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STELLAR EJECTA AND THEIR INTERACTION WITH THE INTERSTELLAR MEDIUM

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RESUMEN

Se hace una revisión de un caso particular de interacción entre eyectas estelares y el medio circundante: la interacción de un "jet" con el medio interestelar. Los casos de jets de estrellas jóvenes y jets asociados a nebulosas planetarias son aquí discutidos. El trabajo hace énfasis en las contribuciones de investigadores latino-americanos en este tema.

ABSTRACT

This paper reviews one special type of interaction between stellar ejecta and the surrounding medium : the interaction of a jet with the surrounding ISM. The cases of jets from young stars and jets associated with Planetary Nebulae (PNe) are discussed. A special effort is made to highlight the contributions of latin american researchers to this topic.

Key Words: **ISM: JETS**

1. INTRODUCTION

This paper describes the contributions by latin american researchers to the fields of jets from young stars and jets associated with Planetary Nebulae (PNe).

The field of Herbig-Haro (HH) objects and jets from young stars from its very beginnings has had strong contributions from latin american researchers. For example, Guillermo Haro is credited (together with George Herbig) for the discovery of the optical emission of HH objects (Haro 1952). Many years later, the discovery of the radio emission of these objects was made by a strongly latin american-biased group (Pravdo et al. 1985). More recently, latin american groups have also been strongly involved in optical (ground based and HST), IR and radio observations of HH jets.

The first dynamical models of HH objects were developed by Cantó (1980). In the following years, latin american researchers have made a large number of contributions in this subject. This work has pioneered and developed the theories of turbulent HH jets, jets from variable sources and MHD HH jets.

Latin american researchers have also made very important contributions to the field of jets in PNe. Many of these jets have been discovered and studied in detail by López and collaborators (López et al. 1993). This group of researchers has also pioneered the theoretical interpretation of these jets. Interestingly, latin american researchers also were involved in carrying out the first more detailed theoretical models of these jets (García-Segura 1997).

The following sections describe in more detail the contributions of latin american researchers which are described above. Section 2 describes the theoretical contributions (with subsections describing collimation mechanisms, HH jet propagation, jets in inhomogeneous environments, variable jets, turbulent jets, and MHD jets) and section 3 the observational contributions (including optical, IR and radio observations of HH objects, and optical observations of jets in PNe).

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2. THEORETICAL CONTRIBUTIONS

2.1. *Collimation Mechanisms*

Cantó (1980) proposed the first dynamically consistent models of HH objects. In these models, the HH emission is associated with highly radiative shocks along the walls of a cavity formed by the interaction of an isotropic stellar wind with a stratified surrounding medium. Cantó and collaborators developed this model in considerable detail, and showed that it could serve as a possible collimation mechanism for the "HH jets" which were discovered and studied in detail in the following years.

Interestingly, it is still not entirely clear whether or not any observed HH object actually does correspond to shocks along the walls of a stellar wind cavity. Also, these cavity (or nozzle) models have currently fallen out of favour as a jet collimation mechanism, since a very high environmental density is required in order to produce the collimation within a small enough distance from the source.

The currently more popular models for jet collimation all involve the presence of a dynamically important magnetic field. Such models have been studied by latin american researchers for the cases of HH jets (Shu et al. 1994) and jets in PNe (Różyczka & Franco 1996).

2.2. *Jet Propagation*

Early models for the formation of steady crossing shocks (Cantó et al. 1989) in the beams of HH jets were developed by Latin american researchers. Though at the time they were quite promising, these models have become less so since the discovery of high proper motions for the knots along HH jets.

The propagation of the head of an HH jet has also been studied in detail (Raga 1988; de Gouveia dal Pino & Benz 1993). Detailed predictions of the observational properties of the working surfaces, and comparisons with observations have been carried out.

2.3. *Jets in Inhomogeneous Environments*

The study of the propagation of HH jets in inhomogeneous environments curiously is a topic in which almost all of the papers in the literature have been written by groups led by latin american astronomers. This work has included time-dependent numerical simulations of jets in environmental pressure gradients (de Gouveia dal Pino & Birkinshaw 1996), and analytic and numerical models of steady jets being deflected by plane-parallel and spherically symmetric environmental pressure distributions (Cantó & Raga 1996; Raga & Cantó 1996).

