TURBULENT MIXING LAYERS IN HERBIG-HARO AND EMBEDDED H_2 JETS

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Abstract. Outflows arising from young stellar objects interact with their surrounding medium through different mechanisms, such as shocks, turbulence and /or entrainment. These two last mechanisms have recently begun to be fully developed in an effort to understand the coupling of the stellar jet gas (mostly atomic) with the molecular environment. Observationally a number of objects are being studied in the near infrared and millimeter wavelengths to map the warm (H_2) and cold (CO) molecular gas, respectively. In this paper we discuss some of the properties in the near infrared of various embedded jets in the context of turbulent entrainment.

1. Introduction

A large fraction of the energy released by stellar jets in their surrounding medium is produced by the collisional excitation of the gas. We associate this excitation process with shocks, but turbulence and entrainment are processes which dissipate energy in a similar way (Taylor & Raga 1995). Most non-adiabatic 2-D hydrodynamical simulations of jets show how the stellar jet engulfs and pushes the surrounding molecular gas at the front and the sides, i. e. entraining it. The gas in a stellar jet is typically at a temperature of 10^4 K, while the molecular gas can be at a temperature of 100 K or lower. In the interaction of the hot atomic gas with the cold molecular gas, there must be a region with "intermediate" properties in chemical composition, temperature and velocity, i. e. a mixing layer where the atomic and molecular gasses meet.

In some optical Herbig-Haro (HH) jets (e.g. HH 1-2, HH 7-11) the morphology is very similar in the atomic lines (Hα and [S II] $\lambda\lambda$6717/31) and

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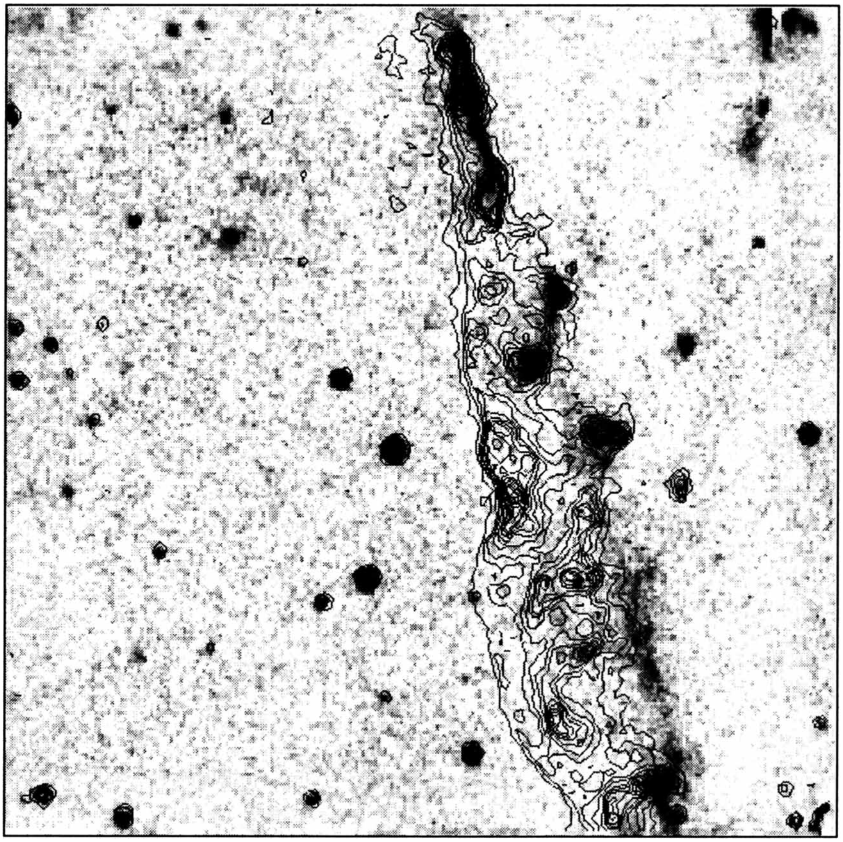

Figure 1. The HH 110 jet in Hα (contour) and H_2 2.121 μm emission (grayscale) in a 2′ field.

