gas forms ionized envelopes around the clouds (the Warm Ionized Medium). The evolution of SNRs is dominated by the evaporation of embedded clouds. They conjectured that the Local Bubble was heated by a supernova remnant that is several hundred thousand years old. Such a remnant, with a pressure $P/k \simeq 1.0 \times 10^4$ K cm^{-3}, could account for the soft X-ray data then available. They did not attempt to explain the low mean density of the Local Bubble; however, in contrast to most other models, this model naturally accounts for the presence of clouds in the Local Bubble.

The first detailed model for the Local Bubble was developed by Cox and Anderson (1982). They considered the evolution of an SNR in a low density ($n \simeq 0.004$ cm^{-3}) ambient medium, which is similar to assuming that the remnant evolves in the hot phase of the McKee-Ostriker model without interacting with the embedded clouds. They included non-equilibrium ionization and thermal conduction, and showed that they could reproduce the soft X-ray count rates for a remnant with an age of about 10^5 yr.

Innes and Hartquist (1984) attempted to model the Local Bubble as an old superbubble. By making several assumptions that they did not attempt to justify—treating the evolution of a superbubble as being the same as that of a blast wave with an energy of 10 SNe, assuming that the ambient pressure of the interstellar medium is very large (7×10^4 K cm^{-3}), and neglecting thermal conduction—they were able to achieve consistency with the X-ray data for a bubble that is 4×10^6 yr old. Related models were considered by Edgar and Cox (1993); they attributed the high external pressure ($3.5 - 6.5 \times 10^4$ K cm^{-3} in their models) to a strong ambient magnetic field.

Three models of the Local Bubble dominated the discussion at this conference. The most innovative is that of Breitschwerdt and Schmutzler (1994), who assumed that a superbubble created by a local OB association evolved in a dense ($n \sim 10^4$ cm^{-3}) cloud, and that the superbubble broke out of this dense gas about 4×10^6 yr ago. Expanding in a steep density gradient, the hot gas in the bubble underwent catastrophic adiabatic expansion, cooling to $T \sim 6 \times 10^4$ K while remaining highly ionized. The advantage of this model is that the thermal pressure ($P/k \simeq 2600$ K cm^{-3}) is comparable to that observed in the Local Cloud, and the electron density ($n_e \simeq 0.024$ cm^{-3}) is comparable to the mean electron density to a nearby pulsar. However, precisely because the model is so innovative, it faces a number of challenges: according to Snowden*, it predicts more M-band emission than is observed; it may not produce the line emission observed in the DXS experiment; the confinement of the superbubble by its natal molecular cloud is problematic in view of the destructive effects of photoionization (Whitworth 1979); the low thermal pressure of the gas is achieved at the expense of a large ram pressure, which was not accounted for; and there is no evidence for the other stars in the association, nor the enormous mass of gas ($M \sim 10^6$ $M_\odot$ for a molecular cloud of radius 10 pc and density 10^4 cm^{-3}). This model is readily testable by the next generation of soft X-ray experiments.

Cox* and Smith and Cox* presented the most sophisticated models yet developed for the Local Bubble. These models include thermal conduction, non-equilibrium ionization calculated with current plasma codes, and the effects of magnetic pressure. Agreement with the data is obtained for a model with 2 or 3 supernova explosions in the Local Bubble, with the last one having occurred several million years ago. An advantage of this model is that it accounts for the low mean density of the Local Bubble. Since the last SN occurred so long ago, the model is also consistent with the presence of relatively quiescent H I in the Bubble. However, the model rests on a crucial assumption: even though thermal conduction both within the bubble and to the walls of the bubble is allowed, it is assumed that no heat is conducted from the hot gas to the embedded clouds (i.e., there is no cloud evaporation).

Finally, Slavin* presented models that allowed for cloud evaporation. His models are incomplete in that they do not attempt to explain the origin of the hot gas–presumably, the Local Bubble was reheated by a supernova several hundred thousand years ago. He accounted for the Wisconsin Be band, B band, and C band intensities with models in which the hot gas far from the clouds has a temperature $T \simeq 10^{6.0-6.2}$ K. Slavin and Frisch* also showed that it is possible to account for the relatively high ionization of helium observed in the LISM, a problem not addressed by the other two models.

