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Astrophysical Plasmas: Codes, Models, and Observations (Mexico City, 25-29 October 1999)
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IS THE PLASMA WITHIN BUBBLES AND SUPERBUBBLES HOT OR COLD?

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RESUMEN

Hago una revisión de lo que se conoce sobre la temperatura del plasma en las burbujas de vientos estelares y las superburbujas. La teoría clásica indica que debía ser caliente, con temperaturas típicas del orden de un millón de grados. Esta temperatura debía ser controlada por el balance entre el calentamiento debido a los choques de reversa de los vientos estelares y las supernovas, que se expanden a miles de km s^{-1}, con el enfriamiento debido a la evaporación del gas frío de las paredes del cascarón. Sin embargo, si el interior caliente se vuelve suficientemente denso debido a la evaporación o la ablación de nubes interiores, se enfriará en menos de un tiempo dinámico, generando una burbuja fría. Las evidencias observacionales son confusas. Por un lado se han detectado rayos-X de burbujas estelares y supernovas. Por otro, ninguna de estas estructuras emite a la tasa predicha por la teoría; las diferencias, hacia arriba o hacia abajo, son de hasta un orden de magnitud. Las posibles explicaciones incluyen remanentes de supernova descentradas, que golpean las paredes de las superburbujas y emisión fuera de equilibrio de gas altamente ionizado. Las estructuras de las burbujas de vientos de estrellas post secuencia principal, expandiendiose dentro de lo que serían burbujas viejas, muestran que en algunos casos el interior está frío (por ejemplo, NGC 6888). ¿Cuál es entonces el estado del interior de las burbujas y las superburbujas?

ABSTRACT

I review what is known about the temperature of the plasma within stellar wind bubbles and superbubbles. Classical theory suggests that it should be hot, with characteristic temperatures of order a million degrees. This temperature should be set by the balance between heating by the internal termination shocks of the central stellar winds and supernovae, which expand at thousands of km s^{-1}, and cooling by conductive evaporation of cold gas off the shell walls. However, if the hot interior gas becomes dense enough due to evaporation or ablation off of interior clouds, it will cool in less than a dynamical time, leading to a cold interior. The observational evidence appears mixed. On the one hand, X-ray emission has been observed from both stellar wind bubbles and superbubbles. On the other hand, no stellar wind bubble or superbubble has yet been observed emitting at the rate predicted by the classical theory: they are either too faint or too bright, by up to an order of magnitude. Alternate explanations have been proposed for the observed emission, including off-center supernova remnants hitting the shell walls of superbubbles, and residual emission from highly-ionized gas out of coronal equilibrium. Furthermore, the structures of post-main sequence stellar wind bubbles, expanding into what are presumably old stellar wind bubbles, appear in at least some cases to show that the bubble interior is cold, not hot. (The classical example of this is NGC 6888.) What is the actual state of bubble and superbubble interiors?

Key Words: **ISM: BUBBLES — STARS: POPULATION II — STARS: WINDS, OUTFLOWS — SUPERNOVA REMNANTS — X-RAYS: ISM**

1. BUBBLE STRUCTURE

The interpretation of observations of plasma within bubbles and superbubble relies on understanding the density and temperature structure over which the observations integrate. The touchstone for such understanding remains the evaporative wind-blown bubble first described by Castor, Weaver, & McCray (1975) and Weaver et al. (1977). Figure 1 shows the two-shock structure that results from continuous mechanical energy input into a uniform medium. The freely expanding wind is shocked at the inner shock, heating it up. The resulting pressurized region drives a shock into the external gas, sweeping up a shell that is usually dense enough to cool. The functional form of the radius of the dense shell R can be derived from dimensional arguments by noting that the only other physical variables in the problem are the time t, the mechanical luminosity L, and the external number density n_0. Only one dimensionless constant can be assembled from these, showing that

$$R \propto L^{1/5} n_0^{-1/5} t^{3/5}. \tag{1}$$

Thermal conduction occurs across the contact discontinuity separating the hot interior from the cold shell, evaporating mass into the interior. The temperature T and number density n in the interior can be derived from similarity solutions to have functional forms $T(r) \propto (1 - r/R)^{2/5}$ and $n(r) \propto (1 - r/R)^{-2/5}$ (Weaver et al. 1977)

