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# THE OPTICAL SPECTRA OF ATOMIC/IONIC MIXING LAYERS

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RESUMEN

Calculamos el cociente de líneas [O I] 5577/6300 Å sensible a la temperatura, emitidas en capas de mezclado turbulentas como los esperados en la interfaz entre el flujo supersónico de un Herbig-Haro y el medio ambiente estacionario.

ABSTRACT

We calculate the temperature sensitive [O I] 5577/6300 Å line ratio emitted by the turbulent mixing layers which is expected to form at the interface between the supersonic flow of an Herbig-Haro jet and the stationary ambient medium.

*Key Words:* **ISM: JETS — LINE: INTENSITIES — STARS: FORMATION**

## 1. BACKGROUND

It has been previously suggested on kinematical grounds that at least part of the emission from Herbig-Haro (HH) objects might be produced in turbulent mixing layers associated with high velocity outflows. In order to explore this possibility, we compute 1D models of the temperature and ionization cross sections of mixing layers between a high velocity flow and a stationary environment (both the jet beam and the environment being atomic). A more detailed description can be found in Binette et al. (1999) and references therein. See also Raga & Cantó (1997).

## 2. EQUATIONS FOR A TURBULENT MIXING LAYER

For the case of a thin, steady state, high Mach number, radiative mixing layer, the advective terms along the direction of the mean flow can be neglected with respect to the corresponding terms across the width of the mixing layer. Under this approximation, the momentum and energy equations can be written as:

$$\mu \frac{d^2 v}{dy^2} = 0 \,, \tag{1}$$

$$\kappa \frac{d^2 T}{dy^2} + \mu \left( \frac{dv}{dy} \right)^2 = L \,, \tag{2}$$

where $y$ is a coordinate measured from the jet beam into the mixing layer, $v$ is the mean velocity (directed parallel to the jet beam), $L$ is the radiative energy loss per unit volume, and $\mu$ and $\kappa$ are the turbulent viscosity and conductivity, respectively (which are assumed to be constant throughout the cross-section of the mixing layer). Equation (1) can be integrated to obtain the linear Couette flow solution

$$v(y) = v_{jet} \, (1 - y/h) \,, \tag{3}$$

where $v_{jet}$ is the jet velocity, and $h$ is the local width of the mixing layer. This solution can be substituted in equation (2), which can then be integrated to obtain the temperature cross-section of the mixing layer. Raga & Cantó (1997) integrated this equation analytically with an idealized energy loss term. In order to obtain more concrete predictions from this model, we now compute a realistic radiative energy loss term. We consider the equations governing the fractional abundance $f$ of each species. This abundance satisfies the equation:

$$D\frac{d^2 f}{dy^2} = S_f\,, \tag{4}$$

where $S_f$ is the net sink term of the species (including collisional ionization, radiative and dielectronic recombination, charge transfer... and processes which populate the current species) and $D$ the turbulent diffusivity which is assumed to be position-independent. To complete the description of the mixing layer, we require lateral pressure equilibrium (which determines the density of the flow as a function of $y$), and calculate the turbulent viscosity with a simple, mixing length parametrization of the form:

$$\mu = \alpha\,\overline{\rho}\,\overline{c_s}\,h\,, \tag{5}$$

where $\overline{\rho}$ and $\overline{c_s}$ are the density and sound speed (respectively) averaged over the cross-section of the mixing layer, $h$ is the local width of the mixing layer, and $\alpha \approx 0.007$ is a constant (with a value determined from fits to experimental results by Cantó & Raga 1991). Considering that the turbulent conduction and diffusion Prandtl numbers are of order one, we can compute the conduction coefficient as $\kappa \approx \mu c_p$ (where $c_p$ is the heat capacity per unit mass averaged across the mixing layer cross-section) and the diffusion coefficient as $D \approx \mu/\overline{\rho}$.

In this way, we obtain a closed set of second order differential equations (2 and 4), which can be integrated with a simple, successive overrelaxation numerical scheme. The source terms for the atomic/ionic rate equations (4) and the calculation of the radiative cooling (equation 2) were computed with the MAPPINGS code (described in detail by Binette & Robinson 1987). We assume that the abundances of the elements included in the models (H, He, C, N, O, Ne, S, Fe) are solar. In order to be able to compute solutions to the mixing layer problem, it is necessary to specify the width $h$ of the mixing layer, the jet velocity $v_{jet}$, and the temperatures, ionization states and pressure of the jet and the surrounding environment.

## 3. RESULTS

TABLE 1

MODEL PREDICTED [O I] 5577/6300Å EMISSION LINE RATIOS

| $h$ (cm) | $v_{jet}$ (km s$^{-1}$) | $n_{amb}$ (cm$^{-3}$) | [O I] line ratio |
|---|---|---|---|
| $2.14\,10^{11}$ | 200 | $10^6$ | 0.059 |
| $6.78\,10^{11}$ | 200 | $10^6$ | 0.047 |
| $2.14\,10^{12}$ | 200 | $10^6$ | 0.037 |
| $6.78\,10^{12}$ | 200 | $10^6$ | 0.025 |
| $2.14\,10^{13}$ | 200 | $10^6$ | 0.030 |
| $6.78\,10^{13}$ | 200 | $10^6$ | 0.020 |
| $2.14\,10^{14}$ | 200 | $10^6$ | 0.017 |

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