MECHANICAL ENERGY SOURCES

INTERSTELLAR WIND-BLOWN BUBBLES

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Summary

'Classical' stellar wind-driven bubbles are either energy or momentum driven, and evolve in smooth media containing only radial density gradients. Real bubbles are produced from winds from moving stars and which blow into non-homogeneous media. The resulting mixing of clump material can produce a variety of thermal, dynamical and chemical effects. In this review we discuss some of the modifications to classical bubbles which ensue, using observational examples where appropriate.

1. Introduction

Continuous mass loss from stars is ubiquitous throughout the H-R diagram. The mass loss rates, $\dot{M}_*$, range from the insignificant $10^{-14}\,M_\odot\,\mathrm{yr}^{-1}$ for the Sun to perhaps as much as $10^{-3}\,M_\odot\,\mathrm{yr}^{-1}$ in some red giants and supergiants. $\dot{M}_*$ varies from one star to another and depends on the evolutionary stage of a particular star. Evolutionary tracks in the H-R diagram can be strongly influenced by mass loss. Mass loss may even determine the initial main sequence mass of low mass stars. The velocity, V_*, of the outflowing material can range from the 20 km s^{-1} or so characteristic of red supergiants to perhaps as much as 3000 km s^{-1} in the winds from some planetary nebulae nuclei. This variation reflects differing escape velocities and differing ejection mechanisms. As will be discussed later (Section 2), the wind velocity is the single most important parameter of the wind for determining the resulting dynamical interaction between the wind and the circumstellar environment—at least as long as the environment is smoothly distributed.

The physical conditions in winds also vary. Winds may be fully ionized (e.g. from early type stars) or may be largely neutral (e.g. from some pre-main sequence objects). It is doubtful if such a thing as a perfectly smooth wind occurs. Blue supergiant winds appear to be highly structured. Similarly, the structures of some planetary nebulae and Wolf-Rayet nebulae clearly indicate that the slow winds ejected prior to the fast wind stage were extremely clumpy.

The mechanisms driving mass loss are varied and sometimes highly problematic. Radiation pressure driven winds (utilising ion resonance line or dust absorption) are well known. Alfvén wave or acoustic wave driven winds may occur. The winds may sometimes not originate on the actual stellar surface. For example, winds from accretion discs have been suggested to account for the exceptionally high wind momenta apparently associated with some molecular cloud flows. It is arguable that the most

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fundamental and important questions relating to stellar mass loss concern the wind driving mechanisms and the wind morphology. In connection with this latter point, the collimation and confinement of winds into jets and bipolar outflows are as yet not satisfactorily understood.

This review is concerned with topics involving a somewhat easier aspect, in the sense that the increasing body of exceptional observational data makes it possible to really discriminate between different models. This is the interaction of winds with the circumstellar gaseous environment. We first briefly review the basic assumptions and results of 'classical' bubble evolution and then relax various of these basic assumptions. Specific observational examples are given which illustrate the various effects.

2. Classical Wind-Blown Bubbles

These bubbles are produced when isotropic stellar winds blow into smooth circumstellar media containing only radial density variations. The basic two-shock flow pattern was first described by Pikelner (1968). The resulting dynamics of the swept-up circumstellar matter are determined by the thermal behaviour of the shocked wind and the form of the radial density distribution (Dyson 1984).

'Energy' driven flows occur when the shocked wind loses energy only by adiabatic expansion. The outer shock, which accelerates the circumstellar matter, has a radius R_s and velocity $V_s(\equiv \dot{R}_s)$ given by

$$R_s = \phi^{1/(5+\beta)} \left(\frac{2\dot{E}_*}{\rho_*}\right)^{1/(5+\beta)} t^{3/(5+\beta)} \tag{1}$$

$$V_s = \left(\frac{3}{5+\beta}\right) \frac{R_s}{t} \tag{2}$$

$$\phi = \frac{(3+\beta)(5+\beta)^3}{12\pi(11+\beta)(7+2\beta)}\,. \tag{3}$$

In deriving these equations, the circumstellar gas has a density distribution $\rho(r) = \rho_* r^\beta$ and the wind mechanical luminosity, $\dot{E}_* \, (\equiv \frac{1}{2}\dot{M}_* V_*)$, is taken as constant.

