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Emission Lines from Jet Flows (Isla Mujeres, Q.R., México, November 13-17, 2000)
Editors: W. J. Henney, W. Steffen, A. C. Raga, & L. Binette

HUNGRY WINDS AND JETS

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RESUMEN

El cargado de masa de vientos y jets ocurre sobre un rango extenso de escalas espaciales y circunstancias astrofísicas. Revisamos brevemente las propiedades generales de flujos estacionarios esféricos simples y comentamos sobre la relevancia de puntos críticos para la carga de masa en ellos. Analizamos la importancia de estructuras de escalas intermedias. A continuación damos una breve reseña sobre la adición de masa a jets, seguido por comentarios sobre la adición de masa a "blisters" impulsados por supernovas en explosión.

ABSTRACT

Mass-loading of winds and jets occurs over a wide range of length scales and astrophysical circumstances. We briefly review the general properties of simple steady spherically symmetric flows and comment on the relevance of critical points to mass pick-up in them. We discuss the importance of intermediate scale structures. A brief overview of mass addition to jets is then given followed by comments on mass addition to bursting supernova driven blisters.

Key Words: **HYDRODYNAMICS — STARS: JETS AND OUTFLOWS**

1. INTRODUCTION.

Most diffuse astrophysical sources on scales ranging from circumstellar to extra-galactic are clumpy media responding to the injection of mass, momentum and energy. Winds and jets propagating in these clumpy media can pick up mass through a variety of processes including photoevaporation, hydrodynamic ablation and thermal conduction. In this sense, winds and jets are 'hungry'. Mass injection is important on three spatial scales. On the smallest, material is stripped from clumps, e.g., in small-scale boundary layers. On intermediate scales, material is accelerated to merge eventually with the global flow. Because of the directionality of the global flows, extended features (i.e., tails) may be produced. On the largest scales, the mass pick-up affects the global flow properties and there can then be a back reaction on the mass pick-up process itself.

A very large fraction of the literature on mass pick-up in flows in an astrophysical context is in connection with the pick-up of ions in the Solar Wind, which is outside the scope of this meeting. A (not even remotely comprehensive) collection of significant papers in areas of interest in this meeting includes the following areas and their contexts. Cloud acceleration, formation, destruction and emission: Woodward (1976, supernova remnants), Scott, Christiansen, & Weymann (1983, broad absorption line QSOs), Schiano (1986, NLR of Seyfert Galaxies), Perry & Dyson (1985, BELR of QSOs), Strickland & Stevens (2000, X-ray emission from galactic superwinds). Boundary layers: Cantó & Raga (1991, YSO jets), Dyson et al. (1995, Fast H_2 in molecular clouds). Intermediate scale features ('tails'): Dyson, Hartquist, & Biro (1993, principles of tail production—henceforth DHB), Lefloch & Lazareff (1994, tails produced by photoevaporation; see also Pavlakis et al. 2001), Cantó et al. (1998, tails as radiation shadows). Large scale flows: Chevalier & Clegg (1985, supernova driven starburst winds), Hartquist et al. (1986, Wolf-Rayet nebulae), Smith (1993, nuclear winds in active galaxies), Suchkov et al. (1996, X-ray emission from galactic superwinds; see also Hartquist, Dyson, & Williams 1997), Williams, Baker, & Perry (1999, AGN winds).

2. GENERAL PROPERTIES OF FLOWS WITH MASS ADDITION.

We address our comments here to the specific case of mass addition to steady state flows with spherical symmetry where the mass-loaded wind originates from a point source. Adiabatic flows have been discussed by Poll (1994) and isothermal flows by Williams, Hartquist, & Dyson (1995—henceforth WHD). Since many of the principles are common to either case, we concentrate on the latter. The two most noteworthy features of such mass-loaded flows are the generation of critical points in the flow (which can separate, e.g., subsonic from supersonic

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flow regions) and the effects on the strengths of any termination shocks.

The two most common types of critical points are nodes (where a smooth transition from supersonic to subsonic is possible, though a shock transition can always be inserted to effect this) and spiral points where a smooth transition cannot be made and a shock transition is always necessary. The sonic point topology depends on the spatial variation of the mass loading. WHD showed that if the mass added out to some radius r varies as r^{β}, then sonic points are nodes if $1 \leq \beta \leq 5/4$. If $\beta > 5/4$, then sonic points are spirals. WHD also showed that termination shocks are appreciably weakened if a wind is mass-loaded (termination Mach numbers of a few are produced). They speculated that this weakening of termination shocks may be responsible for the relative radio quietness of wind-driven bubbles compared to supernova remnants if it is assumed that the acceleration of the necessary relativistic electrons takes place in a termination shock and their energy increases with termination shock strength.

WHD did not specify the nature of the physical processes leading to mass injection. More recently, Pittard, Dyson, & Hartquist (2001) and Pittard, Hartquist, & Dyson (2001) have derived similarity solutions for mass-loaded wind blown bubbles where the mass-loading takes place by the specific mechanisms of conductive evaporation and hydrodynamic ablation respectively.