the molecular hydrogen lines in the near infrared (e.g. 1-0 S(1) 2.121 μm). Furthermore, there is a growing number of embedded jets without optical counterparts, which look very well collimated and closer in shape to the optical jets than to the CO outflows. The morphological similitude prompts various questions, for instance: is the H_2 emission observed in HH jets produced in a mixing layer? Are the highly supersonic optical jets coupled with the CO molecular outflows through turbulent entrainment? What are the physical properties and emitting characteristics of a mixing layer? We do not have yet definitive answer for these questions, but see e. g. Chandler & Richer (1997) and Raga (1995) for some observational and theoretical arguments in favor of this picture.

The numerical and analytical models for mixing layers along the jet beam show that the layer is thin, long and with small column densities

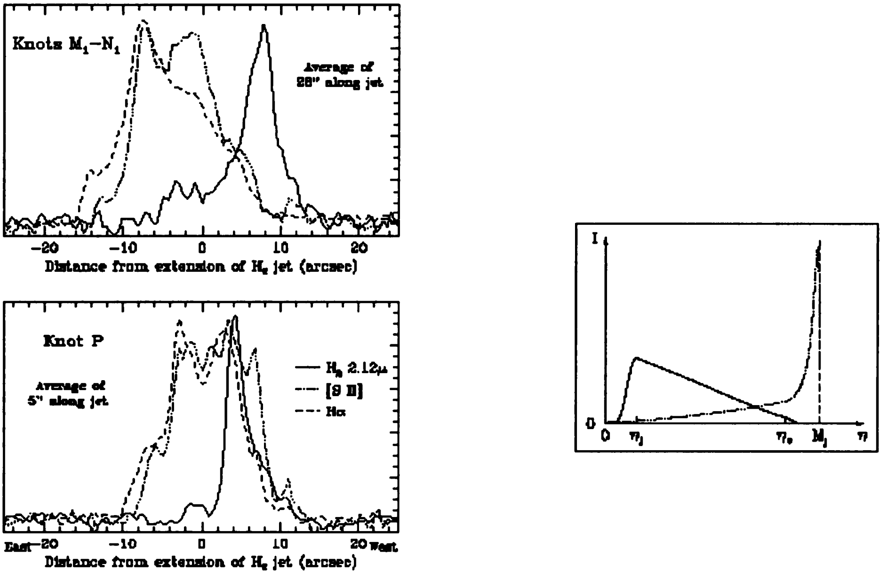

Figure 2. The observed (left) and predicted (right) spatial intensity distribution across two knots (M-N & P) of the HH 110 jet in Hα, [S II] and 2.121 μm(see for details Noriega-Crespo et al. 1996).

(Taylor & Raga 1995), which perhaps is not the best general model for a large CO outflow, but similar to some of the observed molecular hydrogen jets. In this paper we look at the HH 110, IRAS 05487+0255 and Cep E jets in the near infrared (spectroscopy and images), in order to gather more data to enrich and better constrain the theoretical models of turbulent mixing layers.

2. The HH 110 Jet

The HH 110 jet has some characteristics that suggest a good starting point to search for the effects of entrainment and turbulence, since the jet has a turbulent optical morphology (Reipurth & Olberg 1991, Reipurth et al. 1996). The lack of an obvious source along its axis may be explained as if the jet originates in a grazing jet-dense cloud core collision (Raga & Cantó 1995). Even more remarkable is the fact that its H_2 emission (Davis et al. 1994) is narrow and "straight", and shifted towards the west (see fig 1) with respect to the optical Hα and [S II] emission (Noriega-Crespo et al. 1996).

Furthermore the ratio of the (1,0) 2.121 to (2,1) 2.248 μm lines, which is a measure of the excitation of the gas, does not remain constant along the jet condensations, i. e. the excitation is not uniform as could be the case for shocks with a similar velocity.

