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THEORY AND OBSERVATIONS OF A JET IN THE σ ORIONIS REGION: HH 444

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RESUMEN

El descubrimiento de un sistema de objetos Herbig–Haro eyectados por estrellas jóvenes de baja masa en la región de σ Orionis (Reipurth et al. 1998) ha motivado a modelar la fotoionización de un chorro neutro por una fuente externa. Presentamos espectros de rendija larga de alta resolución espectral de HH 444 y simulaciones numéricas para este objeto Herbig–Haro usando "yguazú", un código 3D que incluye la dinámica del gas y transferencia radiativa (Raga et al. 1999). Encontramos que es necesario incluir un perfil de velocidad en el haz del chorro para explicar el diagrama posición–velocidad del chorro HH. También necesitamos suponer un ángulo de apertura no nulo en la base del chorro para explicar el decrecimiento de la intensidad Hα con el aumento de la distancia a la fuente y una velocidad de eyección variable para reproducir los nudos que se observan a lo largo del chorro.

ABSTRACT

The discovery of a system of Herbig–Haro objects ejected by young, low mass stars in the σ Orionis region (Reipurth et al. 1998) has given rise to models of the photoionization of a neutral jet by an external source.

We present long–slit spectra of high spectral resolution of HH 444 and numerical simulations for this Herbig–Haro object using "yguazú", a 3D gasdynamic +radiative transfer code (Raga et al. 1999). We find that a velocity profile in the jet beam is necessary to explain the observed accelaration in the position–velocity diagram of the HH jet. We also need also assume a non–zero opening angle at the base of the jet to explain the decreasing Hα intensity at increasing distances from the source and a variable ejection velocity to reproduce the well separated knots observed along the jet.

Key Words: **HYDRODYNAMICS — ISM: INDIVIDUAL OBJECTS: HH 444 — ISM: JETS AND OUTFLOWS — SHOCK WAVES — TECHNIQUES: SPECTROSCOPIC**

1. INTRODUCTION

The observations reported by Reipurth et al. (1998) show collimated outflows ejected by young, low mass stars embedded in the σ Orionis region. These jets, which are probably initially neutral, emerge into the photoionized nebula, and start to be photoionized by the radiation from σ Orionis.

It is very interesting to compare physical processes in jets embedded in different environments. While in the "standard", quasi–neutral HH jets the emission comes from the region of the beam which is excited by shocks, in the photoionized HH jets most of the jet beam should be photoionized by the passage of an oblique ionization front that gradually unveils it, so that the emission should be produced by a large fraction of the volume of the jet beam.

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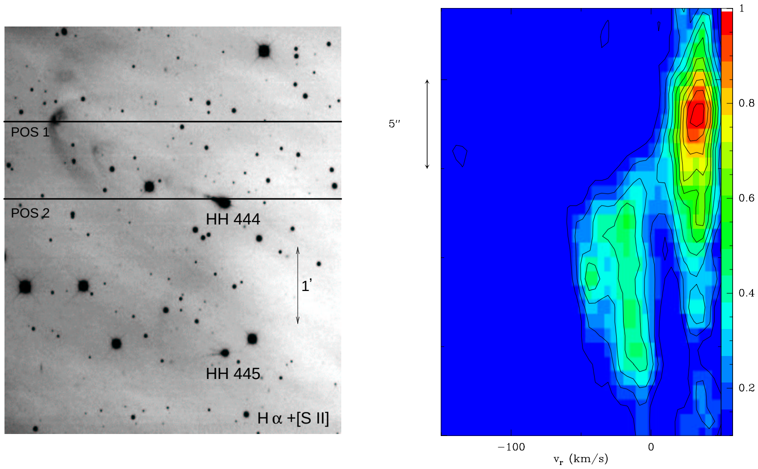

Fig. 1. Left: Image of the region with the HH 444 and HH 445 jets in the light of Hα + [S II] (Reipurth et al. 1998). The slit positions (POS 1 and POS 2) are marked with the two horizontal lines. North is to the top. Right: Contour map, (with linearly spaced contours) of the Hα position–velocity map for the POS 1 slit (see Fig. 1) over the bow–shock of HH 444. The nebular emission from the H II region has been subtracted.

We have obtained high resolution spectroscopic observations of the brightest HH jet of the σ Orionis region (HH 444), isolating the Hα and [N II] emission lines. We also computed model predictions which can be directly compared with these data.

2. OBSERVATIONS

The kinematical observations were obtained with the Manchester Echelle Spectrograph (MES; Meaburn et al. 1984), at the f/7.9 focus of the 2.1 m San Pedro Mártir UNAM Telescope. This spectrometer has no cross–dispersion. A Tektronix CCD with 1024 × 1024 24 μm (0.3 arcsec) square pixels was the detector. Two times binning was employed in both the spatial and spectral dimensions. For the present observations, a filter of 90 Å bandwidth was used to isolate the Hα and [N II] 6584 Å nebular emission lines. The spectra were calibrated to ± 1 km s^{-1} accuracy using a Th–Ar arc lamp. Two long–slit positions were used, passing through the most external observed bow shock (POS 1) and through the base of the jet (POS 2) (see Fig. 1).

