Stellar Driven Flows in Multi-Phase media

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Abstract

After a brief overview of the evolution of flows driven by winds and explosions in single phase media, we briefly describe some of the features of mass injection. We then describe recent work on mass injection into wind-blown bubbles and supernova remnants. We make some final remarks on shocks in multi-phase media.

1. Introduction

Most flows in diffuse astrophysical sources are driven by the injection of mass, momentum and energy. This injection can be impulsive e.g. flows driven by stellar explosions such as novae and supernovae or can be continuous e.g. flows driven by stellar winds and radiation fields. Of course these are not mutually exclusive and in some situations, this distinction is not clear cut. So, for example, a sequence of impulsive events (e.g. supernovae) may often be reasonably approximated as a continuous wind with a mean power of the supernova energy divided by the characteristic time between explosions.

The literature on these flows is vast and just a very few classic papers are mentioned here. Flows driven by the action of stellar UV radiation were classified by Kahn (1954); supernovae induced flows were studied by Shklovskii (1962) and flows driven by fast stellar winds by Pikel'ner (1968). We will here deal only with the latter two types of flow. A useful overview of a variety of problems associated with shock propagation has been given by Bisnovatyi-Kogan & Silich (1995).

2. A brief overview of the evolution of flows in single phase media

2.1. Supernova remnants

In the initial free expansion phase, a forward shock is driven into the supernova site surroundings at velocity $\mathrm{V}_s \cong$ constant, so the shock radius $\mathrm{R}_s \propto \mathrm{t}$, where t is the time. An accelerating reverse shock propagates into the supernova ejecta. When the mass swept up by the forward shock is O(10) times the ejected mass, the remnant enters the Sedov-Taylor stage of evolution in which only the forward shock remains. Radiation losses are negligible and the remnant evolves with time as $R_s \propto t^{2/5}$, $V_s \propto t^{-3/5}$. Eventually, radiation losses remove thermal energy from all except the very hot interior and the remnant enters the 'pressure-driven snowplough' regime during which $R_s \propto t^{2/7}$ and $V_s \propto t^{-5/7}$. Depending on circumstances, the hot interior may eventually cool and the resulting 'momentum-driven snowplough' evolves as $R_s \propto t^{1/4}$, $V_s \propto t^{-3/4}$. A very comprehensive overview of supernova remnant evolution is given by Truelove & McKee (1999).

2.2. Wind driven interactions

As in the supernova driven interaction, there are two shocks generated, a forward one into the ambient gas and a reverse shock into the ejecta (i.e. the wind). However, the continuous wind means that the reverse shock never collapses onto the stellar surface and the 'two-shock' flow pattern first described by Pikel'ner (1968) moves outwards in the stellar frame. The flow depends largely on the thermal behaviour of the shocked wind. If this wind behaves adiabatically, the outwards shock is driven by the pressure of the shocked wind and the flow is often referred to as 'energy' driven. In that case the outer shock evolves as $R_s \propto t^{3/5}$, $V_s \propto t^{-2/5}$. On the other hand, if the shocked wind cools quickly, the flow is driven by the wind momentum and, unsurprisingly, is then referred to as 'momentum driven'. In that case the outer shock evolves as $R_s \propto t^{1/2}$, $V_s \propto t^{-1/2}$. The type of flow that occurs is determined effectively by the wind velocity. Roughly for wind speeds less than 100 kms^{-1} or so momentum driven flows occur and energy driven flows occur if the wind speed is higher (e.g. Dyson, 1984). So, at least in single phase media, the very fast ($\geq$ few hundred kms^{-1}) winds from stars such as OB stars, Wolf-Rayet Stars and planetary nebula nuclei set up energy driven flows. Winds from YSOs (Young Stellar Objects) which are slower ($\approx$ hundred kms^{-1}) produce either momentum driven flows or energy driven flows since the transition is extremely sharp (Dyson, 1984). Flows can evolve from one type into another dependent on temporal variations in wind power output and/or spatial variations in the ambient density. A thorough treatment is given by Koo & McKee (1992a) and Koo & McKee (1992b).

3. Why study flows in multi-phase media?

Practically every diffuse astronomical source consists of 'cool' clumps embedded in a 'hot' substrate. These include stellar envelopes ejected in the late stages of stellar evolution, molecular clouds and star forming regions and the nuclear regions of active galaxies. Mass from the clumps can be picked up by the global flow initiated by any of the mechanisms above and the resulting dynamics, physics and chemistry of this global flow are thereby altered. The back reaction on the flow may also affect the mass injection mechanism.