Also, the problem of the interaction of a jet impinging on a dense clump (Raga & Cantó 1995) as well as the interaction of a jet propagating through a field "mined" with a distribution of dense clumps (Raga et al. 1996) have been studied. Finally, analytical and numerical models have been developed for the problem of a jet deflected by a lateral relative motion between the outflow source and the surrounding environment (Cantó & Raga 1995; Lim & Raga 1998).

2.4. *Variable Jets*

A subject that was first studied by a group of latin american researchers is the effect on the jet structure of different type of variabilities of the outflow source. Starting with the paper of Raga et al. (1990), which defined the problem of a radiative jet with an ejection velocity variability, there is a long list of papers (see, e. g., de Gouveia dal Pino & Benz 1994) in which the problem is studied in detail both numerically and analytically.

An example of the success of these models is shown in Figure 1, a comparison of Hα and [S II] maps of HH 34 with the corresponding predictions from a model of a jet which has a time-dependent velocity variability composed of three sinusoidal modes (of different periods and amplitudes, see Raga & Noriega-Crespo 1998).

A number of related problems have also been explored : the effect of a direction variability, the effects of a general (velocity modulus and direction) variability, and the effect of random variabilities in the ejection (see the review of Raga 1993). These models have been not so conspicuously successful at reproducing the structures observed in HH jets, but appear to have been better suited for modelling the structures observed in jets in PNe (Palmer et al. 1996).

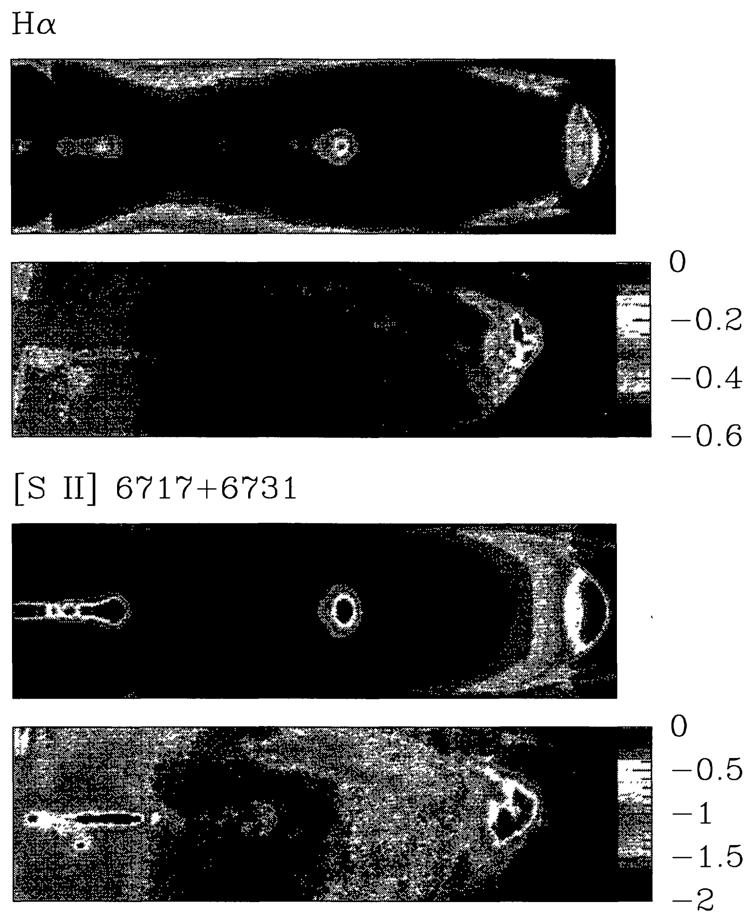

Fig. 1. Comparison between the Hα (top) and [S II] 6717+31 (bottom) maps of HH 34 with the corresponding predictions from a 3-mode variable ejection velocity jet numerical simulation. The color scale corresponds to the logarithm of the intensities, normalized to the peak intensity in each map. This figure has been taken from Raga & Noriega-Crespo (1998).

