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TRACING SHOCK EVOLUTION IN YSO JETS

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RESUMEN

Hemos realizado nuevas observaciones que trazan la evolución de choques a lo largo de los ejemplos mejor resueltos de jets protoestelares por medio de espectroscopía profunda de alta resolución en la banda K en UKIRT y NTT. En este artículo analizamos tendencias en la excitación de H_2 dentro del jet bien colimado de HH 212, que incluye varios arcos a lo largo de cada eje de flujo. El objetivo de nuestro levantamiento es entender mejor el origen de la secuencia de nodos que se observa a lo largo de muchos jets, comparándolos con modelos teóricos, incluyendo la variabilidad de la velocidad de flujo e inestabilidades Kelvin-Helmholtz (KH). También investigamos cualquier evolución en la excitación por choques del tipo C, cercanos a la fuente del jet, donde la fracción de ionización podría ser baja y el campo magnético fuerte, a choques del tipo J más adelante en el flujo donde bajan las densidades ambientales. En cada sistema determinamos si la excitación fluorescente se hace significativa para nodos más cercanos a la fuente. Usando estos resultados podemos continuar a comparar nuestros resultados directamente con las predicciones de los modelos, como por ejemplo la luminosidad de los nodos, su separación y excitación en modelos de jets pulsantes (Smith et al. 1997).

ABSTRACT

We have undertaken new observations tracing the evolution of shocks along the best resolved examples of protostellar jets by means of high resolution, deep K-band spectroscopy at UKIRT and NTT. In this paper we analyse trends in H_2 excitation within the well collimated jet of HH 212, comprising multiple bows along each flow axis. The aim of our survey is to better understand the origin of the sequence of knots observed along many jets by directly comparing to theoretical models including flow velocity variability and Kelvin-Helmholtz (KH) instabilities. We also investigate any evolution in shock excitation from C-type near the jet source, where ionisation fractions may be low and B-field strengths high, to J-type further downstream where ambient densities decrease. We establish whether fluorescent excitation becomes significant for knots closer to the source in each system. Using these results we can now go on to directly compare our results with model predictions, e.g., knot luminosity, separation and excitation in pulsating jet models (Smith et al. 1997).

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1. INTRODUCTION

The origin of many of the features common to protostellar outflows observed in the near IR is not completely understood. In particular, we do not understand the origin of the sequence of knots observed along many jets. Early theoretical studies suggested the knots to be a result of steady-state crossing shocks until recent proper motion studies demonstrated that the knots seem to move along the beam of each jet (Coppin, Davis, & Micono 1998). It has therefore been suggested that Kelvin-Helmholtz (KH) instabilities (Micono et al. 1998) or flow velocity variability (Volker et al. 1999; Suttner et al. 1997) may explain the observed internal shock features within protostellar jets.

In order to attempt to constrain these models we have undertaken a survey tracing the evolution of shocks along the best resolved examples of protostellar jets of different morphological types by means of high resolution, deep K-band spectroscopy at UKIRT and NTT. We will compare trends in H_2 excitation for a sample of sources including collimated jets comprising multiple bows along each flow axis (HH 212, HH 111) and more turbulent systems (HH 110, HH 46/7) where the initially straight, laminar jet decays into a meandering, subsonic flow.

We also investigate any evolution in shock excitation from C-type near the jet source, where ionization fractions may be low and B-field strengths high, to J-type further downstream where ambient densities decrease. We establish whether fluorescent excitation becomes significant for knots closer to the source in each system and measure any continuous line-emission along the full length of each jet. This last parameter enables estimates of the molecular