There are several ways of injecting material into a flow. The photoevaporation of clumps depends on the presence of an ionizing radiation field. Conduction from cool clumps to the hot substrate may occur; depending on circumstances the inverse may also happen. Clumps can be shredded when overrun by shock waves and the clump material added to the global flow. Finally, simple hydrodynamic ablation via the Bernoulli effect may also happen.

A wide variety of problems involving mass injection have been studied in the literature. A far from exhaustive (though biased) selection includes: the internal dynamics of Wolf-Rayet nebulae (e.g. Hartquist et al., 1986; Arthur et al., 1993, 1994, 1996); ultra-compact HII regions (e.g. Dyson, 1994; Dyson et al., 1995; Lizano et al., 1996); planetary nebula jets (Redman & Dyson, 1999); supernova remnants (McKee & Ostriker, 1997).

4. The scales involved in mass-addition

There is a distinct hierarchy of spatial scales involved in the mass-pick up process. On the smallest scales, mass is accelerated in boundary layers towards full integration with the global flow. Because the global flows are directional, there is the tendency for the accelerated material to be stretched in the flow direction-these are the intermediate scale 'tail' features. The integration of the swept-up material into the global flows takes place on these scales. Finally, the largest scale is the flow itself. Provided there is suitable diagnostic emission or absorption, these various structures can be investigated in astronomical sources giving information on processes that are either difficult or impossible to study under terrestrial laboratory conditions.

5. Remarks on tails

Tail features are interesting for (at least) two reasons. Firstly they provide some of the most intriguing examples of morphology (e.g. the tails in the Helix Nebula NGC 7293, and those of the Orion PROPLYDs). Secondly, it is over these scales in which the integration of the picked up material into the global flow finally takes place and the efficiency of this integration (i.e. the coupling between the global flow and the picked up material) depends on the tail morphology. Very clearly, there is much better coupling if the tails are broad rather than thin, although the number of clumps per unit volume also plays a role. It is worth noting here that all the work discussed later assumes that the mass injection and assimilation into the global flow occurs over length scales much shorter than those associated with the global flows. Thus the likely coarse grain nature of real flows is ignored.

There are in fact several ways of generating visible tail structures. Although we are here concerned with real tails (in the sense that they contain real moving material), what appear observationally to be tails can be formed by the shadowing of radiation fields (e.g. van Berkblom & Arny, 1972; Cantó et al., 1998). The hydrodynamic formation of tails has been discussed on a phenomenological basis by Dyson et al. (1993). These authors considered the way gas liberated from a long-lived source interacted with a uniform stream of gas. There are in principle four possible basic interactions since the source and stream gas can be subsonic or supersonic. Dyson et al. (1993) concluded that wide tails are generated whenever a supersonic stream interacts with either subsonic or supersonic source material or a subsonic stream interacts with supersonic source material. They thus suggested that long thin tails are produced only if a subsonic stream interacts with subsonic source gas. This statement needs the caveat that in addition, any viscous energy dissipation in the tail must be balanced by radiative cooling (Hartquist et al., 1996).

This basic premise has been supported by numerical calculations (Falle et al., 2001) which looked at the interaction of subsonic and supersonic streams with subsonic source material. The wind was assumed to behave adiabatically and the stream gas isothermally. The subsonic-subsonic interaction gave a long thin tail.

An important related problem under study is the interaction of winds with distributed sources and the question of whether a global shock is formed or whether individual shocks occur around individual sources. Some important work has been done on the interaction of global shocks with multiple clumps (Poludnenko et al., 2002), but in these calculations, the clumps are destroyed by the shocks.

Since the forms of intermediate scale structures depend on the Mach numbers of the global flows, and they in turn determine the coupling between the source and the flow, it is clear that self-consistent flows really need to be studied. In the next sections we will consider a step in this direction by investigating the flows that can be produced with distributed mass loading terms.

6. Mass injection into stellar wind driven flows

Pittard et al. (2001a) and Pittard et al. (2001b) have constructed similarity solutions that describe adiabatic wind-blown bubble evolution with mass loading. Although similarity solutions are rather specialised, they do give some insight into the problems they attempt to describe. The basic equations are the usual conservation of mass, momentum and energy with an appropriate mass injection term added to the continuity equation, specified according to the mode of mass injection.

