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NEUTRAL WINDS AND MIXING LAYERS: THE CASE OF L1551

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RESUMEN

Resumimos brevemente las observaciones en la línea de 21 cm realizadas hasta ahora en vientos neutros de objetos de la presecuencia principal. En particular, mostramos los mapas que hemos obtenido de L1551 en Arecibo y el VLA, discutiendo las restricciones que éstos imponen sobre el fenómeno de la eyección. Suponiendo que los flujos de CO son conducidos por vientos rápidos de HI, realizamos un modelo sencillo de capas de mezcla para la incorporación del gas de la nube ambiente, poniendo un énfasis especial en el balance de energía y la estructura térmica resultante en la capa. En particular, encontramos capas de mezcla casi isotérmicas, con temperaturas de 3000–5000 K. Esto se debe a la disipación de la energía cinética del viento y al enfriamiento por el H_2. En el caso de L1551 la emisión del H_2 en la capa de mezcla [$v = 1 - 0$ $S(1)$] se espera que se extienda por los lóbulos de CO y ser detectada por cámaras y espectrógrafos trabajando en el cercano infrarrojo.

ABSTRACT

We briefly report the status of 21cm line observations of neutral winds from PMS objects. We present the mapping of L1551, obtained at Arecibo and VLA, and discuss the constraints put on the ejection phenomenon. Assuming that CO outflows are driven by fast HI winds, we present a simple model of a mixing layer for the entrainment from the ambient cloud with particular reference to the energy balance and the resulting thermal structure of the layer. We find quasi-isothermal mixing layers with temperatures of 3000–5000 K. This results from dissipation of wind kinetic energy and cooling by H_2. In the case of L1551 the H_2 emission from the mixing layer [$v = 1 - 0$ $S(1)$] should be spread over most of the CO lobes and detectable by current NIR spectrographs and cameras.

Key words: **ISM: MOLECULES — LINE: PROFILES — STARS: MASS LOSS — STARS: PRE-MAIN-SEQUENCE**

1. INTRODUCTION

Are large scale molecular outflows the result of entrainment of ambient material by fast winds and jets? Although not definitely established yet, this unifying scenario has gained a relatively wide acceptance and hydrodynamical simulations of the phenomenon are presented in these proceedings by Dyson et al. (1995) and Raga (1995). We present here some modeling of a mass entraining mixing layer with a different perspective. Instead of a selfconsistent approach, we specify a priori the dynamics of the entrainment process by using a plausible model for the kinematics of the neutral wind observed in L1551. By doing so, the problem is greatly simplified and we are able to study in an easy way the energetics of the mixing layer, to derive its temperature radial profile, and to estimate the resulting emission in different tracers.

We will first present a short review of the observations of neutral winds from YSO's in the HI 21 cm line, and in particular of our study of the L1551 wind. Then we introduce our frame of hypotheses and proceed to illustrate the results and predictions for our putative mixing layer. It must be said that the overall geometry of our layer is quite different from those generally modeled in HH jets: first, we consider an initially conical flow instead of a cylindrical one, and, second, both the thickness and the actual entrainment rate in the layer are substantially larger than those usually assumed or computed. Despite all this, the results are similar to what is obtained for jets, both in terms of temperature and of relative importance of the various cooling agents.

2. 21 cm OBSERVATIONS OF NEUTRAL WINDS

Although, especially in low luminosity YSO's, neutral flows are thought to be the driving agent of molecular outflows their direct detections in the 21cm line are rare. This stems mainly from matters of (instrumental) sensitivity and confusion with diffuse Galactic emission. The first detection dates back to 1983, at the VLA, by Bally & Stark in NGC2071. Since then only two "surveys" have been performed, at Arecibo, by Lizano et al. (1988) and by Giovanardi et al. (1992), where survey means that more than three objects were observed. In addition a (marginal) detection in T Tau has been achieved by Ruiz et al. (1992), and a neutral flow around DR21 has been mapped by Russell et al. (1992). In total, 13 sources have been observed with good sensitivity, either at Arecibo, or at the VLA, or both; the situation is summarized in Table 1.