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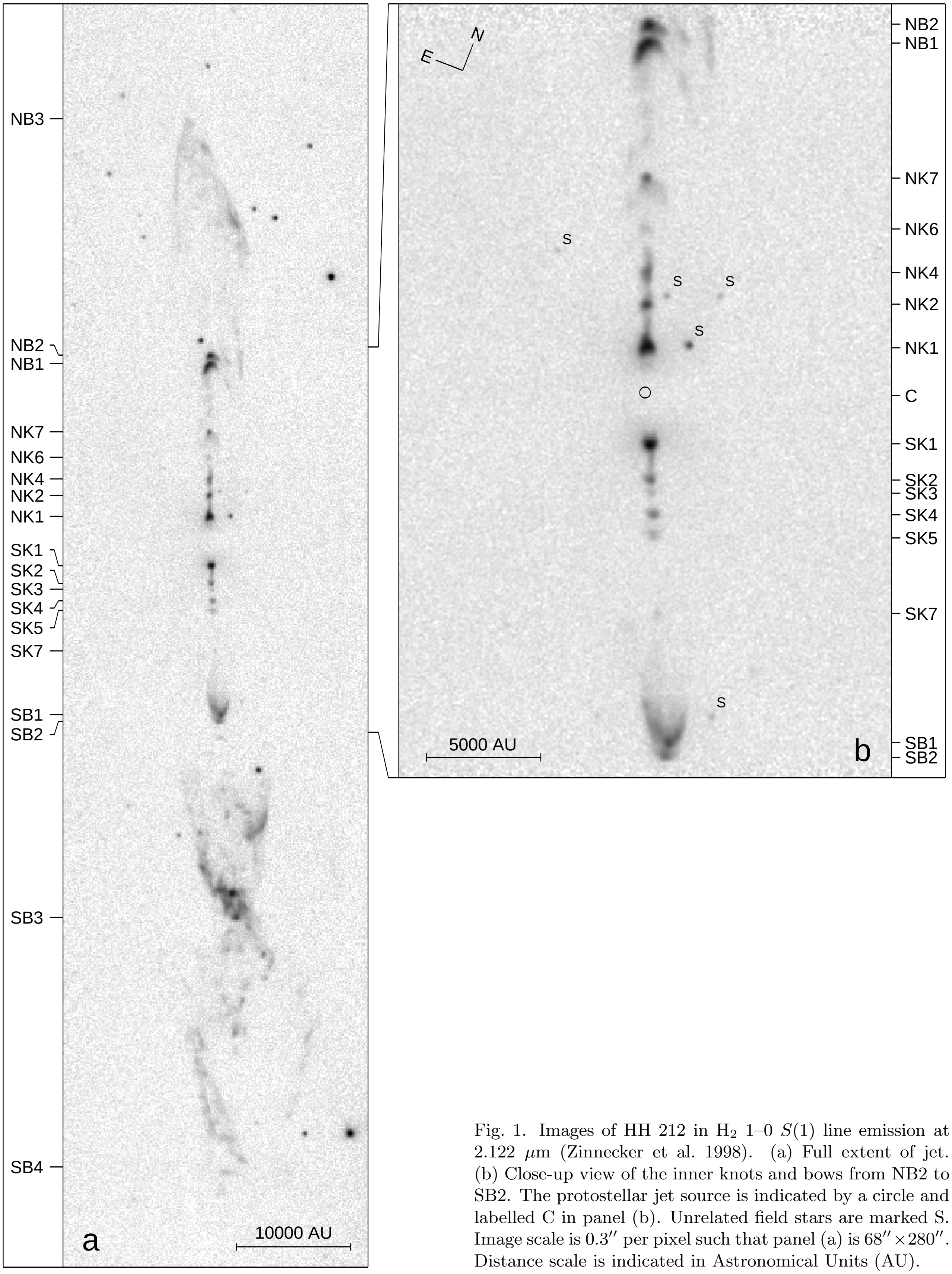

Fig. 1. Images of HH 212 in H_2 1–0 $S(1)$ line emission at 2.122 μm (Zinnecker et al. 1998). (a) Full extent of jet. (b) Close-up view of the inner knots and bows from NB2 to SB2. The protostellar jet source is indicated by a circle and labelled C in panel (b). Unrelated field stars are marked S. Image scale is $0.3''$ per pixel such that panel (a) is $68'' \times 280''$. Distance scale is indicated in Astronomical Units (AU).

fraction, gas density and temperature in the interknot gas for each flow and is vital to any molecular jet model or simulation. We directly compare our results to model predictions, e.g., knot luminosity, separation and excitation in pulsating jet models (Smith et al. 1997).

2. OBSERVATIONS

In this paper we will concentrate on first results for the HH 212 outflow since compared to most jet sources it is relatively easy to discriminate source variations from flow instabilities. Observations were carried out at the NTT with the SOFI near-IR imaging spectrometer on the night of 27th November 1999. In contrast to typical analyses of outflows, in which a long slit is stepped across individual flows, we used just one on-axis position per flow with 2″ slit width and integrated as deeply as possible at *J*, *K* band in order to measure the excitation of H_2 *along* each jet. By measuring the relative strengths of the many H_2 lines in the *K*-band, we can accurately measure the gas excitation conditions summed up spatially for each knot along each jet via column density ratio plots (Brand et al. 1988). We then searched for any variations in excitation, from knot to knot, with distance from protostellar source.