At late times, radiative cooling can become important to the interior of a bubble. If the density in the interior follows the similarity solution given above, then the cooling time can be approximated by taking the cooling rate $\Lambda = (10^{-22}\text{ erg s}^{-1}\text{ cm}^3)\zeta T_6^{-07}$, where $T = (10^6\text{ K})T_6$ and ζ is the metallicity compared to solar. The cooling rate for the bubble is then given by $L = \int n^2(r)\Lambda(T(r))d^3r$, and the cooling time is (Mac Low & McCray 1988)

$$t_c = (16\text{ Myr}) L_{38}^{3/11} n_0^{-8/11} \zeta^{-35/22}, \tag{2}$$

where $L = (10^{38}\text{ erg s}^{-1})L_{38}$. Weaver et al. (1977) computed cooling rates including non-equilibrium ionization in the interior, and found cooling rates compatible with this result, as shown in their Figure 6. For typical external densities, the cooling times are longer than the lifetimes of massive stars, so for individual stellar wind bubbles cooling will not be very important in the classical picture described here.

The question of thermal conduction across the interface has been considered extensively. The physical mechanism acting is that fast electrons from the hot interior can penetrate significant distances into the cold shell before depositing their energy in collisions with the gas, transferring heat across the contact discontinuity. This heating raises the pressure of the inner edge of the shell, which then expands into the hot interior. This heat conduction saturates due to the electric fields set up by the movement of the electrons (Cowie & McKee 1977). Tangled magnetic fields are often invoked to suppress conduction. The idea here is that electrons tied to tangled field lines will have long pathlengths without travelling very far into the cold shell, reducing the efficiency of thermal conduction. However, magnetic fields cannot actually be tangled very much, as magnetic pressure and tension will climb as they become more tangled. Tao (1995) and Pistinner & Shaviv (1996) have shown that tangling can suppress thermal conduction by at most an order of magnitude. (Note also that Boroson et al. [1997] have observed evidence of conductive evaporation as discussed below at the end of § 3.) This will make a difference; however Slavin & Cox (1993) studied the effect of reduced conduction in SNRs and found that, although the interiors are indeed hotter, even small amounts can lead to effective cooling in the end.

2. OBSERVATIONS

If the cooling time given by equation 2 is within a factor of three of being correct then bubbles and superbubbles should be filled with hot gas that emits X-rays. The theoretical spectrum of this X-ray emission, including the effects of non-equilibrium ionization, was already modeled by Weaver et al. (1977). After the launch of *Einstein*, Bochkarev & Lozinskaya (1985) used the Weaver et al. temperature and density profiles along with an equilibrium ionization model to compute the expected X-ray luminosity of a stellar wind bubble, applying the model to the Wolf-Rayet bubble NGC 6888.

NGC 6888 was indeed detected by Kähler, Ule, & Wendker (1987) using *EXOSAT* and by Bochkarev (1988) using *Einstein*, but with much an order of magnitude lower X-ray luminosity than originally predicted. Inspired

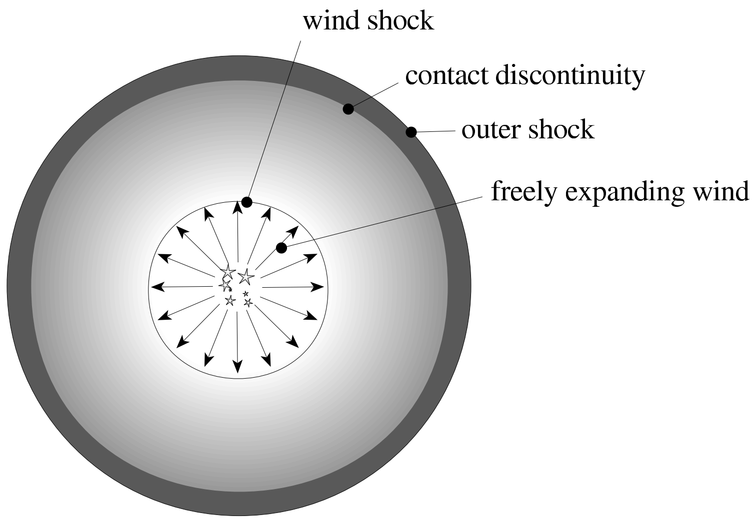

Fig. 1. Structure of a classical bubble driven by continuous input of mechanical energy from a central star or star cluster. Diagram shows inner and outer shocks, separated by a contact discontinuity across which mass flows driven by conductive evaporation.