Table 1
21cm HI line observations of neutral winds

Source	*Telescope*	*Detected*
AFGL 961	Arec.	
B335	Arec.	
DR 21	VLA	*
FU Ori	Arec.	
HH 7-11	Arec.+VLA	*
L 1448	Arec.	
L 1551	Arec.+VLA	*
NGC2071	VLA	*
NGC 2264	Arec.	
R Mon	Arec.	
RNO 43 N	Arec.	
RNO 43 S	Arec.	
T Tau	Arec.	*

Out of the five detections (and some have to be definitely confirmed), two pertain to high luminosity sources, DR21 and N2071, where the physics at work could be radically different (recombination winds?). By far the best case, among low luminosity YSO's, is L1551. This is due to its angular extent ($\sim 0.5°$), the nice bipolarity and collimation, the orientation of the flow axis to the line of sight ($\sim 90°$) and to the fact that, being a prototype, it has been widely observed at all λ's with high resolution and sensitivity. The single dish spectra of L1551 have shown the existence of an atomic neutral flow coextensive with the CO outflow, and that the momentum content measured in HI fits nicely with the requirements of a momentum conserving driving of the molecular flow (Giovanardi et al. 1992). Moreover, the shape of the spectra were shown to be inconsistent with a completely free flowing of the atomic gas within hollow lobes, but rather suggestive of the presence of a free flowing section (near the axis) plus a thick decelerating layer along the walls.

The Arecibo spectra at different positions along the axis of the red lobe are reported in Fig. 1, together with the simulations for our best fitting model of the flow. These kinematical models assume that the deceleration is due to mass entrainment and that momentum is conserved, for the rest they are a purely parametric exercise. The best fitting flow was characterized by a cone of free flow with semiaperture 12°, and by a decelerating layer between 12° and 20° with a characteristic braking length (to half the initial velocity) of ~ 1.4 arcmin. Notably, models with high dissociation of the entrained material, and therefore with continuous addition of HI from the walls, did not fit well the observed profiles.

We have recently mapped at the VLA the intermediate velocity counterpart (up to $\sim 50\,\mathrm{km\,s^{-1}}$) of the neutral flow. This is in fact the spectral range which is most difficult to observe at low spatial resolution, due

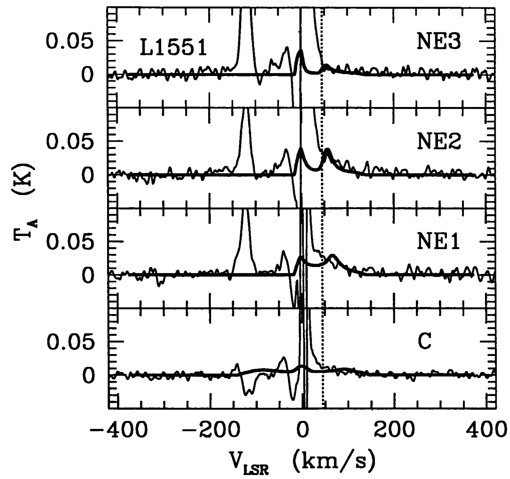

Fig. 1.— Arecibo HI spectra observed at different positions along the axis of the red lobe in L1551 (thin line). The blue side is disturbed by intervening high velocity clouds. The wind shows up as the faint wing on the red side which extends up to 150 km s^{-1}. The wing disappears in NE3 which is taken at the limit of the CO lobe. Also shown are the model spectra (thick line) for our best fitting decelerating flow.

to the fine structure of the Galactic line core. Although the distribution appears quite patchy and irregular, the agreement between the interferometric maps and the single dish spectra (and their models too) is remarkably good.

3. THE TEMPERATURE OF MIXING LAYERS

A fast and massive wind, such as the one actually detected in L1551, is expected to entrain and accelerate material from the surrounding cloud in a mixing layer such as those studied in the context of optical jets, by Cantó & Raga (1991, CR91). As we have seen the HI profiles in L1551 seem to require a decelerating layer along the walls of the cone. One of the most direct explanations is to advocate mass entrainment through the walls with conservation of linear momentum. On the other hand, if one considers that the total kinetic luminosity of the L1551 wind is about 17 $L_\odot$, in order to decelerate it notably, an energy of the order of a few $L_\odot$ has to be dissipated. In absence of efficient cooling mechanisms this could heat the gas and ionize it easily, a situation which is not supported by the observations.

In what follows, we investigate the thermal structure these mixing layers should have, given the wind properties observed in L1551. We consider only a steady-state situation. The overall geometry of the flow is illustrated in Fig. 2. The flow is confined within a cone with opening angle α. Outside the cone ($\theta > \alpha$) is the ambient cloud with mass density profile $\rho_c \propto r^{-\gamma}$, where γ is a constant exponent. Between α and θ_{ent} is the mixing layer, that is, the region where cloud (molecular) material, entrained from the "wall" ($\theta = \alpha$) mixes with (atomic) wind material; θ_{ent} is the inner limit to the entrainment.