For conductive (saturated Spitzer) injection, the volume mass injection rate is proportional to $\mathrm{T}^{5/2}$, where T is the temperature. For hydrodynamic ablation, the prescription given by Hartquist et al. (1986) is used. In this, the mass injection rate is proportional to M^{γ}, where γ takes the value of 0 if the flow is supersonic relative to the clumps and 4/3 if the flow is subsonic. M is the flow Mach number. We specify the inter-clump density as $\rho = \rho_o \mathrm{r}^{\beta}$. A spatial dependency of the mass injection is included through a term r^{λ}.

In the case of hydrodynamic ablation, the similarity variable is $\mathrm{x} = \mathrm{r}\mathrm{Q}^{1/(5+\lambda)}\dot{\mathrm{E}}^{-1/(5+\lambda)}\mathrm{t}^{-2/(5+\lambda)}$, and for conductive injection $\mathrm{x} = \mathrm{r}\mathrm{Q}^{1/(10+\lambda)}\dot{\mathrm{E}}^{-1/(10+\lambda)}\mathrm{t}^{-7/(10+\lambda)}$. Here, Q is the constant of proportionality in the mass injection term, $\dot{\mathrm{E}}$ is the energy injection rate and t is the time. In the usual way, the coupled partial differential conservation equations reduce to a set of ordinary differential equations. In order to do this, there is the requirement that $\lambda = (2\beta - 5)/3$ in the ablation case and $\lambda = (5 + 7\beta)/3$ in the conductive case.

To summarise the results:

i) Hydrodynamic ablation. Substantial mass loading of wind-blown bubbles occurs over a wide range of λ. If $\lambda \leq -2$, the bubble mass is larger than that of the swept up shell. The profiles of the flow variables are significantly altered under conditions of large mass loading. In contrast to cases with little mass loading, the density and temperature increase and the velocity and Mach numbers drop. As expected, mass loading of the wind strongly reduces

the Mach number of the inner shock (c.f. Williams et al., 1995). Indeed the wind can mass-load sufficiently to go through a sonic point and thus avoid a termination shock altogether. Importantly, depending on circumstances, the flow may have anything from none to several sonic points. (Note that the mass loading is determined so as to be self-consistent with the Mach number of the local flow).
ii) Conductive evaporation. As before, substantial mass loading can occur over a wide range of λ. Here though the bubble mass is larger than that of the swept-up shell if $\lambda \geq 4$. With high mass loading, the average density of the shocked region is larger, the deceleration of the flow is shallower and the temperature of the shocked wind rapidly decreases. The shocked wind region can be entirely subsonic, entirely supersonic or have one or sometimes two sonic points. For a given value of λ and ratio of the radii of the inner and outer shocks, there is a maximum value of the mass loading that can occur.

These solutions give some idea of the complexities produced when mass injection occurs in stellar wind driven bubbles. It is clear that the effects of mass injection are such that the results on bubble dynamics and evolution obtained from calculations in smooth media (e.g. for planetary nebulae) should be viewed with caution.

7. Mass injection into supernova remnants

As in the case of stellar wind driven bubbles, by far the majority of investigations do not include the effects of mass addition. Cowie et al. (1981) numerically modelled the effects of a supernova explosion on medium where discrete clouds are embedded in a lower density substrate. The cloud material is thermally evaporated into the remnant. There have been various similarity solutions derived where, as above for the wind-blown bubbles, clouds are treated as continuously distributed mass injection sources. McKee & Ostriker (1997), Chièze & Lazareff (1981) and White & Long (1991) assumed that conductive evaporation drives mass injection. (Dyson & Hartquist, 1987) assumed that material is hydrodynamically ablated into remnants according the prescription given in Section 6. Arthur (1994) made a preliminary numerical study of the effects of hydrodynamic mass loading due to hydrodynamic ablation on supernovae remnants in the adiabatic case. Arthur & Henney (1996) used numerical simulations of mass loaded supernova remnants to explain the excess soft X-ray emission in bubbles in the Large Magellanic Cloud.

