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THE THEORY OF PHOTOIONIZED JETS

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RESUMEN

En un artículo anterior, hemos discutido la fotoionización de un jet Herbig-Haro (HH) inmerso en una región H II. Aquí presentamos nuevos cálculos de un jet HH fotoionizado eyectado por una fuente variable, y comparamos los resultados con espectros de alta resolución de HH 444.

ABSTRACT

In a previous paper we have discussed the photoionization of the beam of a Herbig-Haro (HH) jet which is immersed in an H II region. Here, we present further calculations of a photoionized HH jet from a source with a variable ejection velocity, and compare the results with high resolution, spectroscopic observations of HH 444.

Key Words: **HYDRODYNAMICS — ISM: HERBIG-HARO OBJECTS — SHOCK WAVES**

1. INTRODUCTION

Reipurth et al. (1998) report the discovery of a system of Herbig-Haro (HH) jets embedded in the H II region photoionized by the O9.5 star σ Orionis (bounded to the E by the edge containing the Horsehead nebula). As described by O'Dell (2000, in these Proceedings), a number of HH jets embedded in the Orion nebula (M42) have now also been detected.

From a theoretical point of view, these HH jets present a new challenge, in which the interplay between the jet dynamics and the external photoionization has to be understood. Also, these objects offer the possibility of making substantial progress in the understanding of HH jets: while in the "standard", quasi-neutral HH jets we only observe limited regions of the jet beam (which are excited by shocks), in the photoionized HH jets most of the jet beam should be ionized, and directly observable optically.

A first effort in modelling the photoionized HH jets has been done by Raga et al. (2000), who carried out analytic and numerical simulations of an initially neutral jet which emerges from the circumstellar region into the strong, ionizing radiation field of the exciting star of the photoionized nebula. These authors described the propagation of the ionization front, and concluded that for the parameters of the objects in the σ Orionis region (Reipurth et al. 1998), the ionization front would simply "unveil" the jet beam, without causing any major dynamic perturbations.

We have now obtained high resolution spectroscopic observations of HH 444 (the brightest HH jet of the σ Orionis region, see Reipurth et al. 1998), and have computed model predictions which can be directly compared with these data. The results are presented in the following section.

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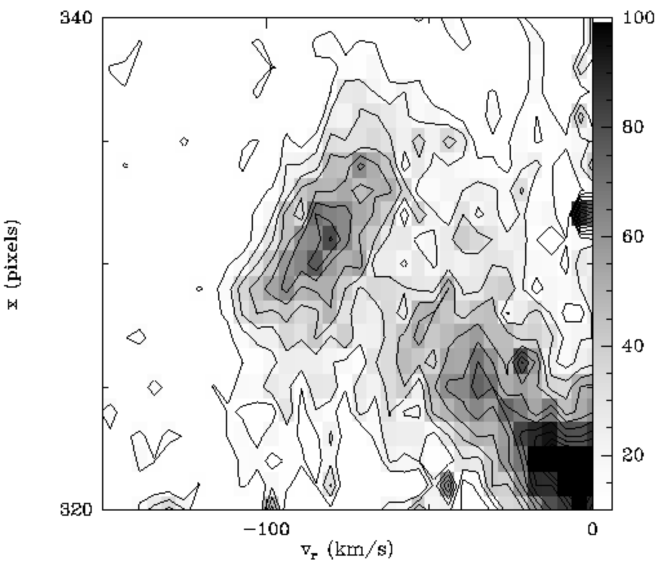

Fig. 1. Hα position-velocity diagram for the base of the HH 444 jet. The slit has been placed approximately parallel to the flow axis, and the emission from the star and from the H II region has been subtracted. Each pixel approximately corresponds to 0.6″. The greyscale gives the number of counts, and the contours correspond to linear spacings of 10 counts.

2. OBSERVATIONS AND MODELS OF HH 444

Raga et al. (2000) note that the beam of an initially neutral jet which emerges into an H II region will be ionized by the passage of an oblique ionization front. This ionization front gradually "unveils" the beam of the jet.

