THE COLLIMATION OF NONADIABATIC WINDS FROM YOUNG STARS

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1. INTRODUCTION

Outflows from young stars in many cases show evidence for collimation. For example, bipolar molecular outflows are sometimes quite well collimated (see, e. g., Snell 1982), and stellar jets and Herbig-Haro objects show an even higher degree of collimation (see, e. g., Mundt 1987).

Different models have been proposed to explain this quite remarkable characteristic of stellar outflows. The better explored theoretical scenario consists of a source surrounded by a stratified "thick disk" environment. The stellar wind, which is assumed to be initially isotropic, is collimated by the interaction between the wind and the environment.

Two different regimes for this flow have been explored in the past (see, e. g., the review of Dyson 1987) :

1 - Cantó (1980) showed that in the limit of very high radiative losses (*i. e.* , cooling distances much smaller than other characteristic distances of the flow) the above configuration leads to the formation of two elongated cavities (see figure 1). These cavities are surrounded by a narrow layer of cold gas, which flows towards the apex of the cavities,

2 - Königl (1982) studied the adiabatic limit, in which two oppositely directed de Laval nozzles are formed (see figure 2).

Raga and Cantó (1989) have recently extended the work of Königl (1982) to the case of nonnegligible radiative energy losses. The results from these calculations describe in an approximate way the regime of stellar wind collimation with moderate radiative energy losses, intermediate between the assumptions of the models of Cantó (1980) and Königl (1982).

Figure 1 :

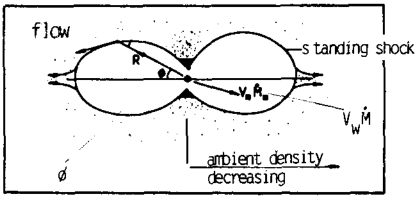
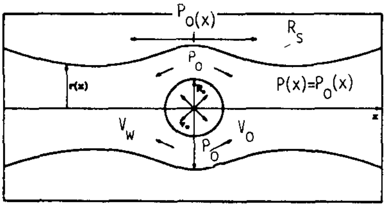


Figure 2 :



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2. ADIABATIC VS. NONADIABATIC COLLIMATION

In order to decide which regime is relevant, we have to evaluate the magnitude of the cooling distance of the postshock gas relative to other characteristic distances of the flow. We can do this by studying a very simplified description of the flow.

In a de Laval nozzle flow, the stellar wind goes through a shock at a radius R_S (see figure 2). The position of this shock and the postshock characteristics are determined by the balance between the ram pressure $(\rho_w v_w^2)$ of the wind and the environmental pressure at the equatorial plane (P_0) :

$$P_0 = \rho_{e,0}\, \Delta v_0^2 = \rho_w\, v_w^2\,, \tag{1}$$

where $\rho_{e,0}$ and Δv_0 are the environmental density and turbulent velocity (respectively) at $x = 0$ (see figure 2).

We define a dimensionless parameter $\kappa = d_{cool}/H$, where d_{cool} is the postshock cooling distance of the stellar wind, and H is the environmental scale height. The limit $\kappa \to \infty$ corresponds to the conditions required for the formation of an adiabatic de Laval nozzle. For $\kappa \to 0$ the flow should resemble the highly nonadiabatic cavity model of Cantó (1980).

Following Cantó (1980), for the environment we assume an "isothermal disk" pressure stratification, so that :

$$H = \frac{P_0^{1/2}}{(8\pi G)^{1/2}\rho_{e,0}} \approx 1.7 \times 10^{16}\mathrm{cm}\left(\frac{\Delta v_0}{\mathrm{km\,s^{-1}}}\right)\left(\frac{n_0}{10^7\mathrm{cm}}\right)^{-1/2}, \tag{2}$$

where n_0 is the number density of the environment at $x = 0$ (see figure 2). For the case of stellar environments, this implies possible scale heights in the range of $10^2 - 10^4$ astronomical units.

Using equations (1) and (2) and the cooling function of Raga and Cantó (1989), we obtain :

$$\kappa = \frac{d_{cool}}{H} \approx 8.3 \times 10^{-3}\left(\frac{\Delta v_0}{\mathrm{km\,s^{-1}}}\right)^{-4}\left(\frac{H}{10^{16}\mathrm{cm}}\right)\left(\frac{v_w}{100\,\mathrm{km\,s^{-1}}}\right)^{6.26}, \tag{3}$$

for wind velocities in the range $v_w \sim 80 - 800$ km s^{-1}.