'Momentum' driven flows occur when the shocked wind cools in a time much less than the dynamical timescale. The accelerated interstellar gas is now driven by wind momentum rather than by shocked wind pressure. The outer shock radius and velocity are now given by

$$R_s = \chi^{1/(4+\beta)} \left(\frac{\dot{M}_* V_*}{\rho_*}\right)^{1/(4+\beta)} t^{2/(4+\beta)} \tag{4}$$

$$V_s = \left(\frac{2}{4+\beta}\right) \frac{R_s}{t} \tag{5}$$

$$\chi = \frac{(3+\beta)(4+\beta)}{8\pi}\,. \tag{6}$$

The wind momentum output rate is here taken as constant.

In both cases, the shell accelerates if $\beta < -2$ and, in principle, Rayleigh-Taylor instability should lead to its break up. We return to this point in Section 3.

Energy driven flows are initiated if the cooling time in the shocked wind is greater than the dynamical timescale at the time when the wind has swept up its own mass of ambient gas. If the converse is true, a momentum driven flow is initiated. Energy driven or momentum driven flows are produced according to whether the wind speed exceeds or is less than a critical value V_{CR} respectively. For the uniform density case, $V_{CR} \approx 100(n_0 \dot{M}_6)^{1/9}$ km s^{-1} (Dyson 1984), where n_0 is the ambient number density and $\dot{M}_6 \equiv \dot{M}_*/10^{-6} M_\odot$ yr^{-1}. This criterion implies that interactions between fast winds (e.g. from O stars) and their environment are initially energy driven. The velocities of winds from stars found in molecular clouds tend to lie in the interestingly intermediate range 100–500 km s^{-1} approximately.

Flows may evolve from one type to another for two reasons. Firstly, the wind velocity may be time dependent. Breitschwerdt and Kahn (in preparation) have discussed planetary nebula dynamics allowing for the increasing wind speed between the post-AGB phase and the constant luminosity phase of the nucleus' evolution. Such evolutionary effects may be important elsewhere. For example, Dyson (1984) suggested that high luminosity stars power up to their main sequence values of $\dot{M}_*$ and V_* through a higher $\dot{M}_*$ and lower V_* phase.

Secondly, the circumstellar density distribution can induce flow changes. Dyson (1984) has shown that the ratio of the radiative cooling time in the wind to the dynamical timescale varies as $t^{-\beta/(4+\beta)}$ for an initially momentum driven flow and as $t^{-(1+2\beta)/(5+\beta)}$ for an initially energy driven flow. Hence momentum driven flows are maintained only if $\beta > 0$ otherwise they become energy driven. Energy driven flows are maintained only if $\beta \leq -\frac{1}{2}$. It is interesting to note (Dyson 1984) that for $\beta = 0$, the time at which an energy driven flow becomes momentum driven scales as V_*^{21}!

In principle, discrimination between the two types of flow can be made by observationally determining the two efficiency factors ϵ and μ for the conversion of wind kinetic energy and momentum into swept-up gas kinetic energy and momentum respectively. In an energy driven flow, $\epsilon = 3(5+\beta)/(11+\beta)(7+2\beta)$ and $\mu = \epsilon(V_*/V_s)$. In a momentum driven flow, $\epsilon = V_s/V_*$ and $\mu = 1$. An estimate of $\epsilon \ll 0.1$ is usually regarded as an indication that the flow is momentum driven. However a number of important reservations regarding derived efficiencies are necessary.

Shells driven by winds from stars with strong radiation fields may be only partially ionized. Both the masses of the neutral and ionized components must be known to derive the efficiency factors. For example, if an efficiency ϵ^i is derived using only the ionized gas mass, $\epsilon^i/\epsilon = (t_c/t)^{(5+4\beta)/(5+\beta)}$ where t_c is the time when the flow becomes fully ionized. For $\beta < -5/4$, $\epsilon^i/\epsilon < 1$ for $t < t_c$ and $\epsilon^i/\epsilon = 1$ for $t \geq t_c$. If $\beta > -5/4$, $\epsilon^i < 1$ for $t > t_c$ and $\epsilon^i/\epsilon = 1$ for $t \leq t_c$. Here the flow is assumed energy driven since such stars have high speed winds.