It is possible to study the spatial intensity distribution of the optical and H_2 emission across and along the jet, and to compare them with simple analytical models of the cross section of a two-dimensional mixing layer. For instance, the fraction of H_2 across the mixing layer should reach a maximum value near the molecular cloud ($\sim$ 1) and it should decrease linearly to a minimum value closer to the atomic jet ($\sim$ 0) (Cantó & Raga 1991). The emission from this layer then should reflect directly this hydrogen fraction, since its structure across is essentially isothermal and in transverse pressure equilibrium (Cantó & Raga 1991). This means that the Hα emission peaks close to the edge of the jet beam and that the $H_2\,(1,0)$ S(1) peaks close to the interface between the mixing layer and the undisturbed molecular environment (Noriega-Crespo et al. 1996). This is the tendency observed in knots M-N and in a less pronounced way in knot P (see fig 2).

3. The IRAS 05487+0255 Jet

Fifty arcseconds west from HH 110 there is a remarkable object that we have named the IRAS 05487+0255 jet because it is near that infrared source. The jet is not visible at optical wavelengths, but is clearly detected in the near infrared. At 2.121 μm the jet (and counter-jet) are very well collimated with a length-to-width ratio $\sim 10 - 20$ (see fig 3). The spectra of the jet and counter-jet in the K-band show a few H_2 emission lines. Perhaps the most noticeable property of the spectra is the shift in radial velocity of the 1-0 S(1) 2.121 μm line (see fig 4). The radial velocities based on this line for the jet and counter-jet are $\sim -275 \pm 50$ km s^{-1} and $\sim 180\pm50$ km s^{-1} respectively. These velocities are comparable to the radial and flow velocities measured in other *optical* jets using the atomic emission lines. This result suggests that at least in IRAS 05487+0255 the molecular hydrogen is moving at a velocity comparable to that of the atomic jet gas.

The H_2 emission of the entire jet extends for at least 40$''$ or $\sim$ 0.1 pc at the distance of Orion. If the flow velocity is comparable to that of the radial velocities, then the dynamical age of the system is quite short ($\sim$ 500 yrs), consistent with a young jet arising from an embedded source. The high degree of collimation of the molecular gas, the short dynamical age and the magnitude of the radial velocities are consistent with the properties expected in a turbulent mixing layer (Garnavich et al. 1997).

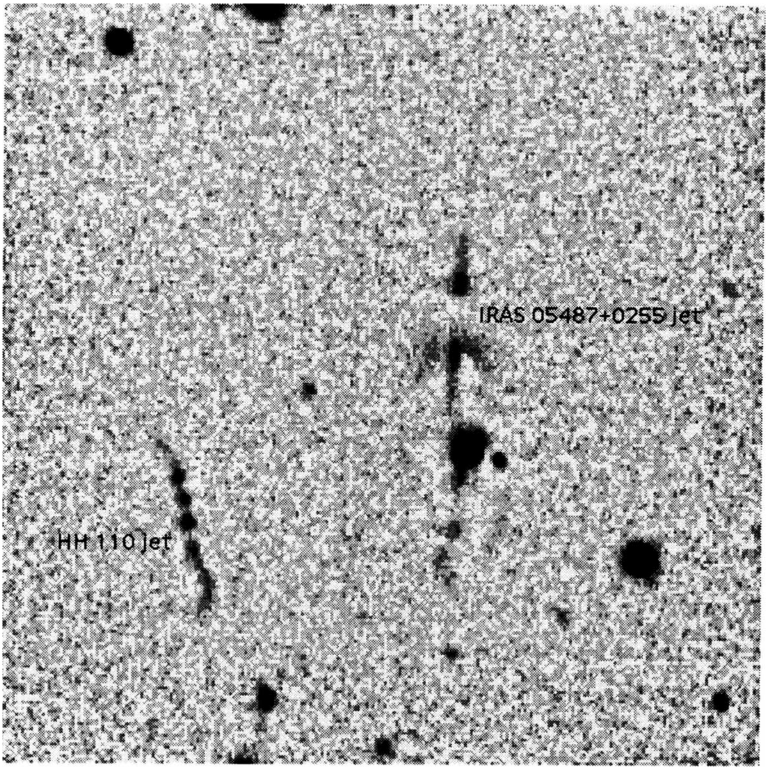

Figure 3. The IRAS 05487+0255 jet (center) in the H_2 2.121 μm line; the HH 110 jet is east (left). The field is $2'$.

