Rev. Mexicana Astron. Astrof., **18**, 29-35 (1989)

FAST WINDS IN LOW LUMINOSITY, PRE-MAIN-SEQUENCE STARS

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RESUMEN. Las observaciones de vientos rápidos (v $\geq$ 100 km s^{-1}) alrededor de estrellas de secuencia principal de baja luminosidad, apoyan un esquema en el cual el viento rápido sale de la estrella, predominantemente neutro y bastante frío (T $\leq$ 7000-8000 K). A ~ 100 AU de la estrella, la temperatura del gas es todavía de unos cuantos miles de grados, ya sea porque el gas no se ha enfriado nunca a temperaturas menores, o porque algo ocurre que lo recalienta a esa distancia de la estrella. El flujo molecular lento, cuya presencia se manifiesta en las alas anchas de CO ($\Delta v \sim$ 10-20 km s^{-1}), es material barrido de la nube ambiental.

ABSTRACT. The observations of fast winds (v $\geq$ 100 km s^{-1}) around low-luminosity, pre-main-sequence stars support a picture in which the fast wind leaves the star, mostly neutral and rather cool (T $\leq$ 7000-8000 K). At ~ 100 AU from the star, the gas temperature is still a few thousand degrees, either because the gas has never cooled below that temperature, or because something happens that re-heats it at that typical distance from the star. The slow molecular outflow, revealed by CO braod wings ($\Delta v \sim$ 10-20 km s^{-1}), is swept-up matter from the ambient cloud.

Key words: **STARS–PRE-MAIN-SEQUENCE — STARS–WINDS**

I. Introduction

Pre-main-sequence stars of low and intermediate luminosity are often associated with massive molecular outflows (Lada, 1985; Snell and Bally, 1986). CO and other molecular lines show evidence of gas moving at velocity of 10-20 km s^{-1} over regions which extend to 10^4-10^5 AU. The rate of mass-loss derived for these outflows spans a large interval, from ~$10^{-8}M_\odot$ yr^{-1}, which is practically the detection limit, to very large values ($\geq 10^{-6}M_\odot$ yr^{-1}) (Edwards and Snell, 1983, 1984, 1989; Levreault, 1988). In the following, I will call these outflows *slow molecular outflows.*

At the same time, stars with similar properties (in several cases, the same stars) are known (mostly from their optical spectra) to lose mass at much higher velocity (v~100-300 km s^{-1}) (cf. Kuhi, 1964). I will call this the *fast stellar wind.*

It has been tempting to link together the two outflows in a simple model, which assumes that the fast wind, originating from the central star, sweeps up matter from the ambient molecular cloud, and that momentum is conserved across the shock (see, for example, Snell, 1987); I will refer to this as the *standard* model. However, this model met some severe difficulties, because it was soon realized that the momentum carried by the ionized component of the stellar wind was in general much smaller than the momentum of the molecular matter (Rodriguez and Cantó, 1983; Snell *et al.*, 1985; Evans *et al.*, 1987).

In this talk, I will first review quickly what we know about the fast stellar wind. Then, I will address the problems with the *standard* model. The discussion will show that we can reconcile the observed properties of the stellar wind with the high momentum required by the *slow molecular outflow*, and that at the same time we can place significant constraints on the mechanism that drives the mass-loss itself.

II. The fast stellar wind

There are several different indicators of high velocity gas.

First, the existence of high-velocity (v~100-300 km s^{-1}) outflowing matter is revealed in the spectra of many pre-main-sequence stars by the P-Cygni profiles of optical lines (about 30% of the stars classified as T Tauri), such as H_α, Ca II H and K lines, and the Na I doublet at 5990, 5896 Å (Hartmann, 1982; Mundt, 1984; Ulrich and Knapp, 1984). These lines form very close to the central star, with typical scales of 1-10 stellar radii, i.e., $\leq$0.1 AU. The physical conditions in the wind (rate of mass loss, temperature, velocity, etc.) that we may infer from them apply to the dense, small region immediately surrounding the star.