3.2 Evolution of Superbubbles

The early work of Cox and Smith (1974) and McKee and Ostriker (1977) treated supernovae as occurring randomly in space and time. Beginning with the work of Bruhweiler et al. (1980), however, it was realized that many supernovae occur in OB associations, and that this would profoundly affect the interaction of supernovae with the ISM. In particular, the larger amounts of energy available meant that gas in the disk could be lofted into the halo, revitalizing the fountain model of Shapiro and Field (1976). Ikeuchi* and his collaborators were major contributors to these studies. His work culminated in the "chimney model" (Ikeuchi 1987; Norman and Ikeuchi 1989), in which superbubbles break out of the Galactic disk, spewing hot gas and nucleosynthesis products into the halo and then onto the disk below.

Several new results on superbubble evolution were presented: Chernin* showed how small superbubbles can be created by the merger of two SNRs, and described the complex hydrodynamics that results. Bisnovati-Kogan and Silich* showed how the three-dimensional evolution of superbubbles can be treated in the thin-shell approximation. Theis et al* and Ehlerova et al* discussed fragmentation and star formation in expanding supershells.

Radiative losses can affect the evolution of interstellar bubbles and superbubbles more than is generally realized. Although the solutions for momentum-conserving bubbles (Avedisova 1971; Steigman, Strittmatter, and Williams 1975) and adiabatic bubbles (Castor, McCray, and Weaver 1975) were developed at about the same time, it has generally been assumed that actual bubbles are described by the adiabatic solution for most of their lives. However, photoevaporation of embedded clouds (including the molecular cloud out of which the association is born) can "poison" the bubble by injecting enough material into the bubble interior so that it can cool, thereby making the expansion intermediate between the momentum-conserving and adiabatic cases (McKee, Van Buren, and Lazareff 1984). Evidence for cloud photoevaporation in the Cepheus Bubble was presented by Patel et al*.

The Sco-Cen Bubble appears to show evidence for the effects of radiative cooling. Egger* presented evidence that the hot gas in the western part of the bubble is cooling (see above). The oldest subassociation is 14-15 Myr old (Frisch 1995), so that the bubble would have begun expanding about 12 Myr ago. The effective wind luminosity of the association is now about 6×10^{37} erg s^{-1} and the ambient density is about 0.6 cm^{-3} (Egger*), so that the predicted bubble radius is $R_b \simeq 130$ pc for the momentum-conserving case and 290 pc for the adiabatic case. Such a model is not very realistic because it does not allow for the lower wind luminosity early in the life of the association, nor for the fact that the density is larger near the association than it is near the Sun (Frisch 1995). We allow for these effects by assuming a wind luminosity $L_w = \mathcal{L}t$ and an ambient density $\rho_0 = \rho_{01} r^{-1}$, where $\mathcal{L}$ and ρ_{01} are constants. These assumptions lead to a bubble radius that increases linearly with time: For the momentum-conserving bubble $R_b = (\mathcal{L}/2\pi\rho_{01}v_{\rm in})^{1/3}t \simeq 70$ pc, where

$v_{\rm in} \simeq 2000$ km s^{-1} is the average velocity of the gas injected by the stellar winds and supernovae; for the adiabatic bubble, $R_b = (\mathcal{L}/8\pi\rho_{01})^{1/4}t \simeq 210$ pc (Koo and McKee 1992). The observed radius of about 150 pc is intermediate between these two cases, suggesting that energy loss has been important in the evolution of the Sco-Cen Bubble. Our approximate attempt to include the effects of the evolution of the Sco-Cen association and the density structure of the ISM is not fully consistent, however: for $R \propto t$, the shell velocity should be $v = R/t = 12.5$ km s^{-1}, less than the observed 19 km s^{-1} (Sofue et al., 1974). If the superbubble is as old as suggested by the ages of the OB stars, then the shell must have undergone acceleration, at least for part of its expansion; this would have been unstable, contributing to the injection of matter into the hot bubble and adding to the radiative losses.