4. The Cepheus E Outflow

The two previous outflows seem to be particular examples where it is possible to infer the presence of entrainment in a mixing layer by observing the molecular hydrogen gas. One would like to compare these tendencies with those from some other embedded outflows. In this sense the Cepheus E bipolar outflow is a good candidate, since at visible wavelengths, e. g. Hα and [S II], only a bright south knot is detected (now called HH 377 - Devine et al. 1997), while in the near infrared (Hodapp 1994; Ladd & Hodapp 1997; Eislöffel et al. 1996) there is a well defined bipolar flow (see fig 5).

The images taken at the different molecular hydrogen lines show a complex structure (Eislöffel et al. 1996), and the K-band spectra indicates a higher excitation than that expected in C-type shocks, at least in the best fitted model (Ladd & Hodapp 1997). We obtained H and K-band spectra of both the South and North outflow components to try to detect any possible

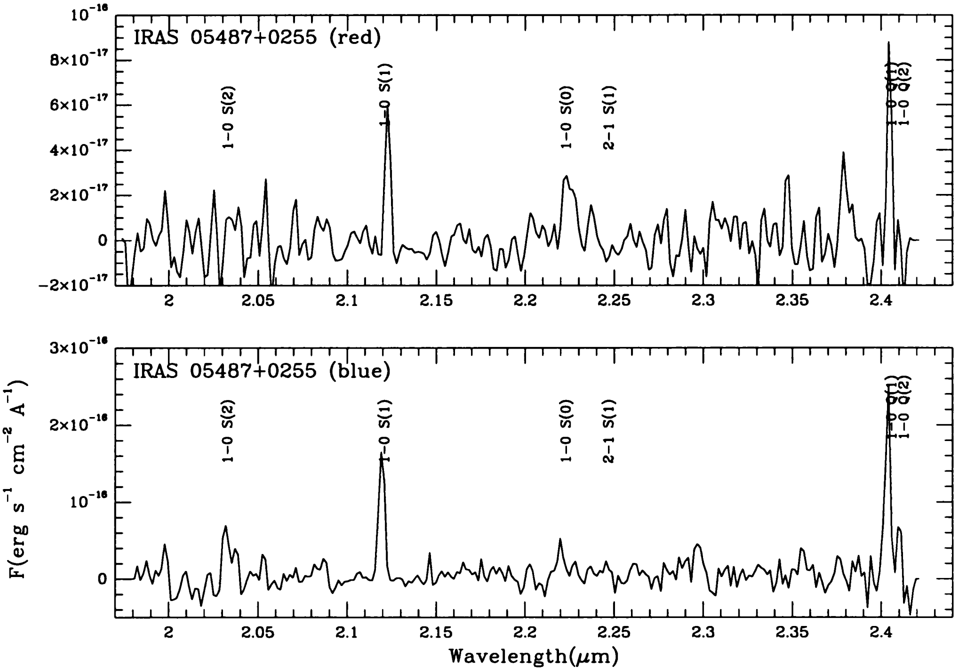

Figure 4. The IRAS 05487+0255 jet & counter-jet K-band spectra.