2.5. *Turbulent Jets*

A still not well understood subject is the formation of turbulent mixing layers in HH jets. The not so cautious "Mex-jet" group has therefore produced a large part of the work published in this subject. 1D (Cantó & Raga 1991) and 2D (Noriega-Crespo et al. 1996) analytic models based on a "turbulent viscosity" approach have been developed. These models have been extended to include a large number of chemical (Taylor & Raga 1995) and atomic/ionic (Binette et al. 1999) processes, in order to be able to make concrete predictions of the emission line spectrum produced by the flow. The comparisons with observations have up to now been somewhat confused, as it is unclear how strong is the contribution of mixing layers to the observed spectrum of HH objects and molecular outflows.

2.6. *MHD Jets*

Finally, the topics of MHD jets in PNe (García-Segura 1997) and in HH outflows (Cerqueira et al. 1997; Cerqueira & de Gouveia dal Pino 1999) have also been pioneered by latin american researchers. These papers present numerical solutions of the time-dependent, 3D MHD equations, and are likely to be followed by an international effort to carry out this kind of simulations for different possible expected stellar jet configurations.

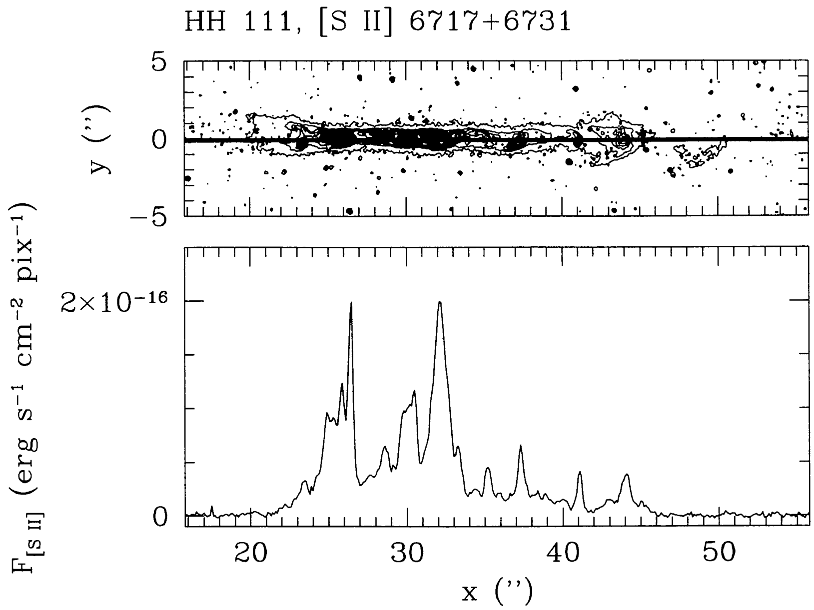

Fig. 2. [S II] 6717+31 HST image of HH 111 (top) obtained by Reipurth et al. (1997), and the flux that would go through the STIS slit when placed along the flow axis (bottom).

3. OBSERVATIONAL CONTRIBUTIONS

3.1. *Optical Observations*

During the last few years, Bo Reipurth (now at the Univ. of Colorado) and Steve Heathcote have been two of the most active astronomers involved in optical studies of HH jets. Among their important contributions are the detection of proper motions in the knots along HH jets (Heathcote & Reipurth 1992; Reipurth et al. 1992), and the first high resolution HST observations of HH jets (Heathcote et al. 1996; Reipurth et al. 1997).

These HST images are most dramatic, resolving many of the jet knots into bow-shaped structures. In Figure 2, we show the HST [S II] 6717+31 image of HH 111 obtained by Reipurth et al. (1997), and a prediction of the flux that would be obtained through the STIS slit. Such spectroscopic observations will be obtained by a multi-national collaboration (involving researchers from México and the USA) in the near future.

A number of other latin american researchers have also been involved in obtaining images (HST : Curiel et al. 1997), spectra and Fabry-Perot interferograms (Rosado et al. 1999) of HH jets.