In other words, the side of the jet beam directed towards the ionizing star gets photoionized first, and the central region of the jet beam becomes photoionized only at larger distances from the source of the jet. Therefore, Raga et al. (2000) speculated that if one has a jet with a higher velocity in the central region of the beam, one should observe an "acceleration" in the position-velocity diagrams as a function of increasing distance from the source.

In our recent spectroscopic observations of HH 444 (see Fig. 1, and the paper of López-Martín et al. in these Proceedings) we do observe such an effect. However, we find other effects that are not present in a simple-minded photoionized jet beam model:

- the observed Hα intensity falls quite rapidly with increasing distances from the jet source. In order to reproduce this effect, we need to assume that we have a jet with a finite opening angle, so that the density of the jet beam decreases with increasing distance from the source,

- HH 444 shows well separated knots along its beam. We reproduce this effect in our model by assuming that the ejection velocity varies with time, leading to the formation of a series of "internal working surfaces".

Using the 3D gasdynamic+radiative transfer code of Raga et al. (1999), we then compute a model of a jet with a mean central velocity of 120 km s^{-1}, going down parabolically to a velocity of 10 km s^{-1} at the outer edge of the jet beam. On this mean velocity, we superimpose a 10% velocity variability with a 100 yr period. Also, we impose an initial (full) opening angle of 30°. The other parameters of the model are identical to the ones deduced for HH 444 and for the photoionizing source of this object by Raga et al. (2000).

In Figure 2, we present the Hα position-velocity diagram computed (after a 130 yr time integration) from this model. We think that the main features of the HH 444 Hα position-velocity diagram (see Figure 1) are reproduced by the model, at least in a qualitative way.

3. CONCLUSIONS

In this paper we discuss a first comparison between model predictions and observations of long-slit spectra of photoionized HH jets. We find that the main observed kinematical features can be quite straightforwardly

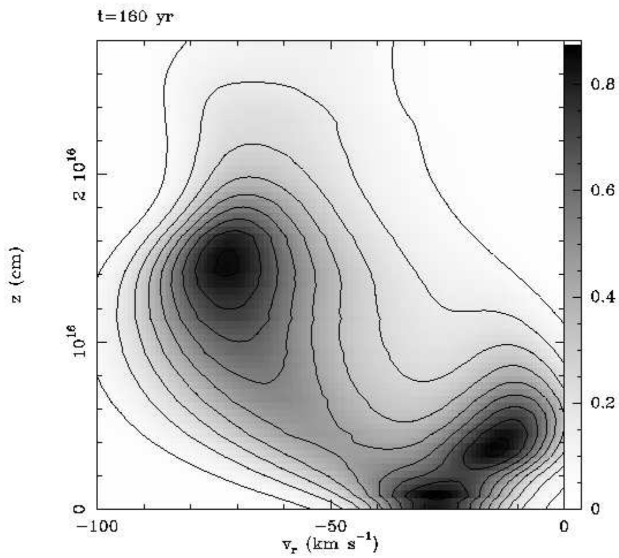

Fig. 2. Hα position-velocity diagram from the numerical simulation described in the text. The intensity has been normalized to a peak value of one, and the contours correspond to linear steps of 0.1 from 0.05 to 0.95 .

reproduced with the following ingredients:

- the gradual unveiling of the jet beam due to the passage of an oblique ionization front,
- the existence of an axially peaked velocity distribution of the jet beam,
- a non-zero initial opening angle for the jet,
- a small-amplitude time variability of the ejection velocity.

Interestingly, it has not yet been possible to obtain such a clear set of requirements for explaining the observed kinematics of "normal" (i.e., mostly neutral) HH jets, which still prove to be quite puzzling. Due to the apparent simplicity of the theory and observational properties of photoionized HH jets, we hope that the study of these objects will lead to a significant development in our understanding of HH flows in general.

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