Figure 1 (Zinnecker, McCaughrean, & Rayner 1998) shows an image of the entire flow in H_2 1–0 $S(1)$ emission showing the many knots spread out symmetrically on each side of the protostar (labelled C). The great advantage of the SOFI instrument over competing near-IR spectrometers is that the slit length of 300″ is sufficient to sample the full length (10^5 AU ~ 0.5 pc) of the outflow from outer bows NB3 to the north to SB4 to the south in one single pointing. This minimises errors normally encountered in such studies due to differences in atmospheric conditions and airmass between pointings. The HK grism also allows simultaneous measurements over a relatively large wavelength range, allowing accurate correction of column densities for reddening, additional H_2 1–0 transitions and detection of any higher energy [Fe II] transitions in the *H* band for the strongest shocks.

3. RESULTS AND SHOCK MODEL FITS

Figure 2 shows a sample column density ratio (CDR) diagram (see caption) for the innermost knot NK1, just to the north of the protostellar source. There is no evidence here for fluorescent H_2 excitation, despite the proximity to the exciting source. In fact, the data are well fit by a C-bowshock model (Smith & Brand 1990; Smith 1991; Smith & Mac Low 1997). Hence, we are observing the cooling of shock-excited gas at a range of temperatures (hence the curvature of points away from a straight line characteristic of a single temperature slab of gas in these CDR diagrams). The fit is very close for the best-constrained $v = 1$, 2 levels of the H_2 molecule and only begins to deviate slightly at much higher

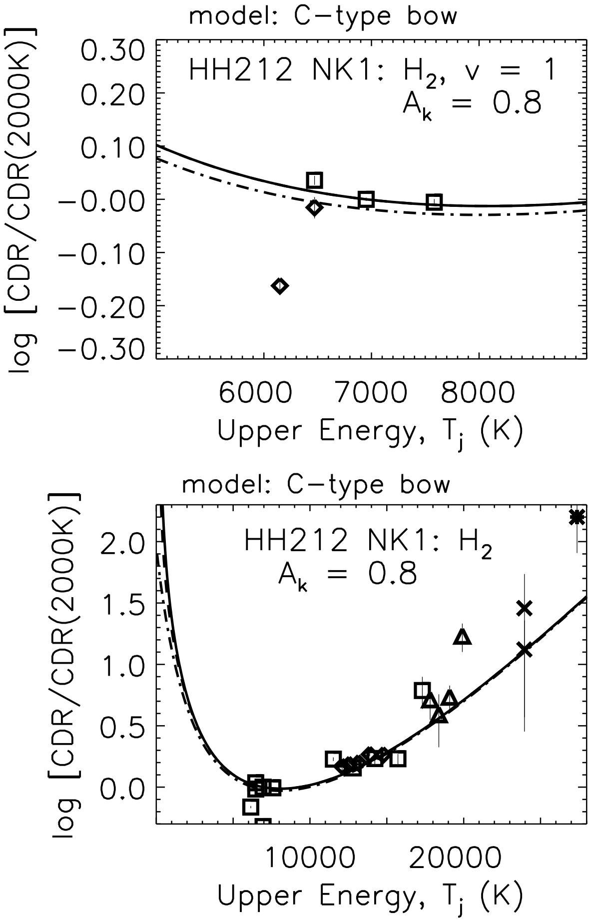

Fig. 2. Dereddened H_2 column density ratio (CDR) diagram for the inner knot NK1 of HH 212 together with best fit C-bowshock model (Smith & Brand 1990). Errors are derived from 1σ line-fits. The *K*-band extinction was determined to be $A_K = 0.8$ mag. The observed column density is divided by the column expected for gas in LTE at 2000 K and then normalized so that the intensity of the 1–0 $S(1)$ line is unity. Here the lower panel shows the full range of upper energy levels observed (squares are $v = 1$, diamonds are $v = 2$, triangles are $v = 3$, and crosses denote $v = 4$). The upper panel highlights the important 1–0 *S*-branch transitions (squares) which are important in constraining models as they are brightest and hence most accurately determined. Some 1–0 *Q*-branch lines are also included (diamonds) but disregarded as unreliable due to atmospheric variations at their particular wavelengths.