A second indication of outflowing matter is provided (in approximately 20% of the T Tauri stars) by the observations of forbidden lines of low ionization species ([O I] 6300 Å, [S II] 6717, 6713 Å, [N II] 6584 Å) with broad, blue-shifted profiles (Jankovics, Appenzeller and Krauter, 1983; Appenzeller, Jankovics and Ostreicher, 1984; Edwards *et al.*, 1987). The velocities derived from these lines range between ~100 and ~150 km s^{-1}. These lines are thought to form at a distance of 50-500 AU, much further from the star than the region where the other optical lines form.

Neutral matter moving at high velocity ($v \geq 100$ km s^{-1}) has been detected in a couple of low-luminosity pre-main-sequence objects known to have high rates of mass-loss by observations of the 21 cm line of neutral hydrogen (Mirabel, Cantó and Rodriquez, 1983; Lizano *et al.*, 1988).

Finally, molecular gas moving at similarly high velocities has been seen in the CO J = 1-0 and 2-1 lines in a few sources (Koo, 1989).

III. Can the stellar wind drive the slow molecular outflow?

This is the basic question, which, as I have already mentioned, has been raised by several authors. The most systematic attempt to clearly define this problem has been that of Evans *et al.* (1987), who measured hydrogen infrared recombination lines in a sample of sources with slow molecular outflows. A first analysis of their results, based on simple, fully-ionized wind models, showed that the luminosity of the infrared lines was often much lower than predicted for objects losing mass at the rate required by the CO lines, and seemed to indicate that the momentum carried by the wind fell short (in some cases by orders of magnitude) of the momentum in the slow molecular outflow. A subsequent, detailed calculation of the ionization and hydrogen excitation structure of the wind around low-luminosity pre-main-sequence stars has shown that in fact the winds are mostly neutral (Natta *et al.*, 1988b). The ionization is primarily due to photoionization from excited levels, and thus depends on the gas temperature as well as on the stellar radiation field. Typically, the ionization fraction (i.e. the ratio of the electron to gas density) ranges between 1% and 50% near the star, and drops to much lower values within 2-10 stellar radii. Only for gas temperatures approaching 10^4 K does the ionization fraction approach unity. Winds with the same rate of mass-loss can have very different ionization fractions, and therefore produce recombination lines of very different intensity. Figure 1 (Natta *et al.*, 1988a) shows how these results have been applied to the sample of objects observed by Evans *et al.* (1987). The low Br_α emission in some of the objects with high mass-loss rates derived from CO observations can be explained if the winds are cold, and, therefore, mostly neutral.

Figure 1 shows that the standard model need not be inconsistent with the infrared line observations. However, it does not necessarily prove that it is consistent, because it shows that it is not possible to derive the rate of mass-loss from the intensity of hydrogen recombination lines, as long as the gas temperature is not independently known.

This fact has made it necessary to look for other, independent diagnostics of the physical conditions in the inner parts of the stellar wind, which, together with the hydrogen recombination line intensities, would allow us to determine both the gas temperature and the rate of mass loss. Resonant lines of trace elements are believed to form in the inner wind region, and can be used for this purpose. We chose the Na I doublet at 5990, 5896 Å ($3S_{1/2}$-$3P_{1/2}$, $3S_{1/2}$-$3S_{3/2}$). In about 1/3 of T Tauri stars, these lines show a P-Cygni profile (Hartmann, 1982; Mundt, 1984). The depth and shape of the absorption vary from object to object within this sample, but two clear features can nevertheless be identified: the absorption component is never deeply saturated; and it never peaks near the terminal wind velocity, but rather near the center of the line. We have compared these characteristics with the results of Monte Carlo calculations of radiation transfer in scattering lines by Beckwith and Natta (1986), and with the line profiles of Na I lines computed by Natta and Giovanardi (1989), for a large grid of wind models. The results indicate that, in order to reproduce the shape of the observed absorption components, the column density of neutral sodium must vary in a relatively narrow range. Expressing it in terms of an optical depth $\tau (\tau = N \times \sigma / \delta v_{th}$, where N is the column density of neutral sodium, σ is the line absorption coefficient, and δv_{th} is the thermal velocity), we find that $10 \leq \tau \leq 100$. Larger values result in deeply saturated absorption components, smaller values result in no absorption at all. This constraint, derived from a study of the line profiles, can be transformed into a constraint on the gas physical condition, by calculating self-consistent models of the ionization and excitation of sodium.