3.3 The LISM as an Astrophysical Laboratory

Study of the LISM enables us to address two fundamental astrophysical questions: How does hot gas cool? How is pressure balance achieved in the ISM? The nature of the cooling of hot gas is important not only for the interstellar medium of galaxies, but also for hot gas in clusters of galaxies and in active galactic nuclei. The best-studied cooling mechanism is radiation by the gas due to collisional excitation and to recombination (Böhringer*). The emitted spectrum depends on the nature of the ionization. Broadly speaking, there are three general cases: the gas can be overionized due to cooling outpacing recombination for $T \lesssim 10^6$ K or to adiabatic expansion; it can be in collisional ionization equilibrium; or it can be underionized, as in the case of evaporation. For $T \gtrsim 10^6$ K, another cooling mechanism can dominate, emission by embedded dust grains (Ostriker and Silk 1973). This is self-limiting because the dust is destroyed by sputtering as it cools the gas (Draine 1981; Dwek et al., 1996). In the Local Bubble, the sputtering time $t_{\rm sp}$ for the large grains that contain most of the mass is about 10^8 yr (Ferrara*); for the smaller grains that dominate the cooling, $t_{\rm sp} \propto$ (grain radius) is less. Thermal conduction can also cool the gas, both by conducting the heat to cooler gas, which radiates it, and by evaporating cooler gas, thereby sharing the heat among more particles. Finally, the gas can cool by adiabatic expansion, as in the model of Breitschwerdt and Schmutzler (1994); however, the radiative cooling time is unaffected by adiabatic expansion for $T \gtrsim 10^5$ K (Kahn 1976). Each of these cooling mechanisms depends on the history of the hot gas, and the Local Bubble provides an ideal laboratory for studying how history can determine the physical conditions and spectrum of hot gas.

What is the nature of pressure balance in the ISM? On the average, the pressure must equal the weight of the material above it (Parker 1969). The ISM is heavy: the weight is of order 3×10^4 K cm^{-3} (Boulares and Cox 1990), far greater than the typical thermal pressure in the ISM, 4000 K cm^{-3} (Jenkins et al., 1983). Thermal pressure $P_{\rm th}$, turbulent pressure $P_{\rm turb} = \rho\delta v^2$, magnetic pressure P_B, and cosmic ray pressure $P_{\rm cr}$ all contribute to the pressure support. Kalberla et al* presented a model for the hydrostatic equilibrium of the ISM based on the inclusion of an H I component with a velocity dispersion of 60 km s^{-1}; such a component is not seen in the Bell Labs data (Blitz, private communication), however, and requires confirmation.

On small scales, cosmic rays cannot sustain pressure gradients in a static medium because they are diffusive. If the nonthermal pressure is truly turbulent, then it depends on the size scale ℓ since $\delta v \propto \ell^p$, where $p \sim \frac{1}{3} - \frac{1}{2}$. (In molecular clouds, this is just the line width–size relation [Larson 1981]). Thus, turbulent pressure is also ineffective on small scales. Recent Faraday rotation observations indicate an rms fluctuating field of only about 1 μG on scales $\lesssim$ 4 pc, confirming the weakness of turbulent fluctuations on small scales in the diffuse ISM (Minter and Spangler 1996). Locally, then, $P_{\rm th} + P_B = {\rm const}$ in equilibrium. The rms interstellar magnetic field is about 4.2 μG (Heiles 1996), corresponding to a pressure of 5100 K cm^{-3}. This is only slightly greater than the typical interstellar thermal pressure, so we expect thermal pressure to be significant on small scales. Why then does the thermal pressure in the Local Cloud ($P_{\rm th} \sim$ 2000 K cm^{-3}) appear to be much less than that of the hot gas in the Local Bubble ($P_{\rm th} \sim$ 14000 K cm^{-3} for CIE models)? A strong magnetic field in the Local Cloud has been suggested as one possibility (Cox and Reynolds 1987, McKee 1996), but the field at the solar bow shock (Lallement*) is inadequate. Understanding the pressure balance in the LISM has broad implications for interstellar gas dynamics, and the LISM provides the laboratory in which we can hope to find the answer.