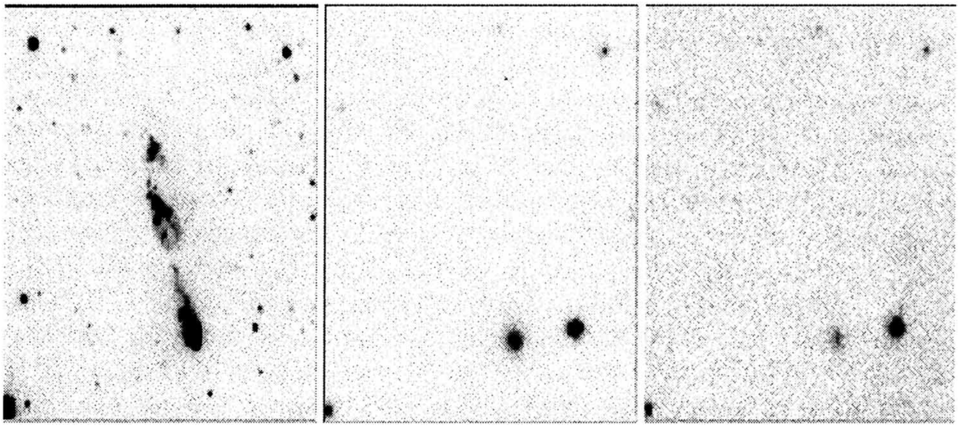

Figure 5. Cepheus E in the NIR at 2.212 μm (left), and at optical wavelengths, [SII] $\lambda\lambda$6717/31 (center) and Hα (right). The field is $\sim 2'$.

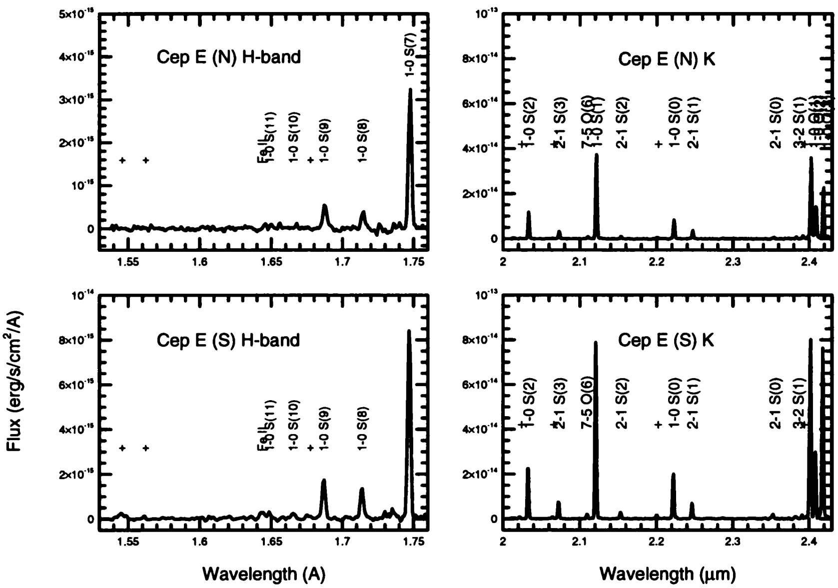

Figure 6. The spectra of the north and south Cepheus E outflow components in the H and K bands.

shift of the brightest lines.

The spectra were obtained with the same set-up and resolution as for the IRAS 05487+0255 jet, and were calibrated in the same way. The spectra (see fig 6) also have a higher signal-to-noise, so in principle it should be possible to detect shifts $\geq$ 50 km s^{-1}, which corresponds to a measurement of $\sim$ 1/3 of a pixel. In the case of Cep E, it was difficult to detect a radial velocity shift for the individual north and south components. Nevertheless it is possible to measure a relative shift between the two outflow components of $\sim$ 110 km s^{-1}. From the morphology the flow is not far from the plane of the sky, and at a first approximation, the relative radial velocity is of the order of the relative flow velocity. Essentially the molecular hydrogen gas in Cep E seems to be moving at a velocity of $\sim$ 50 km s^{-1}, i.e. higher than the 30 – 40 km s^{-1} dissociation shock velocity. If shocks are not driving the bulk of the motion of the molecular hydrogen gas in Cep E, then the alternative is that some of it is being excited and entrained by turbulence at the mixing layer.

5. Summary

We have presented observations in the near infrared of three different jets which have different morphological characteristics. For the HH 110 jet the analysis of the spatial intensity distribution of the Hα, [S II] and H_2 emission can be explained in the context of a turbulent mixing layer. For the IRAS 05487+0255 jet the narrowly collimated H_2 emission and the large radial velocities of their beams ($\sim$ 100 km s^{-1} suggest again the presence of a turbulent mixing layer. And finally in the Cep E outflow the H_2 could be moving at velocities of $\sim$ 50 km s^{-1}, which are difficult to explain by shock acceleration, but more easy to understand as the result of entrainment by the fast moving gas beam of the jet.

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