by this, Bochkarev & Zhekov (1990) included the effects of non-equilibrium ionization into a computation of the X-ray luminosity, showing that it would be expected to reduce the luminosity. An alternative explanation of the unexpectedly low luminosity was offered by García-Segura & Mac Low (1995a, 1995b) who took into account the post-main sequence evolution of the central Wolf-Rayet star, and used the shell dynamics to predict the X-ray luminosity, as further explained in the following section.

The X-ray luminosity expected from superbubbles was computed assuming equilibrium ionization and the Weaver et al. (1977) interior profile by Chu & Mac Low (1990; typos corrected in Chu et al. 1995). They used a constant X-ray emissivity of $\Lambda_x(T) = (3 \times 10^{-23}\ \mathrm{erg\ cm^3\ s^{-1}})\zeta$ for $T > 5 \times 10^5$ K (Raymond & Smith 1977), to find

$$L_x \simeq (8 \times 10^{27} \mathrm{erg\ s^{-1}})\zeta I(\tau) n_0^{10/7} R_{\mathrm{pc}}^{17/7} v_{\mathrm{km}}^{16/7}, \tag{3}$$

where R_{pc} is the shell radius measured in pc, and v_{km} is the shell expansion velocity measured in km s^{-1}, both of which can be observed. The ambient number density can be estimated using the emission measure through the shell, with some assumptions, as explained in the cited papers.

The effect of a non-uniform interior temperature and density on spectral fits was investigated by Strickland & Stevens (1998) using non-equilibrium ionization and the actual *ROSAT* response function but neglecting thermal conduction in a numerical computation (some conduction occurred anyway due to numerical dissipation). Although their computation probably did not have an accurate internal structure because of the neglect of thermal conduction, their main point was to emphasize how badly astray one can be led by simple one or two temperature fits to an X-ray spectrum coming from a complex structure. Metallicities more than an order of magnitude too low can be derived with such fits, for example.

3. STELLAR WIND BUBBLES

As it turns out, the only stellar wind bubbles that have actually been observed in the X-ray are two Wolf-Rayet ring nebulae, NGC 6888 (Kähler et al. 1987; Bochkarev 1988; Wrigge, Wendker, & Wisotzki 1994) and S 308 (Wrigge 1999). Main sequence bubbles tend to be too large and dim to be potentially observable by the instruments available up until the latest generation of large-aperture, X-ray telescopes, just as their shells are often too dim to be observed in the optical (McKee, Van Buren, & Lazareff 1984). Nevertheless, the observed post-main sequence bubbles may offer revealing insights into the state of the interiors of main sequence bubbles, as well as posing interesting problems themselves.

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Stellar wind bubbles around Wolf-Rayet stars must be interpreted taking into account the mass-loss history of the star during its post-main sequence evolution. D'Ercole (1992) and García-Segura & Mac Low (1995a) summarize the basic idea, which was explored in more detail by García-Segura & Mac Low (1995b) and García-Segura, Mac Low, & Langer (1996). While a massive star remains on the main sequence it blows a main sequence bubble having roughly the structure described in the introduction. It then evolves into a red supergiant with a slow, massive wind that expands into the cavity left by the main sequence bubble, possibly still filled with high-pressure hot gas from the shocked main sequence wind. After the star loses its atmosphere, it will evolve back to a blue Wolf-Rayet star with a high-velocity, low-density wind that sweeps up the red supergiant wind.