Mass loaded supernova remnants are important in a variety of contexts. A remnant propagating inside a molecular cloud propagates through a multiphase medium with a complex structure partly determined by the interaction of the progenitor star or neighbouring stars with the cloud. The range of the remnant in the cloud is a significant factor in the importance of the remnant for e.g. sequential star formation. On larger scales, the collective effects of supernova explosions drive galactic superwinds (e.g. Chevalier & Clegg, 1985; Heckman et al., 1990; Suchkov et al., 1996) showed that the superwind in the starburst galaxy M82 must be mass loaded to account for the observed X-ray emission. This necessary mass injection can be supplied by conductive or ablative cloud evaporation in the core of M82 (Hartquist et al., 1997). The ranges of individual remnants are affected by mass loading; clearly these in turn affect the global wind dynamics. Quite accurate approximations, confirmed by appropriate numerical modelling, are available to describe remnant evolution in smooth media (Cioffi et al., 1988; Truelove & McKee, 1999, and references therein). These approximations represent unified solutions for remnant evolution in the early (Truelove & McKee, 1999) and later (Cioffi et al., 1988) stages. Such solutions have the convenient property that only one simulation need be performed for each regime to determine the evolution of all remnants with the same form of initial ejecta and ambient medium density. In principle these solutions could be used to study problems where multiple supernova events occur and where it would be inconvenient to model each individual event. Since, as noted above, mass loaded remnants are important in a variety of contexts, it is useful to have similar approximations available for the mass loaded case.

Dyson et al. (2002) have calculated the evolution of supernova remnants in which mass loading takes place by hydrodynamic ablation. A related calculation where mass loading takes place by conductive evaporation has been made by Pittard et al. (2002). The basic equations are as in Section 6 with the addition that radiative cooling (assumed to be collisional ionization equilibrium cooling) is added to the energy equation.

In all cases studied, once mass loading becomes significant, the internal structures of remnants deviate appreciably from the structures of standard remnants with no mass loading. The distribution of the remnant energy between thermal and kinetic also changes from that of standard remnants.

In the case where mass injection is hydrodynamic, most significantly, the ranges of supernova remnants (defined at the time they have retained 50% of the initial explosion energy), are strongly influenced by the mass added. For example, a remnant that is heavily mass loaded can affect less than 1% of the volume which would be affected by a standard remnant with the same energy and evolving in a medium with the same ambient density. Clearly ranges are very seriously affected. It is worth noting that there are significant differences between the evolution of remnants where the prescription for mass loading of Hartquist et al. (1986) is used and where a constant (i.e. Mach number independent) injection rate is assumed only once cooling has occurred. Up to this stage, the differences, given the uncertainties in the physics, are negligible.

The situation is very different when mass addition takes place by thermal evaporation. The reason is straightforward; this latter mass injection is very temperature sensitive and the internal temperature structure can change dramatically spatially and temporally during remnant evolution. Moreover, conductively driven mass loading has a built in limitation mechanism. Mass addition tends to result in lower temperatures that reduce the mass loading rates. Once the interior temperatures of remnants drop below about 10^7K, mass addition rates decrease very sharply. Thus the main differences between these mass loaded models and standard models occur in the earlier stages of evolution. The later stages, where swept up gas dominates in either case, are rather similar.

The main differences between the ablation and conductively loaded remnants are that at late times, the former are dominated by added mass and most of the energy is thermal; the latter are dominated by swept up mass and kinetic energy. Ablation loaded remnants evolve more quickly and reach all dynamical stages earlier than conductively loaded remnants. At any given age, they tend to be more massive and smaller than equivalent remnants that are conductively mass loaded.

8. Discussion

Although the effects of mass addition to flows have been studied at some level for over two decades, it is evident that an enormous range of investigations still remains. In part, this is due to increasing observational data (e.g. on superwinds) which demand the inclusion of mass loading for their interpretation. In part there are fundamental processes associated with mass injection and the assimilation of the injected mass into global flows that remain badly understood. For example, there is evidence that clumps in molecular clouds may be magnetically supported but little work has been done on the photoionization of magnetised clouds. There are even more basic problems that need elucidation. Williams & Dyson (2002) have made a study of the structure of shock waves in two-phase media where simple assumptions were made for the dynamical coupling between a tenuous hot phase and a dense cool phase. The results, even for these simple models, show very important changes from standard shocks, since the ‘shocks’ now are resolved regions where the two components interact. Another important question is what determines whether global shocks are set up in flows or whether individual shocks around injection sources predominate. Mass loaded flows will continue to provide gainful employment for astronomers and astrophysicists for some time.

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