From this equation we see that κ is extremely sensitive on the wind velocity. For example, for an environment with $H = 10^{16}$ cm and $\Delta v_0 = 1\,\mathrm{km\,s^{-1}}$, a $v_w = 100\,\mathrm{km\,s^{-1}}$ wind corresponds to $\kappa \approx 10^{-2}$, while a somewhat faster $v_w = 300$ km s^{-1} wind already implies $\kappa \approx 10$! This result illustrates the fact that nozzles with a very large range in κ values are possible for stellar outflows, ranging from almost adiabatic to highly nonadiabatic flows.

Figure 3 :

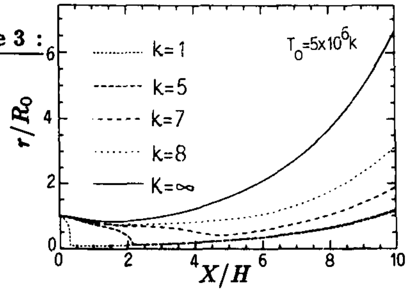
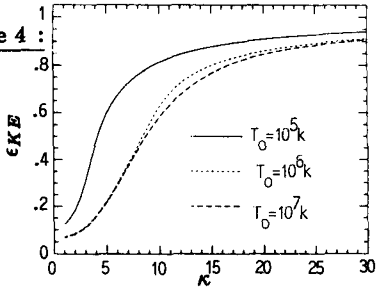


Figure 4 :



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3. GENERAL PROPERTIES OF NONADIABATIC NOZZLES

As we have described in §1., both the adiabatic (*i. e.* , $\kappa \to \infty$) and the highly nonadiabatic (*i. e.* , $\kappa \to 0$) regimes have been studied in the past. The recent work of Raga and Cantó (1989) extends these calculations to the finite κ regime.

However, the models of Raga and Cantó (1989) are extremely simplified, and based on assumptions almost completely identical to the ones of Kõnigl (1982), the only difference being the introduction of a radiative energy loss term in the equations. Because of this, while the Raga and Cantó models do reproduce the adiabatic results for the $\kappa \to \infty$ limit, they do not converge to the Cantó (1980) cavity solution in the $\kappa \to 0$ limit. This is a direct result of the fact that the approximations of the Raga and Cantó models break down for $\kappa < 1$.

In the following, we will limit our discussion to outflows with $\kappa > 1$, so that results based on the calculations of Raga and Cantó (1989) are applicable.

3.a Morphology of the nozzle

We find that the nozzle flow has two distinct regimes.

1 - "Quasi-adiabatic" nozzles : flows with $\kappa = d_{cool}/H > 6$ show general characteristics which are qualitatively not very different from the adiabatic (*i. e.* , $\kappa \to \infty$) nozzle (see Figure 3). These nozzles result in the formation of an overpressured jet of relatively low Mach number ($\sim 2-5$).

2 - "Collapsed" nozzles : flows with $\kappa < 6$ show a remarkably different behaviour. These highly nonadiabatic nozzles look similar to the adiabatic nozzle close to the star, but at larger distances, the nozzle radius "collapses" towards the axis. This collapse (which is caused by the strong temperature drop due to the radiative cooling) halts when the gas is cool enough to recombine and the cooling rate decreases drastically (see figure 3). These nozzles produce a very highly collimated, narrow, high Mach number ($\sim 10-100$) overpressured jet.

3.b Efficiency and luminosity

Figure 4 shows the efficiency of a pair of nozzles as a function of $\kappa = d_{cool}/H$. The efficiency ϵ_{KE} is defined as the ratio between the kinetic energy flux of the jets (produced by a pair of nozzles) and the kinetic luminosity of the wind :

$$L_w = \frac{\dot{M}\, v_w^2}{2} \approx 8.1 \times 10^{-3}\,\mathrm{L}_\odot \left(\frac{\dot{M}}{10^{-8}\mathrm{M}_\odot\mathrm{yr}^{-1}}\right)\left(\frac{v_w}{100\,\mathrm{km\,s}^{-1}}\right)^2 , \qquad (4)$$

where $\dot{M}$ is the mass loss rate of the outflow. Curves are given for three values of the post-stellar wind shock temperature $T_0 = 10^5$, 10^6 and 10^7 K, corresponding to wind velocities $v_w \approx 82$, 260 and 820 km s^{-1}, respectively.