Dyson and Smith (1986) and VanBuren (1986) have given observational examples where these effects are of importance.

Cappa de Nicolau and Niemela (1984) estimated the neutral mass of the Wolf-Rayet nebula θ Mus from an apparent hole in the 21cm H emission as $M_n \approx 10^4 M_\odot$, giving an estimated $\epsilon^n \lesssim 0.01$, implying momentum driving. Dyson and Smith (1986) reanalysed the flow and obtained an ionized mass $M_i \approx 4.4\, M_n$ giving $\epsilon \approx 0.05$. The interpretation of the dynamics of this particular nebula is complicated by the presence of an O type companion to the W-R star, but Dyson and Smith (1986) concluded that energy driving was marginally possible.

VanBuren (1986) noted that the ionized mass of the nebula around the O8 III star λ Ori is $M_i \approx 2.10^3 M_\odot$ leading to $\epsilon^i \approx 0.007$. Momentum driving is implied. However, again analysis of the flow dynamics leads to a neutral gas mass $M_n \approx 13\, M_i$ and hence an $\epsilon \approx 0.1$, consistent, within observational and theoretical uncertainty, with energy driving.

Analysis of molecular flow dynamics can, in principle, give important data on the wind characteristics of the stars driving the flows. The expressions for the efficiencies clearly show that the type of flow must be known and further, as pointed out by Dyson (1984), the wind momentum and mechanical luminosity can be independently derived from the same set of data only if an additional parameter, the wind velocity V_*, is simultaneously known. A related problem concerns the use of measurements of the luminosity of the extended IR emission seen around some molecular flows to discriminate between the two types of flow. In an energy driven flow, the radiated energy can only derive from the cooling swept-up gas. The luminosity is constant in time and is $L_E = (3(3+\beta)/(5+\beta))\epsilon\dot{E}_*$ which ranges from $27/77\ \dot{E}_*(\beta = 0)$ to $1/3\dot{E}_*(\beta = 2)$. In a momentum driven flow, the luminosity is dominated by the energy radiated from the shocked wind, $L_M \approx \dot{E}_*$. It is clear that a very accurate independent determination of $\dot{E}_*$ is needed to discriminate between the two types of flow on this basis.

In the remainder of this review, we examine departures from the above description with illustrative examples where appropriate.

3. Shell Break-Up and the Circumstellar Density Distribution

As noted previously, radial density distributions with $\beta < -2$ lead to immediate shell acceleration and consequent Rayleigh-Taylor instability. More interesting examples occur when the acceleration occurs later on in the bubble evolution.

The general principles are easily established. For energy driven flows, the internal bubble pressure P_i is spatially uniform because of the high sound speed there. (This is the basis of the variant of the Kompaneets (1960) explosion theory first applied to stellar wind bubble evolution by Dyson (1977a.) For simplicity we assume a plane stratified ambient density distribution, $\rho = \rho_0 f(z)$ where $f(0) = 1$. The shell velocity in the direction $\theta\,(\equiv \cos^{-1}(z/R_s))$ satisfies $V_s^2(\theta) \sim P_i/f$. Since $P_i \sim t/R_s^3$, $V_s^2 \sim t/R_s^3 f$ or $V_s^3 \sim 1/R_s^2 f$. In the plane $z = 0$, $V_s^3 R_s^2 \sim$ const., i.e. the standard uniform density equation. If now f has an exponential (or related) form, $f = e^{-z/\Delta}$, where Δ is a scale height, $V_s^3 \sim e^{R_s/\Delta}/R_s^2$ in the direction $\theta = 0$ (R_s along the z axis). The shell velocity decreases to a minimum at $R_s \approx \Delta$ and acceleration then occurs with $\dot{V}_s$ increasing. Similar behaviour obtains in all directions for a radial density distribution $\rho(r) = \rho_0 e^{-r/\Delta}$. (This phenomenon is often referred to as 'blow out'.)

The examples cited below are for energy driven flows, but very similar behaviour occurs for momentum driven flows. For the plane stratified distribution, $V_s(\theta) \sim t/\mu(\theta)$ where $\mu(\theta)$ is the mass swept up per unit solid angle in the direction θ. For small R_s or near $z = 0$, $\mu \sim R_s^3$ and $V_s^2 R_s^2 \sim$ const., the uniform density equation. At large R_s along the z axis, $\mu \rightarrow$ const. and hence $V_s \sim t$. Again the transition from deceleration to acceleration occurs at $R_s \approx \Delta$. An important distinction between the two types of flow is that now $\dot{V}_s \rightarrow$ constant.