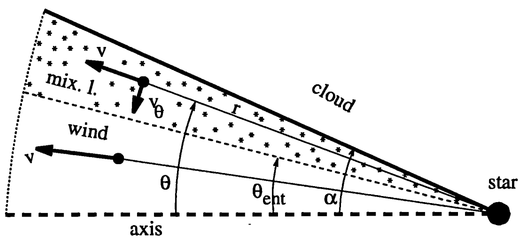

Fig. 2.— Geometry of the conical mixing layer. The flow is confined between the origin and a maximum distance which is equal to the extent of the CO flow. The paraxial region with $\theta < \theta_e nt$ is filled by the unperturbed, radially streaming atomic wind. The outer region, up to the boundary with the ambient cloud is the decelerating mixing layer, where a transversal diffusive velocity is also present.

The radial velocity is $v(r,\theta)$. Note that within the mixing layer the flow is not completely radial. Since the radial flow is highly supersonic, while the transversal transfer is due to a diffusion process, we can assume $v_\theta \ll v$. If v_0 is the wind injection velocity (independent of θ), momentum conservation in the radial direction implies

$$v(r,\theta) = \frac{v_0}{1+\epsilon(r,\theta)}, \tag{1}$$

where we have introduced an entrainment function $\epsilon(r,\theta) \geq 0$. In case of an isothermal cloud with a power-law density profile, $\rho_c \propto r^{-\gamma}$,

$$\epsilon(r,\theta) = \left(\frac{r}{r_{\rm ent}}\right)^{2-\gamma} F(\theta), \tag{2}$$

here $r_{\rm ent}$ is a scale length defining the entrainment efficiency. $F(\theta)$ describes the run with θ, with the constraint $F(\theta_{ent}) = 0$, and depends on the detailed mass transfer in the θ direction.

If $\dot{A}_1$ is the initial mass loss rate per unit solid angle, (independent of θ), the density at each point is given by

$$\rho(r,\theta) = \frac{\dot{A}_1 v_0}{r^2 v^2(r,\theta)} = \frac{\dot{A}_2}{r^2 v^2(r,\theta)}, \tag{3}$$

where $\dot{A}_2$ is the (constant) momentum flux per steradian.

We simplify the model even further by taking a mean velocity and density in the θ direction with $F(\theta) = 0.5$ in equation (2), and then treat the energy equation in a single parcel approximation as a function of radial distance only.

Assuming that all the gas components (atoms, electrons, and molecules) but the dust, have the same temperature, we write the energy equation in the form

$$\rho\,(\vec{v}\cdot\nabla)\,(c_v T) = \Gamma - \Lambda - P\nabla\cdot\vec{v}, \tag{4}$$

here T and P are the gas temperature and pressure, c_v is the specific heat, Γ includes all the heating mechanisms and Λ all the cooling mechanisms. The last term on the right hand side is the adiabatic expansion.

Heating.

Due to mass entrainment, the stellar wind is radially decelerated within the mixing layer and some of the wind kinetic luminosity must be dissipated. A substantial fraction will first excite supersonic turbulent motions in the layer which will be subsequently damped and converted into thermal energy. The entrainment heating function is then given by:

$$\Gamma_{\rm ent} = -\eta\nabla\cdot\left(\rho\vec{v}\frac{1}{2}v^2\right), \tag{5}$$

where η is the fraction of dissipated energy actually available to heat the gas $(0 \geq \eta \geq 1)$.

Cooling.

As cooling sources we have considered:

a) vibrational/rotational emission by H_2;
b) collisional dissociation of H_2;
c) rotational/vibrational emission by molecules with dipole moments;
d) atomic line emission; and,
e) dust continuum emission.

H_2 emission and dissociation. We have assumed that the content of molecular hydrogen in the layer is determined by a balance between injection of fresh H_2 from the cloud (i.e. the entrained material) and collisional dissociation. Assuming that all the entrained material is molecular, the H_2 injection can be easily derived from equations (1) and (3). The dissociation rate is a function of temperature, of the HI density, and of the H_2 density.

Molecules with dipole moments. Molecular cooling functions were computed in an optically thin approximation.

We consider rotational transitions of ^{12}CO, ^{13}CO, HD, H_2O, OH, and HCl. We also included vibrational cooling by H_2O and vibrational cooling via the excitation of the $v = 1$ state of OH.