3.2. *IR Observations*

Several researchers from latin american countries have been involved in IR imaging and spectroscopy in the $\lambda \sim 2\mu$ wavelength range. In particular, Reipurth has been active using the ESO IR cameras and spectrographs for detailed studies of a number of HH flows (see, e. g., Moneti & Reipurth 1995). Mexican astronomers have also been active in this field, obtaining images and spectra with the new IR camera/spectrograph at the Observatorio Astronómico Nacional (Salas et al. 1998). Latin american researchers also participated in the first detection of proper motions in IR images of HH objects (Noriega-Crespo et al. 1997)

3.3. *Radio Observations*

Interestingly, the first detection of radio continuum emission from HH jets was made by a group of mostly Mexican observers (Pravdo et al. 1985), following the tradition of Haro (who obtained some of the first optical

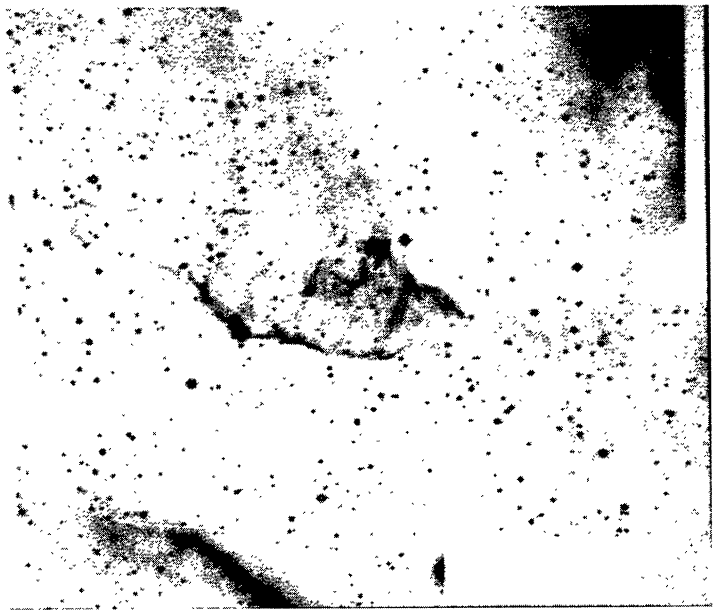

Fig. 3. Mosaic of Hα CCD frames of KjPn 8 from López et al. 1995. Each CCD frame has a $5' \times 5'$ size.

detections of HH objects). This work was followed by a number of papers showing the radio continuum structure at high angular resolution (Rodríguez et al. 1990), and measuring (for the first time) proper motions of the radio continuum knots (Rodríguez et al. 1989).

These observations have proved to be crucial to the understanding of the collimation of HH jets. Due to the very high angular resolution of the VLA, the observations sample a region of ~ 10 AU around the central star, showing that the jet is already collimated at those scales. This result is fundamental for the theoretical modelling of the production of HH jets.

3.4. *Optical Observations of Jets in PNe*

López et al. (1995) proposed that some of the point-symmetric structures observed in PNe could be interpreted in terms of "bipolar, rotating, episodic jets" (BRETS). This group then proceeded to obtain images and long-slit, high resolution spectra of several objects which showed these properties (e. g., López et al. 1997). The probably most impressive object showing this type of behaviour probably is KjPn 8, an image of which is shown in Figure 3.

These papers gave rise to a new subject within the field of PNe. It appears that the central sources in some objects eject bipolar jets, which then travel away from the source and interact with the surrounding PN. It will be interesting to see future theoretical work trying to establish to what extent these jets are similar to the better known HH jets.

4. SUMMARY

The fields of HH jets and jets in PNe have had strong contributions from latin american researchers. The principal contributions appear to be :

- HH objects : discovery (Haro 1952), radio detection (Pravdo et al. 1985), radio proper motions (Rodríguez et al. 1989), IR proper motions (Noriega-Crespo et al. 1997), HST imaging (Heathcote et al. 1996), first dynamical models (Cantó 1980), variable ejection models (Raga et al. 1990), MHD models (Cerqueira et al. 1997).

- Jets in PNe : discovery (López et al. 1993), spectroscopic/imaging studies (López et al. 1997), first dynamical models (Palmer et al. 1996), MHD jet models (García-Segura 1997).

These contributions have been strong enough that it is fair to say that latin american astronomers have had a leading role in these two subjects. We can only hope that the exciting developments achieved by the "mature" group of scientists involved in these studies will give an incentive to younger latin american astronomers to try to do research in this field, preserving this line of research into the future.

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