We now discuss three examples. Dyson (1981) noted that winds from groups of O stars could produce large scale bubbles in the galactic plane which could blow-out because of the finite scale height. Since acceleration commences at $R_s \approx \Delta$, the associated time and shell velocity are respectively $t_a \approx (\Delta^5\rho_0/\dot{E}_*)^{1/3}$, $V_a \approx 0.6\ (\dot{E}_*/\Delta^2\rho_0)^{1/3}$, where $\dot{E}_*$ is the integrated mechanical luminosity of the stellar group. As a simple example, if we require a group of stars to blow out in the solar neighbourhood ($\Delta \approx$ 100pc, $\rho_0 \approx 10^{-24}$ gm cm^{-3}) in a time $\sim 5\,10^{13}$ sec, the necessary integrated mechanical luminosity is $\sim 3\,10^{36}$ erg, i.e. some tens of O stars. The associated shell velocity near blow-out is $V_a \approx 20$ km s^{-1}. More realistic calculations include the effects of the inevitable accompanying supernovae (MacLow and McCray 1988).

Optical line splitting observed across the south lobe of the bipolar nebula S106 (Solf and Carsenty 1982) is clearly indicated of an expanding shell structure. Dyson (1983) modelled the nebula in terms of the interaction between a fast stellar wind and a surrounding stratified disc. The ragged end of the south lobe is attributed to the operation of Rayleigh-Taylor instability as blow out occurs. The gas dynamical model and the optical emission combine to require a stellar mechanical luminosity $\dot{E}_* \approx 2\,10^{35}$ erg s^{-1} and a Lyman continuum photon output $S_* \approx 4\,10^{47}$ s^{-1}, consistent with observational data on O9.5V stars. The observed infra-red luminosity implies a spectral type O9-B0V (Eiroa et al. 1979). S106 is an interesting example where gas dynamics can be applied to stellar spectral typing.

Molecular hydrogen features with velocities exceeding 250 km s^{-1} are observed towards the proto-planetary nebula CRL618 (Burton and Geballe 1986). Other high velocity features include the H_2O maser spots with velocities greater than about 74 km s^{-1} (line-of-sight) seen towards W51 MAIN (Genzel et al. 1981). Serious problems exist with simple shock acceleration of molecule bearing gas to such velocities since molecules are dissociated at shock velocities greater than about 50 km s^{-1} even with magnetically moderated shocks. Ram pressure acceleration of non-gravitationally bound clumps (e.g. Norman and Silk 1979) is a widely invoked but mythical process (e.g. Hartquist and Dyson 1987).

Hartquist and Dyson (1987) suggested that the coherent acceleration of a shell to high velocities is a more dynamically plausible mechanism. They argued that density distributions with scale heights $\sim 10^{17}$ cm should exist around some stars and that molecular material would be directly incorporated into the expanding shell once the shell velocity dropped below about 50 km s^{-1}. This molecular material would then be reaccelerated as the shell reaccelerates down the density gradient.

They argued that Rayleigh-Taylor instability is in itself not a sufficient condition for the shell fragmentation needed to produce discrete features. They conjectured that the shells would try to reseal themselves by the ablation of material off the fragments. This conjecture has received observational support from high resolution echelle spectroscopy of filaments in the Vela supernova remnant (Meaburn, Hartquist and Dyson 1988) where small scale velocity blisters are clearly seen. Since self-gravity of these shells is never important, it is likely that only genuine thermal instability (as well as Rayleigh-Taylor instability) can result in shell fragmentation (Hartquist and Dyson 1987). Thermal instability behind the shock sets in at velocities $\geq 100-130$ km s^{-1} (e.g. Innes, Giddings and Falle 1986), consistent with the maser data. (The model for S106 discussed above also satisfies this criterion.)

