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A POSSIBLE ORIGIN OF THE H-H OBJECTS IN YOUNG STELLAR OUTFLOWS

Elisabete M. de Gouveia Dal Pino and Reuven Opher

Instituto Astronômico e Geofísico, University of São Paulo, Brazil

RESUMEN. La presencia de flujos colimados asociados con objetos estelares jóvenes es un fenómeno común en regiones de formación estelar. Estos chorros frecuentemente muestran una cadena de regiones de líneas de emisión, a varias de las cuales se les conoce desde hace mucho tiempo como objetos Herbig-Haro (H-H). En el presente trabajo examinamos la posibilidad de que estos nudos sean condensaciones producidas por inestabilidad térmica en un plasma que se se expande sujeto a 'bremsstrahlung' recombinación y pérdida por radiación en líneas de emisión. Mostramos que el valor mínimo de $\beta = P_o/P_{Mo}$ bajo condiciones isobáricas para el crecimiento de la inestabilidad térmica es $\beta_m = (6/5)\ [9/(5\tau_c\nu_e) - 3/2]$; en donde P_o es la presión de partículas, P_{Mo} la presión magnética, ν_e la tasa de expansión y τ_c el tiempo de enfriamiento radiativo en el flujo del plasma ambiente. Haciendo cálculos no lineales, encontramos que los flujos colimados de temperatura $T_o \approx 10^5$ K, tasas de pérdida de masa $\dot{M} = 10^{-6} - 10^{-8}\ M_\odot\ a^{-1}$ y velocidades de flujo V_J = 100-400 km/s, resultan favorables para la formación de condensaciones por inestabilidad térmica con contrastes de densidad $\rho_p/\rho_o \approx 1.3 - 2.0$ creados en intervalos de tiempo más cortos que el tiempo estimado de expansión en los chorros, en donde $\rho_p(\rho_o)$ es la densidad en la región (ambiente) perturbada.

ABSTRACT. The presence of collimated outflows associated with young stellar objects is a common phenomenon in star-forming regions. These jets frequently show a chain of emission-line regions several of which have long been known as Herbig-Haro (H-H) objects. In this paper we examine the possibility that these knots are condensations produced by thermal instability in an expanding plasma subject to bremsstrahlung, recombination and emission-line radiation losses. We show that the minimum value of $\beta = P_o/P_{Mo}$ under isobaric conditions for the growth of a thermal instability is $\beta_m = (6/5)/\ [9/(5\tau_c\nu_e) - 3/2]$; where P_o is the particle pressure, P_{Mo} the magnetic pressure, ν_e the expansion rate and τ_c the radiative cooling time of the ambient plasma flow. Performing nonlinear calculations, we found that collimated flows of temperature $T_o \approx 10^5$ K, mass-loss rates $\dot{M} = 10^{-6} - 10^{-8}\ M_\odot\ yr^{-1}$, and flow velocities V_J = 100-400 km/s, are favorable to the formation of condensations by thermal instability with density contrasts $\rho_p/\rho_o \approx 1.3 - 2.0$ created in time intervals shorter than the estimated expansion time scales of the jets, where $\rho_p(\rho_o)$ is the density at the perturbed (ambient) region.

Key words: HERBIG-HARO OBJECTS — STARS-MASS LOSS

I. INTRODUCTION

The presence of collimated energetic outflows or jets associated with young stellar objects is now recognized as a common phenomenon in star-forming regions. Mundt et al. (1987) examined and reviewed the optical appearance of the jets. So far, nearly 20 jets have been discovered. The jets frequently show linear chains of high-velocity bright condensations or knots and several of these bright knots have been long known as H-H objects. All H-H objects showing evidence for a bow-shock structure are internally highly structured, i.e., they are rather knotty and patchy, as for example the H-H 2 objects of Orion. This is an important point, since it strongly suggests that these knots are not isolated entities(e.g. bullets), but part of one large-scale flow pattern (Mundt et al. 1987). A natural interpretation of the observed knots is that they represent dense clumps which have been accelerated by the jet. These condensations resemble some of the optical emission knots in the extragalactic radio jets (Königl 1984, see also GOV, this conference).

We investigate here the possibility that the knots are condensations produced in the ionized thermal outflow by a thermal instability. A general discussion of the various types of thermal instabilities of relevance in astrophysical phenomena was previously made by Field (1965), Simon and Axford (1967), Eilek and Caroff (1979), Heyvaerts (1974),Ferrari et al.(1982), and Bodo et al. (1985). Recently, we performed nonlinear analysis of the production of condensations by a thermal instability in outflows emitting primarily synchrotron radiation (Gouveia Dal Pino and Opher 1989a - GOI; 1989b - GOII; and 1989c - GOIII). In the present work, we discuss the linear and nonlinear development of condensations by a thermal instability in young stellar outflows, assuming that the expanding flows lose energy primarily by bremsstrahlung, recombination and emission line radiation losses.