This new bubble evolves not in a uniform background medium, but in the r^{-2} density distribution of the red supergiant wind. This enhances the strength of the Vishniac (1983) instabilities in the swept-up shell of red wind. At the edge of the dense red supergiant wind, the shell accelerates as it suddenly blows out into the low-density main-sequence bubble. The density enhancements already produced by the Vishniac instabilities are then strongly amplified by Rayleigh-Taylor instabilities, fragmenting the shell. NGC 6888 appears to be at just this stage of development, while S 308 appears to be just at the beginning of the blowout (Chu et al. 1982). The morphology of the blowout can be used to probe the temperature of the gas in the fossil main-sequence bubble as well. If that gas is hot, the expansion velocity of the shocked Wolf-Rayet wind blowing out past the fragmented shell is subsonic, so it merely drives a sound wave into the surrounding hot gas, generating no observable density enhancements. On the other hand, if the surrounding gas is cold, the expansion of the hot Wolf-Rayet wind is supersonic, so it drives a strong shock into the gas, compressing it and generating an observable signature. García-Segura & Mac Low (1995b) demonstrate this effect in their numerical models (though the figure must be examined carefully to understand this due to the dynamic range covered). Over the short lifetime of the massive progenitor of the central Wolf-Rayet star of NGC 6888, the hot shocked wind in its bubble should not have had the chance to undergo significant radiative cooling. However, observations of NGC 6888 in [OIII] (e.g., Mitra 1989, 1990) clearly show strong filaments bounding the nebula a few tens of arcsec outside of the fragmented shell, indicative of a strong shock expanding into the surrounding medium, and thus of a cooled main-sequence bubble, contrary to expectation.

The X-ray luminosity, combined with the shell dynamics revealed by imaging and spectroscopy in emission lines such as Hα, yield additional puzzles. García-Segura & Mac Low (1995a) show that the radius, velocity, and shell properties of NGC 6888 can be consistently explained only if the mechanical luminosity of the central star is roughly an order of magnitude lower than the generally accepted value. Clumping in the wind could give a factor of three lower value (Moffat & Robert 1994), but the last factor of three remains mysterious. Using the lower mechanical luminosity and the observed shell parameters, García-Segura & Mac Low (1995a) are able to recover the observed X-ray luminosity of NGC 6888 (Kähler et al. 1987; Bochkarev 1988; Wrigge et al. 1994) from their model as well. The other Wolf-Rayet wind nebula detected in the X-ray, S 308, shows the same inconsistency between shell dynamics and accepted wind parameters. In this case, however, the observed X-ray luminosity is even fainter than the value predicted (Wrigge 1999).

Causes for this enhanced cooling could include stronger conductive evaporation than generally assumed, and higher metallicities in the cooling gas. Enhanced conductive evaporation may well occur due to the increased surface area and mixing produced by Vishniac (1983) instabilities (Mac Low & Norman 1993; García-Segura et al. 1996). Evidence for the existence of conductive evaporation has been observed in S 308 by Boroson et al. (1997). They used the GHRS on HST to observe the C IV and N V resonance absorption lines in the spectrum of the central star of S 308. The N V line was extremely broad (over 50 km s^{-1} FWHM), as predicted by models of conductive evaporation. Its strength was rather greater than predicted by those models, however, suggesting that the interior of this Wolf-Rayet bubble was enhanced in nitrogen. This is not unexpected, as the interior mass should consist primarily of mass evaporated off the cold shell of mass swept-up from a previous red supergiant wind, which should indeed be enriched in fusion products such as nitrogen.

4. SUPERBUBBLES

X-ray emission has indeed been observed from young superbubbles both in our own Galaxy and in the Large Magellanic Cloud (LMC), as well as from the even larger bubble structures blown from starburst galaxies (e.g., Suchkov et al. 1994; 1996). The LMC superbubbles are easier to analyze as they lie at known distances in

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a roughly face-on disk with little obscuration along the line of sight. The resolution of *ROSAT* and even of *Einstein* was high enough to resolve even smaller superbubbles, allowing the correlation of emission from cold H I and warm ionized gas emitting in Hα with hot, X-ray emitting gas.