4. Distortion of Bubbles by Stellar Motion

Energy driven bubbles eventually distort into high asymmetric structures as a result of stellar motion (Weaver et al. 1977). The stellar wind acts as a snowplough with a high brightness bow wave of gas in the direction of motion. Initially momentum driven shells distort similarly. The subsequent flow pattern has been described by Dyson (1977b). The shocked wind does not radiate as it flows through the bow-shock pattern if the wind speed $V_* \gtrsim 100\,(V_0/20 \text{ km s}^{-1})^{4/11}\, n_0^{1/11}\, \dot{M}_6$ km s^{-1}, where V_0 is the stellar velocity with respect to the interstellar gas. Under most circumstances of interest, the shocked stellar wind occupies a thick hot region. The distance of the stand-off shock follows from momentum balance with allowance made for the finite thickness of the hot region and is $d_0 \approx 2(V_*/100 \text{ km s}^{-1})^{1/2} \dot{M}_6^{1/2} (V_0/20 \text{ km s}^{-1})^{-1} n_0^{-1/2}$pc (cf. Dyson 1977b). Thus arc-like structures with dimensions of a few pc should be produced. VanBuren and McCray (1988) have shown that such structures can be found in the IRAS data.

Dyson and Ghanbari (1989) have modelled the Wolf-Rayet nebula NGC 3199 as just such an interstellar snowplough. The observationally determined mass of NGC 3199 ($\sim 200 M_\odot$) clearly shows that it is of interstellar and not stellar origin. Dyson and Ghanbari (1989) show that the snowplough was set up in the O phase preceding the W-R phase, and obtain an excellent fit to the nebular morphology by assuming the ambient gas is of uniform density. From the nebular dimensions and density and the kinematic data of Whitehead, Meaburn and Goudis (1988), they derive a stellar velocity $V_0 \approx 60$ km s^{-1} and a wind mechanical luminosity $\dot{E}_* \approx 4\,10^{37}$ erg s^{-1}. This latter value is in excellent agreement with derived data on other WN5 stars (Barlow, Smith and Willis 1981). The ambient gas density $n_0 \approx 10$ cm $^{-3}$, and the nebula contains about 110 $M_\odot$ of ionized gas and about twice this amount of neutral gas. The difference between the derived and measured ionized mass is probably due to clumping. Although this model suggests that the central star of NGC 3199 is a runaway, no compact companion has yet been observed. It is worth noting here that estimates of ϵ for this nebula imply that it is momentum driven, but ϵ has no relevance to this steady flow pattern (Dyson and Smith 1986).

5. Effects of Non-Homogeneities on Bubble Structure

Hartquist and Dyson (1988) have reviewed the effects of mass pickup from clumps on many kinds of flow of astrophysical interest. If the general flow relative to a clump is subsonic in the clump frame, material is ablated into the flow by the Bernouilli effect. If the flow is supersonic, expansion of the clump into the wake behind a bow shock results in mixing. Mass addition affects flow dynamics, thermodynamics and chemistry.

A very simple example of the modification of flow dynamics is given by Hartquist et al. (1986—henceforth HI). Momentum driven bubbles moving into clumpy media and where the ablated mass dominates the shell mass have radii which evolve as $t^{1/4}$ instead of the usual $t^{1/2}$ (provided that the mass input rate per unit volume is constant).

The dynamics of the clumpy Wolf-Rayet nebula RCW 58 exemplifies the effects of mixing on flow dynamics and thermodynamics (H1; Smith, Pettini, Dyson and Hartquist 1984—henceforth S1—and 1988—henceforth S2). The low ($\sim 5M_\odot$) mass, clumpy structure and observed He, N enrichment imply that RCW 58 is composed of stellar ejecta from the red supergiant phase preceding the W-R phase (Maeder 1984). The conversion efficiency is $\epsilon \sim 0.001$ (S1) and the likely cause is the enhancement of radiative losses by the mixing of cool clump gas with hot shocked stellar wind. IUE absorption data show a linear velocity/ionization potential correlation which cannot be contained by standard bubble theory (S1). Analysis of the flow dynamics behind the wind shock show a bubble structure far removed from the classical model (H1). Moving outwards from this shock, there are four distinct zones (H1):-

1. A post-shock zone where mass loading from the clumps occurs and there are no radiative losses. The temperature of the gas changes from $5\,10^7$K to $2.5\,10^7$K and the Mach number (in the shock frame) increases to about unity.