II. THE MODEL

A detailed description of our basic assumptions and equations is given in GOIV. The initial configuration is taken to be an expanding jet of thermal plasma embedded in a magnetic field. Consistent with observations, the magnetic field $\vec{B}$ is assumed to be parallel to the axis of the jet. Similar to our previous calculations (GOI, II), we choose for the volume element of plasma to be perturbed a field-aligned cylindrical volume moving with the expanding jet in the axial direction (z). Since the growth of longitudinal perturbations to the magnetic field tends to be inhibited by the thermal conductivity of the gas, we restrict the analysis to transverse perturbations to the magnetic field and neglect effects of thermal conduction in this direction. We separate the ambient (or equilibrium) and perturbed quantities, which we designate with subscripts "0" and "1", respectively. The ambient temperature of the plasma flow is considered approximately constant. This assumption is reasonable due to the high thermal conductivity along the magnetic field lines. The ionized fraction (x) is also nearly constant.

For the evaluation of the energy losses (L) of the thermal plasma by bremsstrahlung, recombination, and emission line radiation, we considered the cooling curves obtained by McWhirter et al. (1975) for an optically thin high temperature gas with a number density $n \lesssim 10^{11}$ cm^{-3}. For the temperature interval 1.5 x 10^4 K - 10^6 K the total radiative loss rate is given by:

$$L_r \simeq 1.8 \quad 10^{-22}\ n^2 x \quad [\text{ergs cm}^{-3}\ \text{s}^{-1}] \tag{1}$$

where $x \equiv n_e/n$ is the ionized fraction and n is the number density of the gas (cm^{-3}) which for cosmic element abundances is predominantly hydrogen.

III. LINEAR CALCULATIONS

The equations of motion appropriate to the plasma we have described, and which must be solved in order to follow the evolution of a perturbed region, are the standard MHD equations for a magnetized plasma with infinite electrical conductivity. Assuming for the perturbed region a cosine density profile, we first examine the effect of small perturbations on the plasma.Under isobaric conditions the linear equations for the perturbation have an analytical solution which results in the following condition in order to have an instability driven by radiation losses (GOIV):

$$\beta \geq \frac{6}{5}\left[\frac{9}{5\tau_c\ \nu_e} - \frac{3}{2}\right]^{-1} \tag{2}$$

where τ_c is the cooling time of the plasma due to the radiative losses, $\tau_c = 3P_o/L_{ro}$, ν_e is the jet transverse expansion rate and $\beta \equiv P_o/P_{Mo}$, where P_o is the particle pressure and P_{Mo} the magnetic pressure.

IV. NONLINEAR CALCULATIONS

We performed a nonlinear analysis of the growth of the thermal instability as in our other studies (GOI - GOIII), since the linear theory does not permit a deduction of the true density enhancements. The nonlinear equations for the perturbed quantities are given in GOIV.

In order to follow the development of a perturbation along the jet we considered the following initial ambient (or equilibrium) conditions in agreement with the observations: an opening angle $2\theta = 0.1$ rad; and thermal ambient plasma temperature $T_o = 10^5$ K. At this temperature, the thermal gas, predominantly hydrogen, is fully ionized (cf. McWhirter et al. 1975) and we take $x \approx 1$. Since we assume a constant ionized fraction, our calculations are truncated when T_p (the temperature of the perturbed region) reaches a minimum temperature $T_{pmin} \gtrsim 10^4$ K. We consider for the mass-loss rate the range of values $10^{-8} \lesssim \dot{M} \lesssim 10^{-6}\ M_\odot\ yr^{-1}$ and for the flow velocity we assume, in general, $V_J \approx 100$ km/s (Mundt et al. 1987).

Our general results are described in GOIV. As an example, Fig. 1 depicts the nonlinear evolution of the density contrast between the perturbed and the ambient regions $\rho_p/\rho_p = (\rho_o+\rho_1)/\rho_o$ (with an initial density perturbation $\alpha_\rho = \rho_1(o)/\rho_o(o) = 0.1$) for curves with an initial ratio between the particle and the electronic pressures $\beta(0) = P_o/P_{Mo} = 5$, an initial jet radius $R(0) = 10^{14}$ cm, and different values of $\dot{M}$. We note that larger the value of $\dot{M}$, more rapidly the increase of ρ_p/ρ_o to its maximum. The reason for this behaviour is the larger product $\tau_c(o)\nu_e(o)$ for decreasing $\dot{M}$, which implies a smaller cooling rate relative to the expansion rate for smaller values of $\dot{M}$ and thus, a slower density amplification and cooling of the perturbed medium.

Fig. 2 shows examples of models which differ only by the value of the ratio $\beta(o) \equiv P_o(o)/P_M(o)$. We see that the increase of the ratio $\beta(o)$ provokes a more rapid density amplification.