3. MODELS AND NUMERICAL RESULTS

From the spectroscopic observations of HH 444 (see Fig. 2), we see an acceleration in the position–velocity diagram as a function of increasing distance from the source. This effect is easy to explain with a simple photoionized jet beam model in which the jet has a higher velocity in the central region of the beam. However, we find some other effects that are not explained by this simple photoionized jet beam model like the decreasing Hα intensity with increasing distances from the jet source observed in HH 444 (see Fig. 2). In order to reproduce this effect we have assumed that the jet has a decreasing density along the beam, resulting from a non–zero initial opening angle at the base of the jet. Another effect present in the position–velocity diagram is that HH 444 shows well–separated knots along its beam (see Fig. 2). To reproduce this effect we have assumed in our model that the jet has a variable ejection velocity with time, leading to the formation of a series of knots that move away from the base of the jet with time.

3.1. *The Parameters for HH 444*

The physical parameters of HH 444 have been estimated by Reipurth et al. 1998. Following these autors, we assume a distance for σ Orionis of 400 ± 50 pc. We obtain a projected separation between the source of

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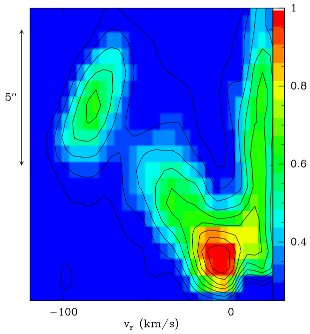

Fig. 2. Contour map, (with linear contours) of the Hα position-velocity map for the POS 2 slit (see Fig. 1) over the base of the HH 444 jet. The nebular emission from the H II region and the continuum of the star (V 510 Ori) have been subtracted.

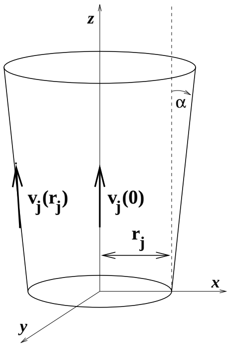

Fig. 3. Schematic diagram of the base of the jet. $\mathrm{V_j(0)}$ and $\mathrm{V_j(r_j)}$ are the velocities in the center and in the edge of the jet at a given time. α is the half–opening angle of the jet.

the HH 444 jet (V 510 Ori) and σ Orionis of ≈ 1.73 pc. The ionizing source is actually a multiple star with an 09.5 star as the brightest component. The electron density assumed for the base of the jet flow is 300 cm^{-3}. The observed angular diameter of this jet is of ≈ 1 ”, that for the distance assumed below gives a jet radius of r$_j = 3 \times 10^{15}$ cm.

3.2. *Numerical Simulations*

We have computed numerical models of an initially neutral jet emerging into an ionizing radiation field with the new “yguazú” code, which is described in detail by Raga et al. (1999). The model has been computed in a uniform, Cartesian grid of $N_x \times N_y \times N_z = 40 \times 40 \times 100$ grid points.The ionizing photon source is placed at a position $(x_s,\, y_s,\, z_s) = (-1.73\,\mathrm{pc},\, 0,\, 0)$, and is taken to have $S_* = 10^{48}$ s^{-1}, emitting as a black body with $T_{eff} = 31000$ K. The jet is assumed to be initially neutral, at a temperature $T_j = 1000$ K, and the surrounding, undisturbed environment is fully ionized. Figure 4 shows Hα position–velocity diagram from the numerical simulations at different evolutionary times. The intensity has been normalized to a peak value of one, and the contours correspond to linear steps of 0.1 from 0.1 to 1.

4. CONCLUSIONS

In this paper, we discuss a first comparison between the model predictions and observations of long–slit spectra of the photoionized HH 444 jet. We can straightforwardly reproduce the main kinematical features with some assumptions about the density and velocity profile of the jet. We confirm that the gradual unveiling

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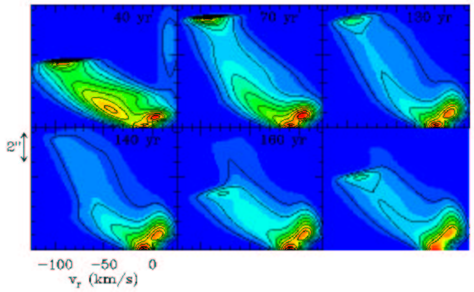

Fig. 4. Hα position–velocity diagram from the numerical simulations described in the text. The intensity has been normalized to a peak value of one, and the contours correspond to linear steps of 0.1 from 0.1 to 1.

of the jet beam is due to the passage of an oblique ionization front of a strong ionizing radiation field from the σ Orionis star. We find that an axially peaked velocity profile of the jet beam can explain the acceleration observed in the position–velocity diagram of HH 444. In order to fit the observations, we use a velocity profile with a central value of 190 km s^{-1}, decreasing "linearly" with cylindrical radius to a value of 20 km s^{-1} at the edge of the jet beam. In order to reproduce the observed decreasing Hα intensity with increasing distances from the source we find that the base of the jet beam should have an opening angle of $\approx 15^o$. In order to reproduce the knots observed in the position–velocity diagram of the jet, we introduce a time variable mass ejection. From comparisons of the simulations with the observations of long–slit spectra we find that a sinusoidal variation with an amplitude of 10% of the velocity, and a period of 50 years is appropriate for reproducing the knot structure of the HH 444 jet.

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