Winds may be magnetised (the classic study is the Weber & Davis (1967) study of the Solar Wind). Williams, Dyson, & Hartquist (1999) adapted the Weber-Davis formalism to include mass-pick up. Their simplifying assumptions included (a) added mass gets straight onto field lines and brings no magnetic flux with it, (b) the mass-loading source terms are functions of radial distance only, (c) the flow is isothermal, (d) the mass-loading zone is finite in extent and (e) that only fast-mode shocks are considered in the mass-loading region. Because there are now three critical speeds, the flow topology can be much more complex than in the non-magnetised case, and again termination shock strengths can be weakened by mass addition. Recent interest in magnetised winds (e.g., in connection with planetary nebulae morphology) make more studies of magnetised mass-loading desirable.

3. RELEVANCE OF CRITICAL POINTS TO FEEDBACK ON GLOBAL FLOWS.

The occurrence of critical points (including, more generally, shocks) is of considerable relevance to the physics of the mass-injection process itself. The temperatures of flow regions can depend on if, for example, the flow is upstream or downstream from a shock with consequences for mass addition by conduction. Also, Hartquist et al. (1986) gave simple arguments on hydrodynamic mass-loading, and proposed that mass injection rates were proportional to M^{γ}, where $\gamma = 4/3$, if the global flow is subsonic relative to an embedded clump, and $\gamma = 0$ if the flow is supersonic (M is the global flow Mach number in the clump frame).

As a specific example of where such considerations are important, we consider the mass-loading of superwinds which has been shown by Suchkov et al. (1996) to be necessary to explain their x-ray emission. Hartquist et al. (1997) showed that for reasonable assumptions, conductively driven and ablation driven evaporation of clouds in the core of the starburst galaxy M82 lead to a sufficient enhancement of the mass addition, compared to that provided by supernovae, to be in harmony with the Suchkov et al. (1996) models. These authors also examined the possibility that the increase of pressure in a starburst causes the burst to develop by inducing gravitational instability in the clouds which are also providing mass for mass-loading. The critical mass for collapse of a magnetised cloud depends on the external pressure and the ablation rate is Mach number dependent. Obviously, elucidation of the interplay between mass-loading and induced star formation depends critically on the global flow structure. A final remark is that it is necessary to consider time-dependent flows in this context.

4. RELEVANCE OF INTERMEDIATE SCALE STRUCTURES TO GLOBAL FLOW STRUCTURE.

All the work described above makes the critical assumption that as far as the global flow structure is concerned, the mass injection sources can be regarded as distributed smoothly through the flow, that is, the coarse structure of the flow is ignored. This question is bound up with the formation of intermediate scale structures. If the intermediate scale structures are long and thin, they present an appreciably smaller cross-section to the global flow compared to short wide-angled structures. Consequently, a greater spatial density of mass-loading sources is needed in the former case as compared to the latter.

DHB argued that the morphology of intermediate scale structures depends on the Mach numbers of

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both global flow and injected material. In particular, they suggested supersonic streams produce short stubby tails and that long thin tails could be produced only when subsonic streams interact with subsonic sources. Recent numerical simulations (Falle et al. 2002) have shown that the former conjecture holds generally and that the latter holds for parameters appropriate to the Helix Nebula (NGC 7293), where long thin tails are a conspicuous feature of the nebula's structure.

However, it is important to note that to date, only simple thermal behaviour in both streams and sources has been considered. The DHB arguments are based on adiabatic and isothermal flow in the tail and do not rule out the existence of wide tails in subsonic flows with different thermal structures. Hartquist, Dyson, & Williams (1996) examined the possibility that wide tails could be produced in a subsonic stream by heating due to viscous dissipation. For parameters most relevant to planetary nebulae, they found that cooling in a photoionized gas with a density greater than a few hundred cm^{-3} would suppress broad tail formation, consistent with data on the tails in the Helix nebula.

An interesting case is that of the hydrogen deficient planetary nebula Abell 30 (Borkowski et al. 1993). Tails closest to the central star of this object are long and thin while a couple of tails further out are short and wide. The simplest possible explanation is that the thin tails are produced in a zone where the incident stream is subsonic and the wide ones where it is supersonic. Thus, the nature of the critical points in the flow is important. However, there are additional possibilities for producing a wide tail even if there is no supersonic zone. Borkowski et al. (1993) noted that the nebula is most likely heated by the photoejection of electrons from dust grains and have shown that a multi-phase structure may then exist, depending on the gas pressure. They showed that the pressure in Abell 30 is near the critical pressure above which two stable phases can be supported by the heating but below which only the warmer (and more rarefied) phase exists. Hartquist et al. (1996) therefore speculated that as the gas from a clump with a broad tail moves into the slightly lower pressure tail region, it undergoes a phase transition and thereby heats sufficiently to prevent a thin tail from forming. Such speculations could in principle be tested if the thermal structures of the tails could be diagnosed. Two major areas for future work are clearly the investigation of stream-source interactions with a variety of thermal structures and of the coarse-grained structures of the global flows.