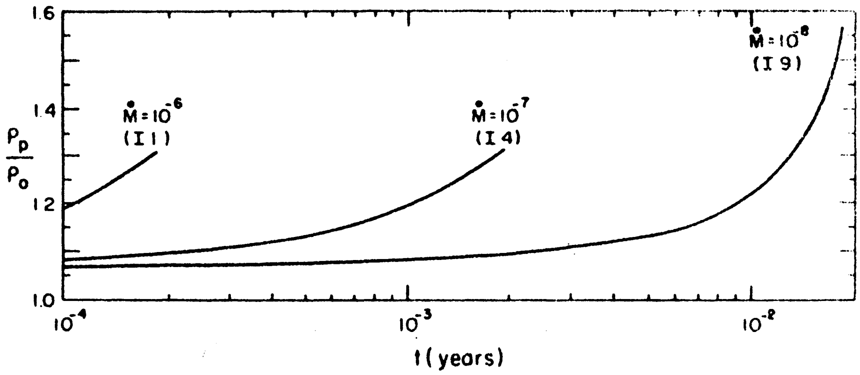

Fig. 1: Nonlinear evolution of ρ_p/ρ_o for models with: $R(0) = 10^{14}$ cm, $\beta(0) = 5$ and $V_J = 100$ km/s.

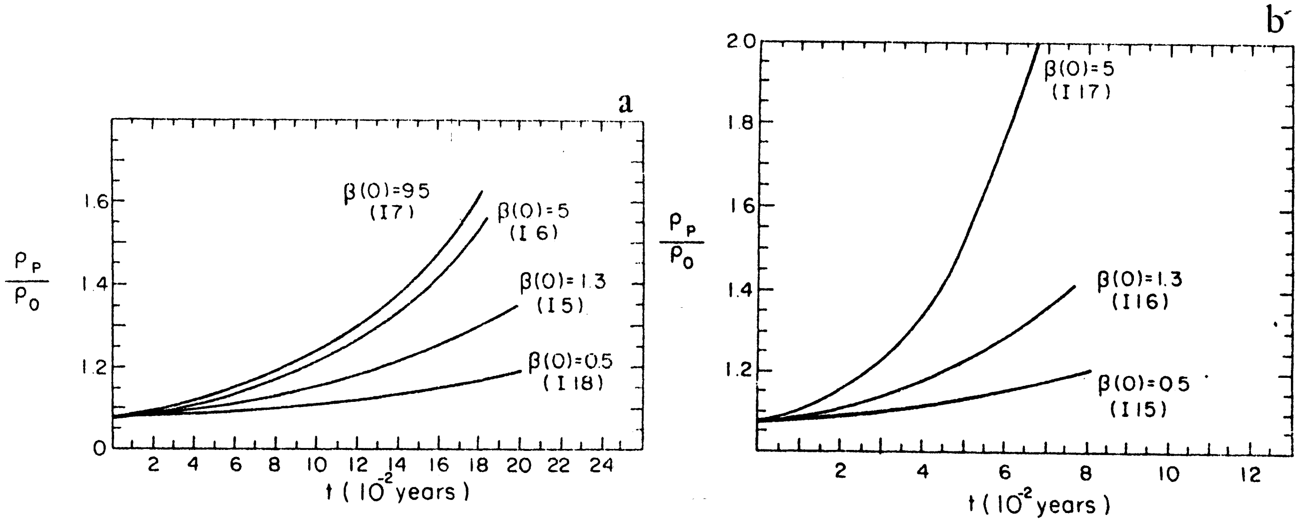

Fig. 2: Examples of models which differ only by $\beta(0)$: a) $R(0) = 10^{15}$cm, $\dot{M} = 10^{-7}\ M_\odot\ yr^{-1}$, V_J = 100 km/s and $\beta(0) \geq 0.5$ and b) $R(0) = 10^{14}$ cm, $\dot{M} = 10^{-8}\ M_\odot\ yr^{-1}$, $V_J = 400$ km/s and $\beta(0) \geq 0.5$.

These results confirm the conclusions of our previous studies (GOII and GOIII): the growth of the magnetic pressure (which implies the decrease of $\beta(o)$) tends to inhibit the growth of the condensation by the thermal instability.

V. CONCLUSIONS

The results suggest that, for the conditions compatible to those of the observed optical jets of YSOs, thermal instabilities grow and are sufficiently strong to form condensation in outflows with initial ratios $\beta(o) = 0.5 - 5$. As shown in Figs. 1 and 2, the growth of the condensations is very rapid. Condensations with density contrasts $1.3 \leq \rho_p/\rho_o \leq 2.0$ and radiative emissivity contrasts $1.4 \leq L_{rp}/L_{ro} \leq 4.0$ (GOIV) are formed in time scales $t_f \lesssim 0.2$ year, which are much smaller than the typical dynamical time scales of the observed jets $\sim 10^2 - 10^4$ years (Mundt et al. 1987) and of the same order as their mean expansion time.

As mentioned earlier, several of the brightest known HH objects are observed as "blobs" at the extremities of the collimated flows and are composed of subcondensations. These blobs could be formed from the interactions with the ISM of the expanding flow carrying the filaments or condensations previously created by thermal instability according to the process described in this study.

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Elisabete M. de Gouveia Dal Pino and Reuven Opher: Instituto Astronômico e Geofísico, Universidade de São Paulo, Caixa Postal 30.627, CEP 01051 São Paulo, SP, Brazil.