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Potential of a combined optical/NIR diagnostics for protostellar jets

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Abstract. The possible existence of supersonic protostellar jets around Brown Dwarfs can shed light on obscure aspects of their formation mechanism. To study this subject one has to start from a firm knowledge of the properties of jets associated with solar-mass stars. We have studied recently the conditions of the plasma along a number of classical stellar jets through a combined optical-infrared diagnostics, applied to moderate spatial/spectral resolution spectra (taken with 3.6m-EFOSC2 and NTT-SOFI). From the fluxes of the emission lines in the range 0.6-2.5 μm we have derived important parameters such as the variation of the visual extinction along the flow, the electron and total density, the ionization fraction, the electronic temperature and the mass flux in the jet channel. Moreover, combining the optical and NIR information we have investigated the relative spatial distribution of the emission lines, and the depletion of emitting refractory species such as Calcium, Carbon and Iron, that are related to the presence of dust in the flow. Results of this kind are very useful for planning observations to identify jets from Brown Dwarfs and analyse their properties.

Key words. ISM: jets and outflows – Stars: Formation – Spectral diagnostics

1. Introduction

We have observed a sample of classical Herbig-Haro (HH) jets from young stars (HH 1, HH 34, HH 83, HH 111, HH 24J, VELA-irs8) in a wide spectral range from 0.6 to 2.5 μm taking spectra with 3.6m-EFOSC2 and NTT-SOFI (R ~ 600). This optical/NIR range comprises transitions from atomic, single ionized and molecular species which have different excitation temperatures and critical densities. Density and temperature stratifications are expected to be present in the interior of stellar jets, as a result of the action of compressing shocks (Hartigan et al. 1994). Our combined diagnostics allows to investigate such variations (Sect. 2). We also observed emission from refractory species like Calcium, Carbon and Iron, and derived some information about the presence of dust in the flows (Sect. 3). Finally we inferred the mass flux in the jets, which is a fundamental parameter for the jet dynamics (Sect. 4). In the following we con-

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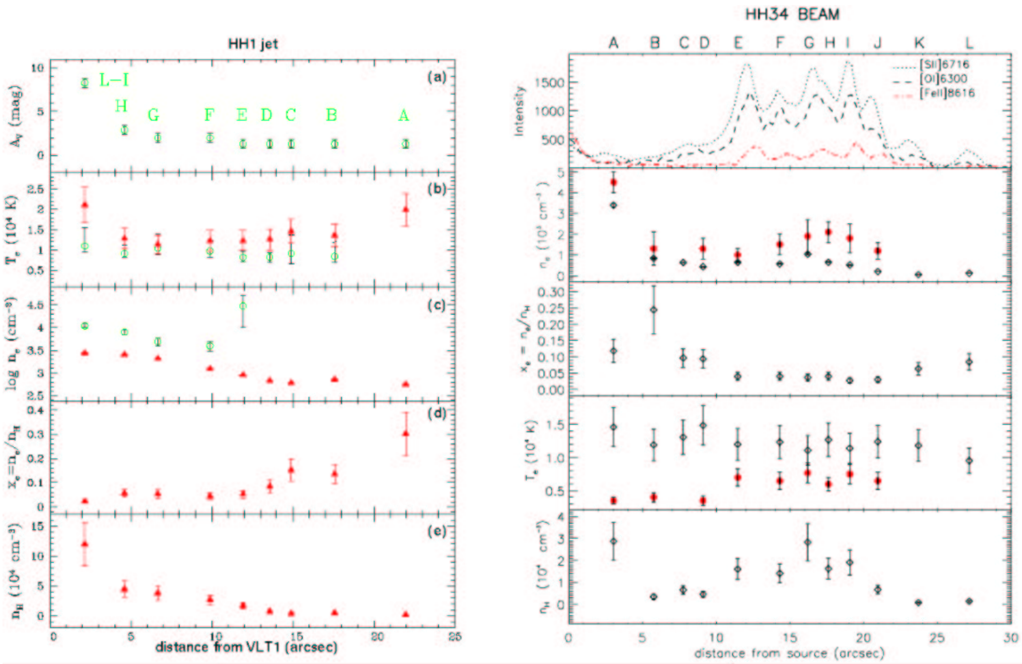