Atomic Cooling. We include in this single term all the line and continuum emission by relevant atoms and ions. This depends on temperature, atomic density, and electron density (or ionization fraction). We have assumed that both atoms and ions are only contained in the atomic fraction of the gas; the atomic content at a certain radius is contributed by the original wind plus the dissociated entrained material. The only processes considered to estimate the electron density were hydrogen collisional ionization from ground level and radiative recombination. We then write a continuity equation for the electrons in the form:

$$\nabla \cdot (n_e(r)\ \vec{v}(r)) = \mathcal{C}_{eH}(r) - R_{eH}(r) \quad , \tag{6}$$

$\mathcal{C}_{eH}$ is the collisional ionization and R_{eH} is the recombination rate to all levels but n=1.

Cooling by dust. In our models the dust turned out to be substantially cooler than the gas. The dust temperature $T_g r$ in the mixing layer is computed including collisions with gas particles (including non-thermal motions), and allowing for diffuse background radiation as well as diluted stellar radiation. We assume: *i*) that the original stellar wind contains no dust; *ii*) that no dust grains condense in the flow; *iii*) that grains are not sputtered and destroyed.

Considering the above heating and cooling sources, and with our flow model, the radial temperature profile $T(r)$ of the mixing layer was determined by integrating the system composed by: *i*) the thermal energy equation, eq. (4); *ii*) the continuity equation for the molecular mass density, ; *iii*) a similar continuity equation for the dust content; *iv* the continuity equation for the electron density, eq. (6); and *v*) the dust temperature equation.

4. RESULTS

The following calculations were performed for a mixing layer with the parameters reported in Sect. 2 as the best estimates for L1551. The gas temperature in the mixing layer depends on which fraction of entrainment energy goes into heating the gas; for the factor η in equation (5) we considered two possible values: $\eta = 0.5$ (equipartition between thermal and turbulent energy), and $\eta = 1.0$ (no turbulence). Figure 3 shows the run of

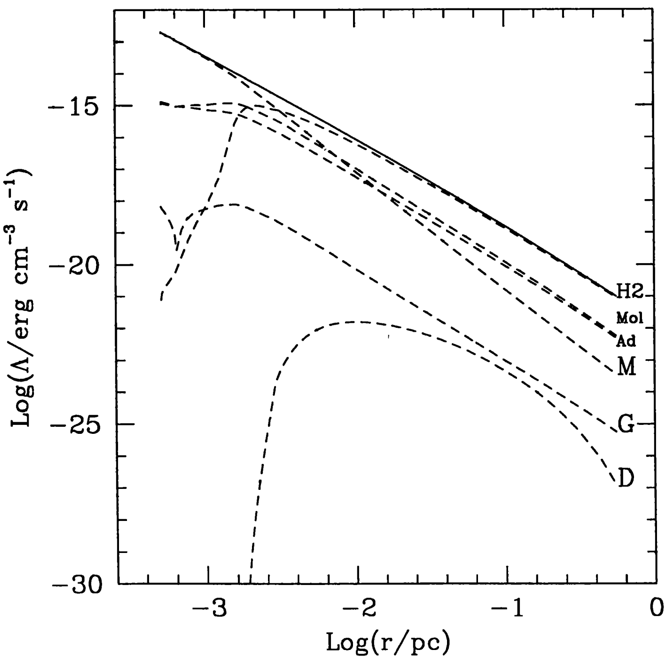

Fig. 3.— Heating and cooling functions for $\eta = 0.5$ and the flow parameters assumed in L1551. The solid line is the entrainment heating. The dashed lines represent the various contributions to cooling: (H2) molecular hydrogen lines; (Mol) radiation from heteropolar molecules; (Ad) adiabatic expansion; (M) atomic radiation by H, He, and metals; (G) dust radiation; (D) dissociation of H2.

the various cooling functions as a function of the distance to the star. H_2 line emission is the dominant coolant in the mixing layer. This is true everywhere but for the very inner part of the flow ($r < 3 \times 10^{-3}$pc) where it is exceeded by atomic radiation. This results from the hypothesis of a fully atomic wind; the rapid decay of atomic radiation is mainly due to the lowering of the electron density with r. As expected, the ionization fraction freezes out, to $x_e \sim 5 \times 10^{-4}$, when the density has dropped below 10^6 cm^{-3}, that is at a distance $r \sim 10^{-3}$ pc. There are several reasons for the preponderance of H_2 cooling: *i*) given the conditions of low density in the mixing layer, collisional dissociation of H_2 is suppressed by radiative stabilization of the population of high vibrational levels (Lepp & Shull 1983), *ii*) the wind radial crossing time is short compared to the H_2 dissociation time and, *iii*) fresh molecular material is entrained at each radius. Notably, the entrained material remains almost completely molecular and the molecular fraction increases with r due to the low dissociation and the replenishment by entrainment.