5. HUNGRY JETS.

Appreciably less work has been done on mass-loaded jets compared to mass-loaded winds. In contrast to at least the simple spherical winds described above, mass injection into jets can take place either by entrainment in boundary layers or by direct injection inside the jets. Boundary layer entrainment has been studied by Phinney (1983) and Cantó & Raga (1991). The mass injection rate per unit area of jet surface S can be written as $S = \varepsilon \rho c \ \mathrm{g\ cm^{-2}\ s^{-1}}$, where ρ and c are respectively the density and sound speed in the jet environment and all the uncertainties reside in the factor ε. For jets in pressure balance with their surroundings, Phinney (1983) proposed this factor to be equal to about unity for a jet moving supersonically into its surroundings and about equal to 0.025 for a subsonic jet. Cantó & Raga (1991) on the other hand showed that constant values of ε do not agree well with values derived from the spreading of laboratory jets. Apart from needing to have a reasonable estimate for ε to compare surface entrainment with internal mass injection, the value of this parameter determines when an initially laminar jet becomes fully turbulent. The mixing layer spreads across the jet after a distance which is proportional to ε^{-1}. Fully turbulent jets have been discussed by e.g., Bicknell (1984), Komissarov (1990), and Raga et al. (1993).

Direct mass injection into jets has mostly been considered in the context of extra-galactic jets. Both Phinney (1983) and Komissarov (1994) have treated the injection of material from stellar winds into jets. The former treated adiabatic non-relativistic jets while the latter treated relativistic jets.

In a galactic context, Redman & Dyson (1999) suggested that mass-loaded jets propagating through planetary nebula envelopes could be responsible for the formation of the enigmatic objects known as FLIERs (Fast Low Ionization Emission Regions). In their model, a jet (or more properly a deus ex machina), mass-loads from embedded condensations to a point at which the jet flow becomes optically thick in the Lyman continuum. FLIERs represent the recombination zones in the jets. If the embedded clumps are assumed to have similar parameters to the clumps in the Helix Nebula, quite reasonable requirements on such factors as clump numbers ensue. However, the model needs much more refinement. Redman & Dyson (1999) took the jet as ballistic but in fact a pressure confined jet may be more appropriate. It is also possible that the entrainment process produces a turbulent jet. One intriguing possibility is that the recombining gas which has traversed the

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recombination front may be supersonically turbulent with consequent shock excitation in this zone. There may also be a reconfinement shock in the neutral jet again with consequent shock excitation.

6. 'NIBBLING' WINDS.

Meaburn, Hartquist, & Dyson (1988) suggested from studies of the velocity structure of the Vela supernova remnant that hot gas in some supernovae remnants might break out of fragmented shells and mass-load (i.e., nibble) at boundary layers set up when the hot gas flowed past the shell edges. They suggested that fragmented bubbles might 'self-seal' in this way. Dyson et al. (1995) suggested mass pick-up in boundary layers set up at wind-molecular clump interfaces might be responsible for the wide (100 km s^{-1} or higher) molecular hydrogen emission line profiles seen towards many sources (e.g., the Orion Becklin-Neugebauer object).

A more recent application of 'nibbling' by winds has been to the structure of the Honeycomb Nebula discovered in the Large Magellanic Cloud by Wang (1992). This object consists of a series of interlocking shells of remarkably similar radii (typically ≈ 1 pc). Meaburn, Wang, & Bryce (1995) detected velocity spikes of up to 200 km s^{-1}. The brightest spikes are blue shifted with respect to the observer. Redman et al. (1999) suggested the following scenario. The action of combined stellar winds and supernova produces a giant shell with radius ≈ 100 pc and thickness $\approx$ few pc. This shell slowly fragments (possibly by Rayleigh-Taylor instability) on scales about equal to its thickness to provide the Honeycomb. A supernova then occurs interior to this shell and the supernova blows out past fragments of the giant shell and pressurises them. Supersonic boundary layers are set up at the fragment edges and gas is accelerated in a manner similar to that proposed by Dyson et al. (1995). The terminal velocity of the accelerated gas is weakly dependent on factors such as the ratio of the magnetic to gas pressure in the pressurised fragment and proportional to the sound speed there and characteristic parameters produce the observed spike velocities. One feature of this is that this requires the pressure in the fragment to be dominated by the magnetic pressure (cf. Dyson et al. (1995)) otherwise the acceleration is insufficient. It maybe that self-sealing occurs where gas pressure dominates and acceleration when magnetic pressure dominates.

7. CONCLUSIONS.

Winds and jets are uniformly hungry, provided of course that food (clumps) is available. There are many problems still to be solved the details of the assimilation of material into flows. We thus do not yet understand their table manners and digestive processes. Of particular interest is the interaction between the global flows and the mass-loading process. It is a familiar process to see the sense of well being produced by ingestion leading to even further ingestion. Finally, we note that a real understanding of the complex processes involved in mass-addition will only come about by the use of appropriate diagnostics. In other words, we need to inspect the kitchen.

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