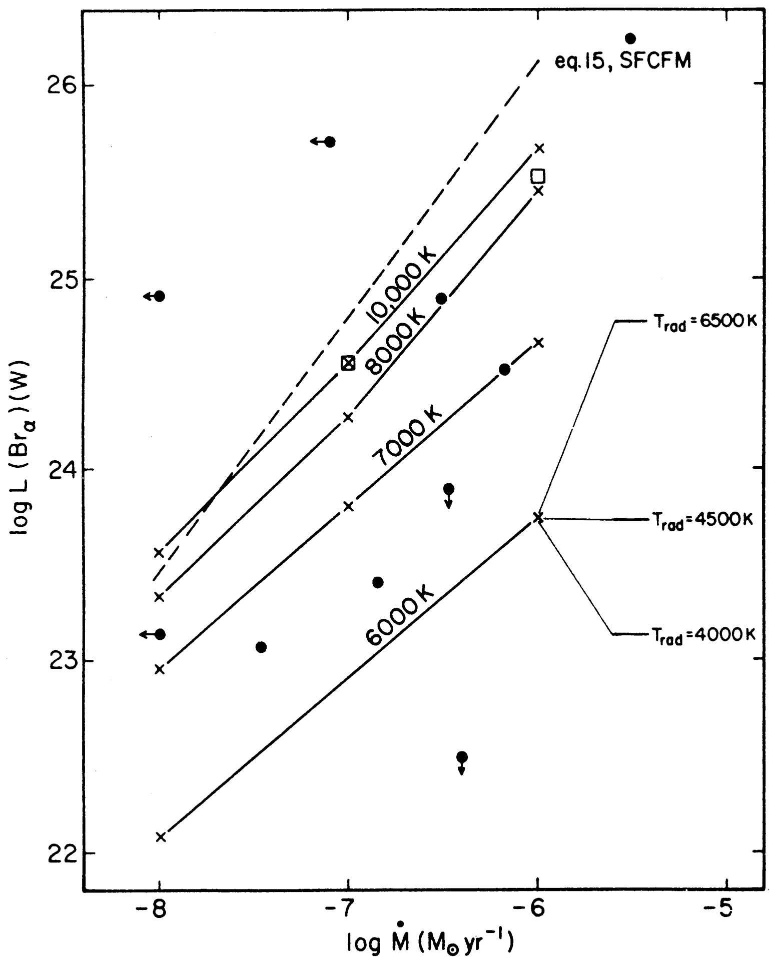

Fig. 1 - The Br_α luminosity in watts from a stellar wind is plotted as a function of the rate of mass loss $\dot{M}$. The solid lines are the results of the model calculations by Natta *et al.* (1988b). They are labelled with the gas temperature. The effects of changing the stellar temperature (from 4000 K to 6500 K) are shown for one model. The two open squares are the results of two non-isothermal models. The filled circles show the observational results of Evans *et al.*. The dashed line plots the expected Br_α luminosity in a constant-velocity, fully-ionized wind at a temperature of 10000 K. (from Natta *et al.*, 1988a).