2. Continuing outwards there is next a zone, again with mass loading and no radiative losses, but where the Mach number stays around unity in some statistical sense. The temperature drops from $2.5\,10^7$K to about 10^5K. The mixing has by now

added about 40 times as much material to the flow as came from the wind. (This figure is required to explain the velocity/I.P. correlation.)

3. At a temperature of 10^5K, cooling by collisional excitation and ionization of H from the clumps becomes dominant. A zone too thin to allow mass loading ensues. The region is isobaric and the temperature falls from 10^5K to the 10^4K characteristic of material radiatively ionized by the stellar radiation field. The UV absorption lines are formed here with the correct velocity variation.
4. Finally, there is a shell of radiatively ionized gas expanding with the same velocity as the lowest UV absorption line velocity (about 100 km s^{-1} with respect to the star).

Recent optical echelle spectroscopy (S2) strongly supports this model. Zone (4), never previously observed, is clearly identifiable. Features relevant to the mixing process are also apparent. For example, good mixing at the clump/mass loaded wind interfaces is indicated by the similarity between the [OIII] and [NII] velocity shifts and line widths over the clearly identifiable clumps. Very interestingly, the line widths from both clumps and shell are about 30 km s^{-1}. These line widths may be subsonic for the clumps since the effective sound speed in the mixing zone could be appreciably higher than 10 km s^{-1}. The line widths are supersonic for the shell and S2 speculate that turbulence in the shocked wind might drive supersonic turbulence in the shell.

Molecular cloud lifetimes are greater than the depletion time of molecules onto grains (cf. Dalgarno, these Proceedings). The correlation between molecular abundances and line widths implies a connection between the abundances and internal cloud dynamics (Williams and Hartquist 1984). To explain the high abundance of C^o in dense molecular clouds, they argued that the dynamical cycling of material between clumps and inter-clump gas prevents equilibrium chemistry from being attained. This dynamical cycling occurs as stellar winds dissipate clumps and produce a shell which then fragments (Norman and Silk 1980). Charnley et al. (1988a) noted that the stellar winds would ablate H_2 and mantle bearing grains from cold clumps and mix them into the mass loaded wind. Bow shocks in the wind around these clumps may produce H^+ and He^+, and mixed-in grains also can lose molecules by sputtering as they pass through these shocks. A complex mixture of grains, molecules, ions and atoms passes eventually through a weak shock where the wind reaches pressure equilibrium with the surrounding cloud. Chemical evolution of the shocked gas occurs, clumps are formed, molecules deplete onto grains and the clumps are then affected by the next generation of stellar winds. Charnley et al. (1988b) followed the chemistry through several evolutionary cycles and have had some success in producing abundances compatible with those observed. More recent work (Charnley et al. 1989) focusses on the chemistry in the clump-stellar wind interface.

6. Conclusions and Acknowledgements

'Classical' stellar wind bubbles have had considerable success in explaining many of the general features of wind-circumstellar interactions. However, the increasing availability of a wide range of high quality observational data has shown that real objects show significant variations from these rather simple models. Of particular importance are the various effects of mixing as the winds blow into non-uniform media. The study of these mixing interfaces, both theoretical and observational, is probably the single most important area of work in bubble dynamics for the immediate future.

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Discussion:

CASTAÑEDA: How sensitive are the conclusions of your model depending of clumps size distribution, density and number density?

DYSON: Well, we need at least one clump!. To be serious, I believe the gross features are probably rather insensitive to such details. However detailed local features certainly are.

TENORIO-TAGLE: Would you comment on how thermal conductivity affects the clumps of matter immersed in the hot wind region.

DYSON: I dont believe in thermal conductivity. I am very convinced that hydrodynamic mixing is much more important.

PECKER: In your cumply approach to the bubble problem, how does evolve the ambiguity between energy-driven winds and momentum-driven winds? Presumably, the question almost loses sense!

DYSON: My guess is that generaly mixing in the cold gas enhances radiative cooling this leading to momentum driven flows even for wind interactions which one might expect were energy driven (e.g., RCW58). However it does depend on how many clumps one has, their distribution etc. and one could certainly imagine situations were although clumps are present, no more than, say 50% of the energy was radiated away and the flow was essentially energy driven.