The energy balance results in the temperature profiles shown in Fig. 4. The upper panel shows the gas temperature as a function of distance to the source. Independently of the initial temperature, the mixing layer achieves rather constant temperatures of a few thousand degrees. Instead, the dust (lower panel) remains cold because collisions with gas particles are quite inefficient at such densities. This particular model assumes a background field temperature $T_B = 3$ K, no stellar radiation, and a sticking approximation for the gas-dust coupling. The sticking coefficient is here $\sim$ 0.05, which is the one for HI on graphite grains estimated at temperatures of some thousand degrees (Leitch-Devlin & Williams 1985). The solid curve is for a heating factor $\eta = 0.5$, and the broken one for $\eta = 1.0$ in equation (5). For a maximum sticking coefficient ~ 1 and including the effect of stellar radiation, the dust warms up to $\sim$ 15K but, due to the effective H_2 line cooling, the gas temperature is not sensitive to it.

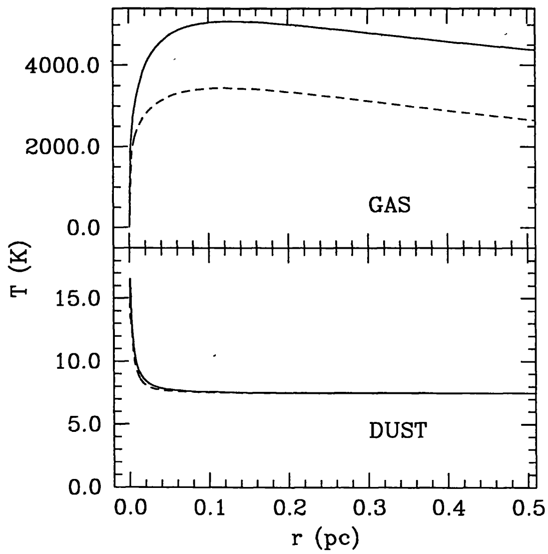

Fig. 4.— Gas and dust temperature, averaged in θ, vs. r in the mixing layer Solid lines for $\eta = 1$, dashed for $\eta = 0.5$. Note the different vertical scale in the two panels. The result is a quasi-isothermal mixing layer.

We can now estimate the extended H_2 line emission in the mixing layer of L1551. The H_2 emission in the vibrational transition $v = 1 \rightarrow 0$ S(1), integrated over the whole mixing layer of a single lobe, is $L_{1->0} = 0.16 - 0.35 L_\odot$, depending on the value of η. At a distance of 140 pc for L1551, this implies a flux, $F_{v=1\rightarrow 0} \sim 15 \times 10^{-10}$erg s^{-1}cm^{-2}. This flux is emitted over almost all of the intercone region which has an extension of $\sim$ 36 arcmin^2 in the sky. This diffuse emission is within the detection limits of current NIR spectrographs and cameras (if extinction permits). The emission in the $v = 2 \rightarrow$ 1S(1) line results to be considerably lower, less than half the one in the $v = 1 \rightarrow$ 0S(1) line.

5. CONCLUSIONS

It has been proposed that high velocity molecular outflows may be due to entrained material in the wake of the bow shock of a collimated jet (Raga & Cabrit 1993; Masson & Chernin 1993; Chernin et al. 1994, Raga et al. 1994). Observations of bright molecular hydrogen 2.122 μm emission associated to HH objects (see e. g. reviews of Lane 1989; Curiel 1992; Eislöffel et al. 1994), and young molecular outflows (e.g. Bally, Lada & Lane 1993; Bally et al. 1993) seem to agree qualitatively with this model. In contrast, the model studied in this work corresponds to a well developed, extended mixing layer of the type first studied by CR91, that would correspond to what is observed as the CO lobe in the source L1551. This source, which is a prototype of the CO outflow sources, has extended CO lobes and an observed atomic wind such that the HI line profiles can be reproduced by a freely flowing conical stellar wind plus an extended zone of deceleration, and is therefore more naturally explained in terms of the model presented here. As discussed above, this type of mixing layers should produce a faint, but detectable, extended H_2 emission.

Finally, in a recent work, Taylor and Raga (1994) modeled the chemistry of a plane mixing layer of the type studied by CR91. They found that the layer has a very high temperature $\sim 10^4$ and emits mostly in vibrational and rotational lines of H_2. At the end, as the mixing layer increases in width, the energy of the entrainment process is deposited in a larger area and the temperature drops to thousands of degrees. This result is in agreement with our model which considers a rather wide mixing layer. Their model then applies to objects with thinner (and shorter) mixing layers, hence closer to the central source, while ours is more apt to describe sources with more extended and developed mixing layers.

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