Figure 2 shows the results of the model calculations in a plot Log $\dot{M}$-Log T_{gas}. Solid lines are curves of equal optical depth for the Na I $3S_{1/2}$-$3P_{3/2}$ line. The dashed lines are curves of equal luminosity in Br_γ. The radiation field has been chosen to mimic that observed in T Tau (Cohen and Kuhi, 1979; Goodrich and Herbig, 1985). The wind is accelerated rather slowly, and reaches half of the terminal velocity at about 4 stellar radii. Faster acceleration can be ruled out by the shape of the absorption component. The results are not strongly dependent on the exact value of the terminal velocity. Those shown in Figure 2 are for $v_\infty = 150$ km s^{-1}. The models assume that the wind is isothermal (see Natta *et al.*, 1988b for more details on the wind structure).

We show in Figure 2 the position of three objects, which have observed slow molecular outflows. Br_γ luminosities are taken from Evans *et al.* (1987) and Hamann *et al.* (1988) and Stanga (1989). In Table 1 we compare the rate of mass-loss derived from Figure 2 (i.e. by comparing the depth of Na I lines with the Br_γ emission) with the mass-loss rate derived from CO observations for these three objects, plus one other for which the Na method can only set upper limits. The agreement is surprisingly good.

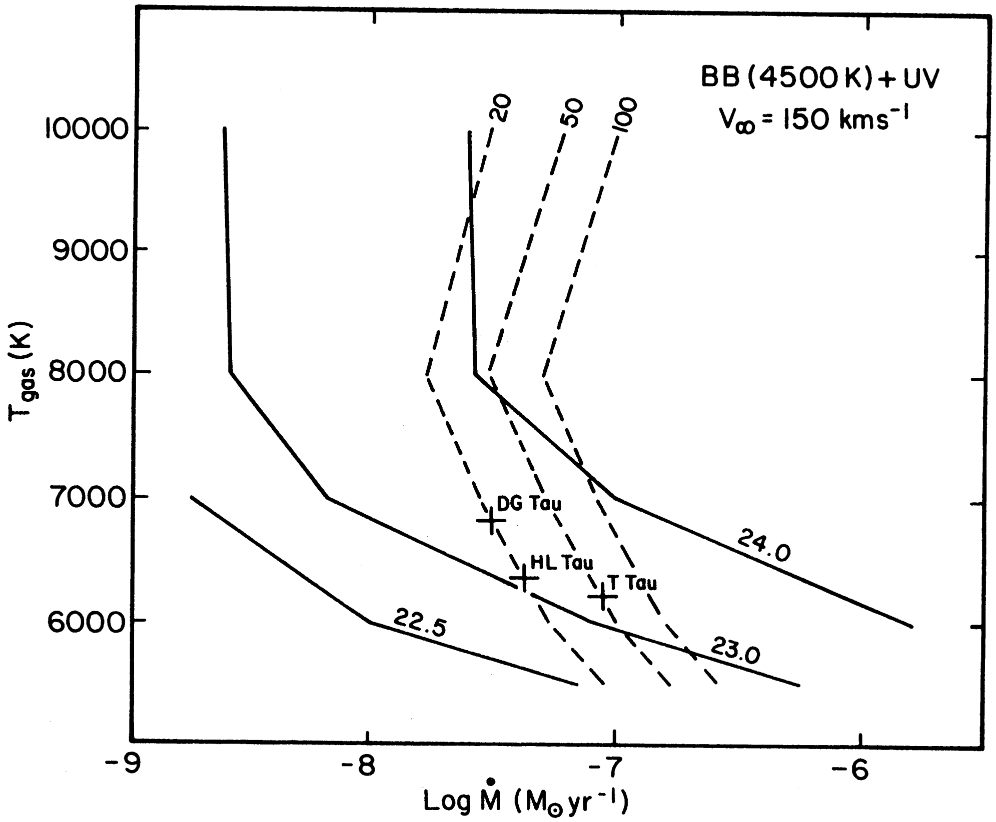

Fig. 2 - The figure shows isocurves in the plane T_{gas}, $\dot{M}$. Solid lines are curves of equal optical depth for the Na I $3S_{1/2}$-$3P_{3/2}$ transition, and are labelled with the value of τ. The dashed lines are curves of equal luminosity in Brγ. The corresponding value of log L(Brγ) in watts is indicated above each line. The crosses show the position of the three objects discussed in the text.