Fig. 1. Variations of the physical parameters along the HH 1 and HH 34 jets. The circles indicate the values derived from [FeII] lines, which trace the denser and cooler portion of the post-shocked gas; the triangles are the values derived from optical S^+, O^0, N^+ lines.

centrate on the results obtained for two well-known objects in our sample: HH 1 and HH 34.

2. Derivation of the physical parameters

Our combined optical/NIR diagnostics allows us to determine the physical parameters of the gas in the various knots seen along the beam. From the ratios between infrared [FeII] lines coming from the same upper level ([FeII] 1.64/[FeII] 1.25 and [FeII] 1.64/[FeII] 1.32) we estimate the visual extinction A_V along the jet; this parameter is fundamental for a combined diagnostics because we use ratios between lines distant in wavelength. The optical [SII], [NII] and [OI] transitions originate from similar regions at intermediate temperatures, T_e, and ionization fractions, x_e, among those found behind a shock-front. Using these lines we determine the physical conditions of the gas (T_e, x_e, the electron and total density n_e and n_H) in the region of optical emission, with the so called BE tecnique (Bacciotti & Eislöffel 1999). For the HH 34 and HH 1 jets we found values of T_e between 8000 and 25000 K, ionization fractions of $0.01 \div 0.3$, electron density of $10^2 \div 3 \cdot 10^3$ cm^{-3} and total density of $10^3 \div 3 \cdot 10^4$ cm^{-3}. Using then both optical and infrared [FeII] lines one can determine in an independent way the values of n_e (from [FeII] 1.64/[FeII] 1.60 and [FeII] 1.64/[FeII] 1.53) and T_e (principally from [FeII] 1.64/[FeII] 0.86) in the region of Iron emission (Nisini et al. 2002, Pesenti et al. 2003). In Fig. 1 we show that along both HH 34 and HH 1 the values of n_e determined through [FeII] lines are higher than those coming from the optical lines (n_e([FeII]) $\sim 10^3 \div 10^4$ cm^{-3}), while the values of T_e are lower (T_e ([FeII]) $< 10^4$ K). This is consistent with the fact that in the post-shocked regions [FeII] lines trace a component of the gas denser with respect to the component traced by the optical lines. However, the dereddened ratios [FeII] 7155/[FeII] 8617 (Hartigan

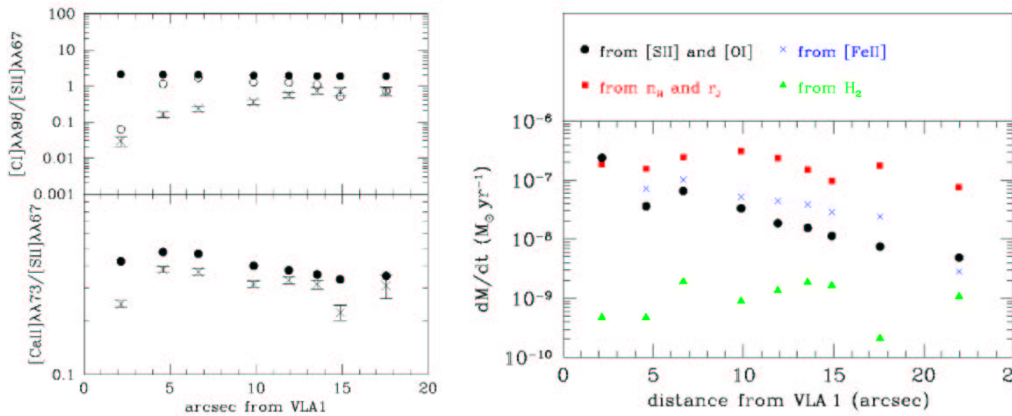

Fig. 2. *Left:* ratios between lines of refractory (Ca and C) and non-refractory (S) species in the knots of the HH 1 jet. Crosses are dereddened observed values; filled circles are the predicted ratios assuming solar abundances and all Calcium in Ca^+ and all Carbon in C^0 forms; open circles refer to the predictions computed with C^0/C^+ fraction given by ionization equilibrium analysis. The discrepancy between the observed and the predicted ratios is attributed to C and Ca depletion. *Right:* mass fluxes in HH 1 computed with two methods: (i) through the estimated total density (ii) through the luminosity of different lines (see text).