Figure 5 shows the radiative luminosity ϵ_L (measured in units of the wind kinetic luminosity L_w) of a nozzle pair as a function of κ. From figures 4 and 5 it is clear that in nozzles with large κ most of the kinetic energy of the stellar wind is converted into kinetic energy of the collimated outflow. On the other hand, for low κ values, most of the kinetic luminosity of the wind is lost by emission of radiation.

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Figure 5 .

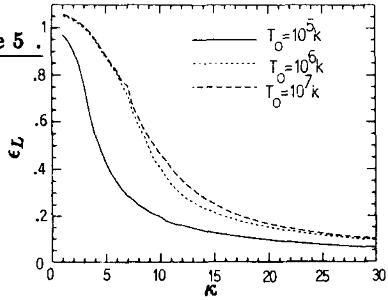
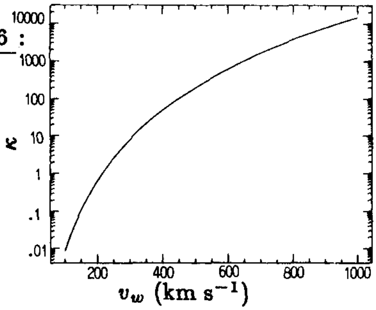


Figure 6 :



3.c Evolution of a nozzle flow

It is well known that while young stars (e. g., T Tauri stars) have very massive outflows, the mass loss of more evolved stars (e. g., main sequence stars) is much less substantial. Also, it seems that protostars (in earlier evolutionary phases than T Tauri stars) have even more massive outflows. Because of this, it appears to be reasonable to assume that through the lifetime of a collimated outflow, the stellar wind feeding the outflow has a monotonically decreasing $\dot{M}$. Provided that the change in mass loss rate is slow compared to the timescale for setting up a stationary de Laval nozzle flow, we can qualitatively describe the evolution of a bipolar outflow with our stationary models.

A decreasing mass loss rate $\dot{M}$ can be the result of changes in the density or in the velocity of the wind (or both at the same time). Let us discuss separately the effects of varying the density and the velocity of the wind.

3.c.1 *Wind with decreasing density*

If $\dot{M}$ decreases with time because of a decreasing wind density, the principal effect on the nozzle flow will be a gradual decrease in the radius R_S of the stellar wind shock (see figure 2 and equation 3). The κ value of the nozzle, however, will remain unchanged (see equation 3), implying that the general properties of the nozzles remain qualitatively unchanged. The radiative luminosity of the nozzles is proportional to the kinetic luminosity of the wind (see equation 4 and figure 5).

3.c.2 *Wind with decreasing velocity*

If the wind velocity v_w decreases with time, a much more interesting result is obtained. Because of the high dependence of κ on v_w (see equation 3), such an evolution can produce all the range from almost adiabatic nozzles (in an early, high v_w phase) to highly nonadiabatic nozzles (in a later, lower v_w epoch). This is illustrated in figure 6, in which we show κ as a function of v_w. These results have been obtained for a nozzle with an initial velocity of 1000 km s^{-1} and initial mass loss rate $\dot{M} = 10^{-7}$M$_\odot$yr^{-1} (the environment is assumed to have $H = 10^{16}$ cm and $\Delta v_O = 1$ km s^{-1}), but can be scaled to other values using equations 2-4.

In figure 6 we see the drastic change of κ during the evolution of the wind. In particular, we see that for $v_w \sim 280$ km s^{-1} we have $\kappa \sim 6$, the point at which the transition between "quasi-adiabatic" and "collapsed" nozzles occurs (see §3.a and figure 3). In other words, while the wind has $v_w > 280\,\mathrm{km\,s^{-1}}$ the nozzles are "quasi-adiabatic", resulting in the production of relatively low Mach number, not very highly collimated outflows. On the other hand, as soon as the wind velocity drops to $v_w < 280\,\mathrm{km\,s^{-1}}$, the nozzles enter the "collapsed" regime, so that very highly collimated, high Mach number jets are produced. This result agrees very well with the wind velocity predicted by Dyson (1987) for the transition between an adiabatic and a nonadiabatic stellar outlfow.