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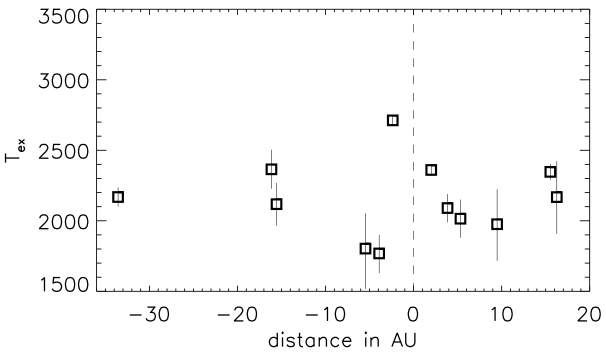

Fig. 3. Plot of evolution in H_2 excitation temperature with distance from central source in HH 212 (Fig. 1), as determined by the 2–1/1–0 $S(1)$ line ratio in cooling gas. Since no significant fluorescent excitation is detected in any knots of HH 212, this is an accurate measure of shock excitation conditions from knot to knot. The distance scale indicated is in units of 10^3 AU. Knots included are from SB3 at −34000 AU to NB2 at +16000 AU (Fig. 1).

upper level energies of $E/k \gtrsim 15,000$ K, corresponding to the $v = 3$ levels and above.

The C-bow model fitted is a 2D paraboloid bow surface with high radius of curvature compared to the shock thickness, full MHD, steady C-type shock at each point over bow surface and no emission at the bow apex where H_2 is dissociated at the highest velocities. The best fit was obtained for a bow speed of 100 km s^{-1}, $n = 10^6$ cm^{-3}, $n_{H_2}/n = 0.2$, with ion conservation, simple O chemistry (abundance 2×10^{-4} converted to H_2O) and a magnetic field of order 1 mG. Further details will be provided in a forthcoming paper (Tedds et al. 2002, in preparation).

4. SHOCK EVOLUTION AND JET MODELS

A detailed fit to the H_2 intensities at each of the bright knots labelled in Fig. 1 was performed and similar model fits to that illustrated in Fig. 2 obtained. It turns out that the same C-bowshock model fits well in all knots analyzed but differences in excitation are determined. Figure 3 plots the variation in H_2 2–1/1–0 $S(1)$ line ratio with position from knot to knot along the jet axis. Since our spectra show no evidence for significant fluorescent excitation at any position, this ratio can therefore be used as a reliable measure of evolution in excitation with position.

It can be seen that the H_2 2–1/1–0 $S(1)$ line ratio is highest ($T_{ex} \gtrsim 2300$ K) at positions corresponding to the innermost knots NK1, SK1 and then again at the termination of the inner series of knots at bows NB1,2 and SB1,2. In between the excitation falls sharply ($T_{ex} \leq 2000$ K) within ~ 4000 AU of the source. The sharp fall from SK1 to SK2 and gentle build up in excitation moving outwards up to the bow SB1 is mirrored quite closely from knots NK1 to NB1 and reflects the near perfect mirror symmetry in the jet morphology. Also plotted is a point corresponding to knot SB3 at a distance of $-34,000$ AU from source with relatively high excitation temperature of $T_{ex} \simeq 2200$ K though lower than SB1 or SK1 nearer the source. This may be due to the lower gas densities encountered at such large distances and dissipation of initial energy.

These observations are consistent with a time variable pulsating jet model in which the excitation rises and falls with outflow pulses superimposed on a continuous outflow (Smith, Suttner, & Zinnecker 1997). In such a model, shocks steepen and then move down the axis of the jet (hence observed proper motions), weakening as pressure falls due to conversion of jet material into the shocked layer. Hence the decrease in excitation from NK1 to NK7 and SK1 to SK5. However, the excitation is then rejuvenated as it sharply increases again as different episodes catch up with each other at NB1,2 and SB1,2 then again at NB3, SB3. This is in contrast to explosive models in which the excitation can only decrease with distance from source. Kelvin-Helmholtz or MHD pinch mode instabilities seem unlikely to produce the kind of near perfect mirror symmetry seen in HH 212.

5. SUMMARY

First results in our survey of shock evolution in YSO jet sources indicates that in HH 212, the simplest jet source known, a time variable pulsating jet model is strongly favoured. Individual knots are well fitted by C bow shock models developed by us and future work will compare our observations in detail with model predictions and numerical simulations as well as corresponding H_2 dynamical datasets and multiwavelength studies of the protostellar source itself. We go on to compare this YSO jet to other morphological types. Our results support the contention that HH 212 may be the textbook case in which to test the accretion/ejection connection in YSOs and AGNs.

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