TABLE 1: SOURCE PROPERTIES

	L(Brγ) Watts	τ	T_{gas} K	$\dot{M}$ $M_{\odot}$ yr^{-1}	$\dot{M}$(CO) $M_{\odot}$ yr^{-1}
T Tau	23.12	50	6300	1(-7)	1.5(-7)
DG Tau	23.20	20	7000	3(-8)	no outflow
HL Tau	23.11	20	6400	4(-8)	4(-8)
RY Tau	21.81	<10		<1(-8)	no outflow

These results seem to further validate the *standard* model for these regions. The momentum carried by these stellar winds is comparable to that required by the slow molecular outflows. Moreover, they confirm the existence of rather cold and massive winds around low-luminosity objects, which are mostly neutral all the way to the stellar surface.

IV. Do forbidden lines form in the stellar wind?

The answer to this question is at present uncertain. Recently, Edwards *et al.* (1987) have studied the forbidden line emission in a sample of 12 low-luminosity, pre-main-sequence stars. The expansion velocity they derive is similar to (although generally smaller than) what is measured from the permitted optical lines (H_α, in this case). From the ratio of the two [S II] lines at 6731, 6717 Å, Edwards *et al.*obtain an electron density for the emitting region of the order of 10^4 cm^{-3}. This, together with the values of the emission measure derived from the line intensities, locates the emitting region at 50-500 AU from the central star. The corresponding rate of mass-loss is about 10^{-8} $M_\odot$ yr^{-1} for ten objects, and about 10^{-6} $M_\odot$ yr^{-1} for two, not very different from what is derived from other wind diagnostics.

This agreement would seem to confirm that the forbidden lines form in an outer part of the stellar wind. However, the mass-loss estimates have been obtained by assuming that the gas in the forbidden line forming region is completely ionized and at a temperature of about 10^4 K. Neither of these conditions occurs in the winds we are considering. In particular, radiative losses and adiabatic expansion cool the wind below 1000 K at a distance from the central star well before the forbidden line region (Hartmann and Raymond, 1989). In such a cold gas, collisional excitation occurs at a very low rate; in order to produce the observed line intensity, the size of the emitting region, and therefore the rate of mass-loss, must be much larger than estimated by Edwards *et al.*(1987). A rough evaluation , obtained by assuming that the density derived from the ratio of the two [S II] lines is not very sensitive to the temperature or to the nature of the colliding particles (more likely to be hydrogen atoms than electrons) gives rates of mass-loss of about 10^{-3} $M_\odot$ yr^{-1} for a temperature of 10^3 K.

Since these rates of mass-loss are unreasonably high, we are led to conclude that, in order to produce the observed forbidden lines in the wind, the stellar wind must be re-heated and possibly partly re-ionized at a distance from the star of ~ 100 AU. In this case, the physical conditions of the region may be very different from those of a typical H II region. Mass-loss rates derived from forbidden lines are therefore very uncertain, and so is, at the moment, our understanding of their formation. In fact, it may be more productive to *postulate* that the forbidden lines form in the outer part of stellar winds and use this information to shed light on the heating mechanism of the wind itself. The only work along these lines that I know of has been recently published by Hartmann and Raymond (1989), who propose that the winds are heated at distances of 50-100 AU by oblique shocks against circumstellar discs. While their model seems able to produce enough forbidden line emission, it requires very thick discs (the shock occurs several scale heights above the midplane) and fails to reproduce some of the observed characteristics, such as the ratio of the [O I] to [S II] line intensities.