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Figures 7 and 8 show the radiative luminosity and average temperature (weighted with the emissivity of the gas) of the nozzles as a function of the wind velocity. We see that for large wind velocities the luminosity of the nozzles is low (a result of the high efficiency of the adiabatic collimation, see figure 4). For low wind velocities, the radiative luminosity is also low (due to the low kinetic luminosity of the wind, see equation 4 and figure 4). A sharp peak in the luminosity is obtained for $v_w \sim 280\,\mathrm{km\,s^{-1}}$, the velocity at which the transition between the "quasi-adiabatic" and "collapsed" nozzles occurs. The radiation field emitted at the luminosity maximum corresponds to the spectrum of a plasma with a temperature $T \sim 5 \times 10^5$ K (see figure 8).

Figure 7 :

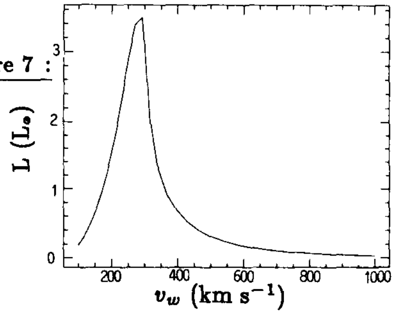
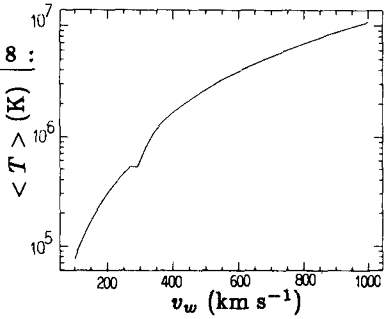


Figure 8 :



4. CONCLUSIONS

Depending on the importance of the radiative cooling, the collimation of a stellar wind by the interaction with a stratified environment produces qualtiatively different outflows. Three distinct regimes are observed :

- for $d_{cool} > 6 \times H$, "quasi-adiabatic" nozzles are formed, producing a relatively low Mach number outflow,
- for $1 < d_{cool} < 6 \times H$, "collapsed" nozzles are formed, producing very highly collimated, narrow, high Mach number jets,
- for $d_{cool} << H$, the outflow results in the formation of elongated cavities surrounded by a layer of cold gas (as described by Cantó 1980).

The regime of cooling distances lower but comparable to the environmental scale height has still not been explored theoretically.

We find that the nozzle flows that are most likely to be directly observed are the ones with $\kappa \sim 6$ (marginally collapsed nozzles), because they show the highest radiative luminosities. Also, these nozzles are the ones that produce the fastest highly collimated jets (nozzles with $\kappa > 6$ can produce higher velocity outflows, but with the poorer collimation and lower Mach number characteristic of the quasi-adiabatic regime).

An outflow source with a wind velocity that decreases with time could initially produce "quasi-adiabatic" nozzles, and later "collapsed" nozzles. The initial phase would produce a high velocity outflow, but with low radiative luminosity and relatively poor collimation (this phase could be associated with the formation of a bipolar molecular outflow). The final phase would produce a lower velocity outflow, but with a much higher degree of collimation (this phase could be associated with the formation of stellar jets or Herbig-Haro objects).

The transition between these two phases would occur (for the typical environmental parameters chosen above) at a velocity of a few hundred kilometers per second. This might provide an interesting explanation of why very high velocity stellar jets are never observed.

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Discussion:

DULTZIN: Extragalactic people worry very much about stability problems of accretion disks in active galactic nuclei. Do you ever worry (about such problems)?

RAGA: I have really not thought about disk stability problems.

PALLA: Given the importance of radiative cooling in your model, shoudn't non-equilibrium effects in the recombination process be taken into account? Namely, the gas can cool to temperatures well below 10^4K, if the assumption of ionization equilibrium is relaxed.

RAGA: Definitely, non-equilibrium ionization effects would be important. The result of including these effects would indeed be to lower the temperature at which the radiative energy losses became negligible, so that the "collapsed" nozzle solutions would produce narrower, higher Mach number jets.

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