et al. 2004, Bautista & Pradhan 1998) and CaII 8542/[CaII] 7290 indicate the presence of even denser material in the beam of both jets ($n_e \sim 10^5 \div 10^6$ cm^{-3}).

3. Dust along the jets ?

Dust grains play a central role in the chemistry of interstellar medium and in many processes related to the observation of star formation regions (light polarisation, visual extinction) and to the formation of stars and planets themselves (as the disk evolution). The properties of interstellar dust, however, are not very well known. According to current theories of dust structure, the grains are expected to be completely destroyed by jet shocks. In this way all the atoms of refractory species should be released in gaseous form and their abundances should be close to solar. Our analysis offers a mean to check the validity of this statement. Through the comparison between observed and predicted emission of lines from refractory and non-refractory species we can infer if Calcium, Carbon and Iron are depleted with respect to the solar abundances. Indeed we found that a fraction of these atoms is still locked on grains (see Fig.2 for the depletion of Ca and C along the HH 1 jet). Therefore, it appears that the weak shocks along the beam are not able to completely destroy the dust. This may have important implications for the studies of dust structure (Böhm & Matt 2001).

4. Mass flux and jet dynamics

The mass flux ($\dot{M}_{\rm jet}$) is a very important parameter for all jet theories, as it governes all aspects of jet dynamics. For example, in the magneto-hydrodynamic models proposed to explain the generation of jets, the ratio between the accretion rate of mass from the disk onto the star ($\dot{M}_{\rm acc}$) and the ejection rate of mass from the star/disk into the jet is fixed ($\dot{M}_{\rm jet}/\dot{M}_{\rm acc} \sim 0.01 \div 0.1$). Moreover, using an estimate of the mass flux rate one can determine the flux of angular and linear momentum carried by the jet. These quantities define, respectively, the capability of the jet of extracting the excess angular momentum from the star-disk system and of accelerating surrounding molecular flows (Königl & Pudritz 2000). We determine $\dot{M}_{\rm jet}$ in two ways. In the first method we use our determination of n_H in combination with the jet radius r_J and total velocity v_J derived from Hubble Space Telescope (HST) data (Reipurth et al. 2000). In this case one has to assume that the knots are uniformely filled with gas at the physical conditions determined by the diagnostics, which may lead to an overestimation of the mass flux. With the second method $\dot{M}_{\rm jet}$ is determined by comparing the absolute line luminosity observed in one knot with calculated predictions (Hartigan et al. 1994). With this method we implicitely take into accout the real filling factor in the beam, but this estimate is affected by the uncertainties in the flux calibration, visual extinction and distance. In summary, we obtain for HH 34 and HH 1 $\dot{M}_{jet} \sim 5 \cdot 10^{-8}$ $M_\odot$ yr^{-1} for the atomic component. From H_2 lines we then deduce that the mass flux carried by this component is $\sim 10^{-2} \div 10^{-3}$ times lower (see Fig.2 for HH 1). From these results we also infer a flux of linear momentum of $\sim 10^{-5} M_\odot$ yr^{-1} km s^{-1}. This value agrees well with those attributed to molecular outflows seen in CO lines, which indicates that the atomic jets can drive such flows. To estimate the flux of angular momentum we would need measurements of the jet toroidal velocity, which require subarcsecond angular resolution (Bacciotti et al. 2002). To this aim we plan to examine existing HST archive data of these flows.

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