The X-ray emission from LMC superbubbles can be compared directly to the values predicted from equation 3 for a Weaver et al. (1977) bubble using measurements of the shell dynamics taken from long-slit or Fabry-Perot spectroscopy in optical emission lines such as Hα. Using such techniques, Chu & Mac Low (1990) and Wang & Helfand (1991) showed that some LMC superbubbles were brighter than predicted. That this is not a universal property of the LMC superbubbles was shown by Chu et al. (1995), who described *ROSAT* observations of other LMC superbubbles with roughly equivalent stellar content and dynamics that have upper limits on their X-ray luminosity consistent with the Weaver et al. (1977) prediction.

Supernova explosions in the interior of the superbubbles appear to be the most likely cause of this intermittent excess X-ray luminosity. However, a supernova in the center of a superbubble will not produce significant excess X-ray emission, as its blast wave expands into hot, low-density, interior gas and only weakly heats and compresses it. Two mechanisms have been proposed to enhance the emission from interior supernovae. Chu & Mac Low (1990) show that off-center supernovae can drive shock waves into the ionized inner edge of the swept-up shell that can produce the observed X-ray luminosity for a few thousand years. Arthur & Henney (1996) suggested that if the interior is full of small clumps of unspecified origin, they would cause enhanced emission when shocked by a supernova blast wave.

A further twist to the tale comes from the discovery by Oey (1996) that X-ray bright superbubbles show faster expansion velocities than can be explained by the mechanical luminosity expected from the observed interior stellar population (including any supernovae expected to have already occurred for older clusters), while X-ray dim superbubbles appear to have dynamics consistent with their stellar populations.

One explanation for the discrepancy between the observed dynamics and stellar population that has been developed is that these rather small superbubbles (with diameters of order only 100 pc) are not expanding in a uniform medium, but rather are blowing out of their dense parental clouds. Comerón (1997) performed numerical models of this process, and Silich & Franco (1999) showed using thin-shell models that such a blowout can explain the observed high velocities. However, they predict that the fast-expanding bubbles should be a factor of 3 *dimmer* than spherical bubbles rather than the observed factor of 3–10 *brighter*, leaving the puzzle unsolved.

All of these models make very simple assumptions about the medium that the superbubbles are expanding into, however: either that it is homogeneous, or that there is a slab of higher density in a homogenous lower-density medium. However, H I observations of the LMC show that the gas is highly structured, with the cold gas being confined between a foam of bubbles (Kim et al. 1998). This structure has been reproduced in three-dimensional computational models that include disk stratification and supernova driving (Korpi et al. 1999a,b; Avillez 2000). An interesting question for the future is whether superbubble expansion in such a medium can reproduce the observational constraints that have prevented a complete theoretical model to date.

5. SUMMARY

I have here reviewed our current understanding of the interiors of stellar wind bubbles and superbubbles. Although there is a detailed theoretical description and plenty of observational constraints, I find that there are some important open issues that have not yet been pinned down.

In the case of stellar wind bubbles, the existence and strength of evaporative conduction will play a crucial role in determining their interior thermal history, perhaps helping to explain the evidence for cold main-sequence bubble interiors. Corrugation and clumping of the swept-up shell due to Vishniac instabilities and a turbulent ambient medium may also contribute to the cooling of the interior. The effects of non-equilibrium ionization, as well as enhanced interior metal abundances, must be taken into account in a dynamical model that includes the effects of post-main sequence evolution in order to understand whether observations of Wolf-Rayet bubble X-ray emission are really consistent with theory or not. There appear to be several hints pointing to enhanced cooling due to these various effects, but solid explanation and observational confirmation is still lacking.

In the case of superbubbles, the set of constraints posed by observations of central stars, shell dynamics, and X-ray luminosities also does not appear to be fit by any single theoretical model. The central problem might be best summarized by asking, “Why are fast bubbles X-ray bright?” The best explanation of fast bubbles as blowouts from their natal molecular clouds would predict that they are X-ray dim rather than X-ray bright, while the best explanation of X-ray bright bubbles as due to off-center supernovae probably cannot explain the strong observed acceleration of the shells (although this point has not been proven with quantitative work so far as I know). The assumption of uniformity or simple structure to the surrounding medium may well be to blame, however, as the actual medium with which superbubbles interact is strongly structured by previous generations of OB stars. Simulations incorporating this structure need to be used to understand whether that can explain the observed dynamics and X-ray emission.

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