4 Is the LISM Typical of the ISM as a Whole?

4.1 Observation

The Local Bubble is too small to be readily detected from a vantage point elsewhere in the Galaxy. However, the Sco-Cen Bubble appears to be large enough that it could be detectable. Observations of superbubbles in Eridanus (Burrows and Guo*), Sagittarius (Miville-Deschênes et al*), and Cepheus (Patel et al*) were presented at the conference. No one addressed the important issue of what fraction of the ISM is filled with these structures. Such an estimate should be more straightforward for the LMC, since we are not embedded within it. The remarkable 21 cm map of the LMC obtained by Kim and Stavely-Smith* with the Australia Telescope Compact Array shows large numbers of superbubbles and provides the basis for such an estimate.

How typical are the properties of the gas observed locally? Dettmar* showed that Warm Ionized Medium of the type seen locally in the Galaxy can be observed in other galaxies as well; the source of ionization of this gas has not been conclusively identified. Dixon et al* showed that the distribution of H I and H_2 beyond the Local Bubble does not vary much over several long sightlines at the solar circle. As for the hot gas, the *ROSAT* shadowing experiments discussed above clearly show that there is a significant amount of emission from the Galactic halo. It is very difficult to unambiguously separate halo emission from that due to the Local Bubble, the disk, and extragalactic sources (Freyberg*). Several groups attempted such a separation nonetheless: Sumner et al* inferred the existence of a halo component by spectral modeling of *ROSAT* PSPC data. Kerp and Pietz* modeled the radiative transfer of X-rays through the ISM and estimated the temperatures of the Local Bubble and halo components. Pietz et al* developed an isothermal model ($T = 1.6 \times 10^6$ K) and estimated a total Galactic X-ray luminosity of 7×10^{39} erg s^{-1}. Finally, in order to model the 0.5-1 keV emission, Wang* generalized the isothermal model of Wolfire et al. (1995) to a polytrope ($P \propto \rho^{5/3}$) and developed a clever iterative technique to fit the parameters for the emitting gas in regions that are not contaminated by disk emission. Locally, he found that the pressure of the hot gas is about 3000 K cm^{-3}, comparable to that of the H I. Kerp et al* showed evidence for interaction of high-velocity clouds with the X-ray background. This supports the interpretation of an X-ray halo for the Galaxy, since two of the larger HVCs are now known to be in the halo: Complex A is in the range $2.5 < z < 7$ kpc (Van Woerden et al*) and Complex M is in the range $z < 4.4$ kpc (Danly et al., 1993). There may also be an X-ray halo around the LMC (Blondiau*).

4.2 Theory

Several theories for the origin of hot gas in the halo were discussed. The fountain model was reviewed by Kahn* but the basic premises of the model were not confirmed in 3D hydrodynamic simulations presented by Avillez et al*. Supernovae in the halo can directly heat the gas there, but Shelton et al* showed that such supernovae could not account for the observed X-ray emission; on the other hand, the remnants of halo supernovae could survive a long time and possibly account for the highly ionized gas seen in absorption in the halo. Simulations of magnetic reconnection, which has been suggested as a heating mechanism for halo gas by Parker (1990) and by Raymond (1992), were presented by Lesch and Birk*. They suggested that reconnection could account for Kerp et al's* observations of excess soft X-ray emission near several high-velocity clouds. It is a challenge to understand how a microscopic process like reconnection, acting on ordered magnetic fields, can account for the large volume emission measure of hot gas inferred by Kerp et al. Finally, there is the cosmic-ray driven wind model of Breitschwerdt and Schmutzler (1994), which produces an X-ray spectrum dominated by adiabatic expansion. This model is confronted with the difficulty of explaining why the H I in the solar vicinity is observed to be falling toward the plane; indeed, there are *no* observed cases in which outflowing gas is seen in UV absorption (deBoer*).