It is interesting to note that 100 AU is also the typical scale over which radio continuum emission is observed (Cohen, Bieging and Schwartz, 1982; Snell and Bally, 1986; Evans *et al.*, 1987). The radio continuum cannot be due to the inner, mostly neutral wind which emits the IR hydrogen recombination lines (Evans *et al.*, 1987; Natta *et al.*, 1988b; Hamann *et al.*, 1988). It may instead be associated with the region where the forbidden lines form.

V. Is the HI wind the outer part of the stellar wind?

Neutral winds were first suggested to account for the discrepancy between the momentum input from the ionized component of the wind and the momentum estimated for the slow molecular outflow, that we have discussed in section III. The calculations of the ionization fraction of winds around low-luminosity pre-main-sequence stars by Natta *et al.* (1988b) show that indeed most of the mass in the wind is in the form of neutral (possibly molecular; Glassgold, Mamon and Huggins, 1989) gas.

High velocity neutral hydrogen was first detected by Bally and Stark (1983) in NGC 2071 (an intermediate luminosity pre-main-sequence object) and in L1551 and HH7-11 by Mirabel, Cantó and Rodriguez (1983) and Lizano *et al.* (1988).

The most convincing low-luminosity case is HH7-11 (Lizano *et al.*, 1988). The 21 cm line wings indicate an expansion velocity of 170 km s^{-1}. The flow is extended, probably over the same scale as the corresponding CO outflow. The momentum carried by the neutral wind is comparable with the momentum in the molecular outflow. To say that we are observing a neutral stellar wind seems indeed the most natural interpretation of the observations.

However, before concluding that indeed neutral winds are always associated with molecular outflows and stellar winds, and that most of the wind momentum is carried by neutral matter, we need to observe a larger sample of objects. In the 21 cm line, this may turn out to be a difficult task, due to the galactic high-velocity emission itself (Rodriguez and Cantó, 1983).

Koo (1989) has observed what he called *extremely* high velocity wings (EHV) in the CO J = 1-0, J = 2-1, and HCO^+ J = 1-0 spectra of seven young stellar objects, three of which can be defined as low-luminosity objects (HH7-11, L1551 and HL Tau). Again, the best case is HH7-11. The EHV wings have a flat profile, and extend to approximately ±150 km s^{-1} on both sides, similar to the extension of the 21 cm line. Mapping of the source has shown that it is as extended as the slow molecular outflow. At the central position of HH7-11, the momentum contained in the EHV CO flow is about 30% of the momentum contained in the slow molecular outflow.

VI. Conclusions

The picture that is beginning to appear supports the standard model. A fast wind leaves the star, mostly cool. The optical and infrared permitted lines probe the physical conditions in the innermost part of this wind, typically 1-10 stellar radii. At approximately 100 AU from the star, something happens to re-heat the gas, and possibly ionize it again. Alternatively, there is a continuous source of heating, effective on scales as large as 100 AU, that keeps the gas temperature at several thousand degrees. The forbidden lines and perhaps the radio flux originate in this low density, relatively warm region. At even larger distances, the wind cools again. The neutral hydrogen lines and EHV molecular lines that we see map this outer part of the wind, where most of the mass resides. The slow molecular outflow is matter from the ambient cloud, which has been swept up in a momentum-conserving fashion.

As a consequence, credible mechanisms of mass-loss must be able to account for a large range of mass-loss rates, up to very high values. This has always been a major problem for theories (see, for example, De Campli, 1981). The acceleration to terminal velocities of the order of 100-300 km s^{-1} occurs rather slowly, with typical scales of few stellar radii. Moreover, the transfer of momentum to the wind must occur in such a way that the bulk of the matter never reaches high temperatures (we find that in many cases it has to be cooler than ~7000 K). However, at large distances from the star (~100 AU) the gas is warmer than expected if the deposition of energy into the wind only occurs near the star.

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