Before closing, I would like to briefly discuss the status of the theory of the ISM that Ostriker and I developed twenty years ago (McKee and Ostriker 1977). The role of this theory in the development of our understanding of the ISM is discussed by Ikeuchi*. The theory is based on the premise that the porosity of hot gas in the ISM (eq. 1) is large. This premise has been criticized in a detailed study by Slavin and Cox (1993), but we have seen ample evidence at this conference that it is valid locally. Frisch's* map of the local ISM shows that hot (or at least very low density) gas is seen along virtually every line of sight from the Sun. Once a line of sight intersects a cloud, however, no further hot gas appears on the map (with the exception of the Sco-Cen Bubble). Is this because the Sun is in a unique place in the ISM, or is it because of the difficulty in detecting the presence of hot gas under typical interstellar conditions?

Several results of the theory have been confirmed by subsequent observation: Large pressure fluctuations were predicted and have been observed (Jenkins et al., 1983); the properties of the Warm Ionized Medium predicted for the disk of the Galaxy are consistent with observations (Reynolds 1993); and the weakness of X-ray emission from other disk galaxies (e.g., McCammon and Sanders 1984) is also consistent with the model, since evaporative cooling is expected to reduce the temperature of the hot gas to $\sim 5 \times 10^5$ K. On the other hand, the weakness of O VI absorption lines (Shelton and Cox 1994) remains a puzzle. Direct evidence for cloud evaporation in the ISM is weak, although Spitzer (1996) concluded that conductive interfaces provide the best explanation for the presence of highly ionized atoms in the disk. The possible detection of a conductive interface in the Local Bubble (Gry and Dupin*), together with the development of an evaporative model for the X-ray spectrum (Slavin*) and the ionizing spectrum (Slavin and Frisch*) of the Local Bubble, suggest that further study of the Local Bubble should prove fruitful in determining the role of thermal conduction in the ISM.

5 Prospects for the Future

The Holy Grail for studies of the Local Bubble is the spectrum of the hot gas, which contains the key to the origin of the gas. A number of missions that are aimed at achieving this goal were described at the conference. On the first day of the conference we heard the dramatic announcement of the successful launch of the EUV spectrograph *EURD*, an international collaboration between Spain (PI: Morales*) and the US (PI: Bowyer*). As this is being written, the spectrograph is successfully gathering data. Other missions that will attempt to measure the spectrum of the hot gas are *CUBIC* (Burrows), *UCB* (Edelstein et al*), *GRADES* (Hurwitz et al*), and *FUSE*. McLean et al* described a rocket-borne spectrograph that will carry out spectroscopy of the C IV and O VI lines. Planned X-ray missions, including *ASTRO-E* and *ABRIXAS*, may also shed light on the spectrum.

It is remarkable that our extragalactic colleagues have made far more progress in mapping the three dimensional distribution of galaxies many megaparsecs away than we have made in mapping the distribution of local interstellar clouds within a hundred parsecs. What is needed is an organized effort to map the LISM, a Local Interstellar Absorption Line Survey. Steps in this direction were described by Beckman*, Gry and Dupin*, Genova et al*, Welsh et al*, and Welty*. The advent of accurate stellar distances from *Hipparcos* should improve the maps considerably.

The Local Bubble poses a number of theoretical problems as well. As emphasized by Breitschwerdt*, the cooling of hot plasma reflects its history; how can we learn to read that history? How can one reconcile the low thermal pressure observed in the Local Cloud with the substantially greater thermal pressure inferred in the Local Bubble? How do SNRs and superbubbles evolve in a magnetized, multiphase ISM, including photoevaporation of clouds by EUV radiation from OB stars? What is the efficiency of thermal conduction in magnetized, turbulent media? How do magnetic fields reconnect in the ISM? We can hope that when the next Local Bubble conference is organized, some of these observational and theoretical questions will have been answered.

Acknowledgements. I wish to thank Dieter Breitschwerdt and Joachim Trümper for the opportunity to participate in this conference. Comments by Dieter, Don Cox, Pris Frisch, Wilt Sanders, and Jon Slavin were invaluable. My research is supported in part by NSF grant AST95-30480.

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