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X-ray Emission Mechanisms in Herbig - Haro objects

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Abstract. X-ray emission in Herbig - Haro objects is a quite recent and uncommon finding still waiting full explanation. With the scope of explaining this X-ray emission, our project is devoted to model the interaction between a supersonic jet originating from a young stellar object and the ambient medium. We have performed a wide exploration of the parameter space to infer the configuration(s) which can give rise to X-ray emission very similar to what recently observed.

Key words. ISM: Herbig-Haro objects - ISM: individual objects: HH 154 - ISM: jets and outflows - X-rays: ISM

1. Introduction

Herbig-Haro (HH) objects are shocks produced at the interaction front between a supersonic protostellar jet and the ambient medium. Optical, infrared and radio studies of HH objects have been made since their discovery (Herbig 1950). Recently X-ray emission has been detected for a few of these HH objects with both *Chandra* and *XMM-Newton* (Pravdo et al. 2001; Favata et al. 2002; Bally et al. 2003; Pravdo et al. 2004; Tsujimoto et al. 2004). In order to explain this X-ray emission, we model the interaction between a supesonic jet originating from a young stellar object and the ambient medium. We have performed a wide exploration of the parameter space to determine the range of parameters consistent with observations and to get insight on the jet physical conditions (Bonito et al. in preparation). Here we discuss the representative case (Bonito et al. 2004) marked by the black dot in Fig. 1 which matches well the observations of HH 154 by Favata et al. (2002).

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2. The Model

We model a supersonic protostellar jet with temperature $T_j = 10^4$ K and density $n_j = 500$ cm^{-3} traveling through an initially unperturbed ambient medium. Our model is based

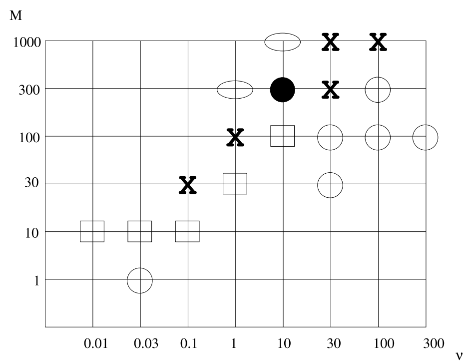

Fig. 1. Exploration of the parameters space: see section 3 for details.

on FLASH code (Fryxell et al. 2000), an adaptive and parallel simulation code. We adopt a bi-dimensional cylindrical coordinate system with the jet axis coincident with the z axis. Reflection boundary conditions are imposed along the jet axis and outflow boundary conditions elsewhere.

The evolution of the protostellar jet traveling through the ambient medium is described by the fluid equations of mass, momentum and energy conservation in which we have taken into account optically thin radiative losses (Raymond & Smith 1977; Mewe et al. 1985) and thermal conduction with saturation effects (Spitzer 1962). From our numerical simulations and using MEKAL spectral code (Mewe et al. 1985), we synthesize the focal plane spectrum, as observed with the last-generation X-ray instruments *Chandra*/ACIS-I and XMM-*Newton*/EPIC-pn (see Bonito et al. 2004 for details).

3. Results

Our model solutions depend on several physical parameters (initial jet and ambient temperature and density, T_j, T_a, n_j, n_a, and initial jet velocity, v_j). Here we assume the initial jet temperature, T_j, and density, n_j, according to observations of HH 154 (Favata et al. 2002) and we assume initial pressure equilibrium between the jet and the ambient. The solutions therefore are defined by the following parameters: the Mach number, $M = v_{\rm j}/c_{\rm a}$, where $c_{\rm a}$ is the ambient sound speed, and the ambient to jet density ratio, $\nu = n_{\rm a}/n_{\rm j}$. The parameter space defined by these parameters is shown in Fig. 1: crosses and black dot refer to models in good agreement with observations for both X-ray luminosity and shock velocity values; empty dots mark models which cannot reproduce observations; squares refer to models in good agreement with observations for shock velocity but not for X-ray luminosity values; ellipses refer to models with too high temperature (10^8 K). Our model, therefore, yields observed X-ray emission only in a very narrow range of parameters, yielding a strong diagnostic power of the physical conditions of protostellar jet giving rise X-ray emission.

The upper panels of Fig. 2 show the evolution of the jet temperature (on the left of each image) and density (on the right of it) both in a logarithmic scale, derived from our numerical simulations for the representative case corresponding to the black dot in Fig. 1. The lower panels of Fig. 2 show the predicted evolution of the X-ray emission integrated along the line-of-sight as observed with *Chandra*/ACIS-I.

We found that the X-ray emission originates from a hot and dense blob localized just behind the shock front, with a radius comparable to the initial jet radius (~ 30 AU). Fig. 2 clearly shows a detectable proper motion for the X-ray emitting region. We derived shock velocity v_{sh} ~ 500 km/s corresponding to ~ 0.7" yr^{-1}.

In order to compare our findings with the results obtained by Favata et al. (2002) for HH 154, we synthesized the focal plane spectra as detected with EPIC-pn. All the spectra derived from our model are well fitted with the emission from an optically thin plasma at a single temperature, in agreement with observations. From the spectra and the best-fit parameters derived from our model with those observed (see Tab. 1), we see that our model agrees well with the observations.

4. Discussion and conclusions

Our model reproduces the X-ray emission observed in protostellar jets as due to mechan-

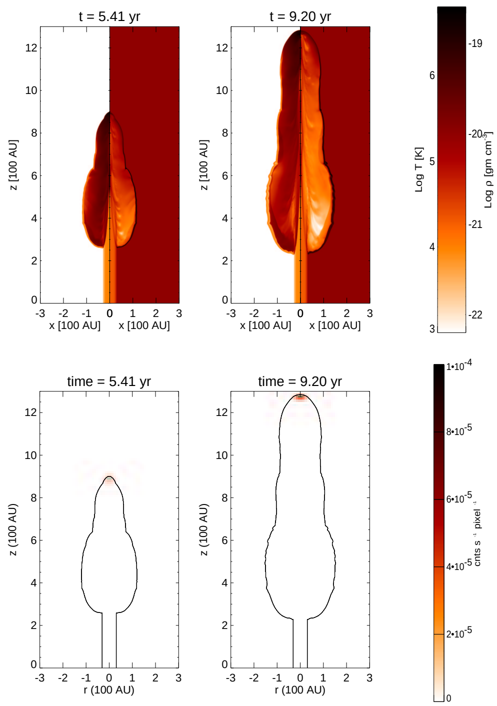

Fig. 2. Evolution of the jet temperature and density (upper panels) and of the X-ray emission (lower panels) as derived from our model.

Table 1. Best-fit parameters.

	model	Favata et al.
count rate (cnts/ks)	1.2	1.0
D (pc)	150	150
$N_{\rm H}$ (10^{22} cm^{-2})	1.5 ± 0.3	1.4 ± 0.4
T (10^6 K)	3.4 ± 1.2	4.0 ± 2.5
$F_{\rm X}$ (10^{-13} erg/cm^2/s)	1.4	1.3
$L_{\rm X}$ (10^{29} erg/s)	2 - 5	3

ical heating from shocks between the jet and the circumstellar medium. From a wide exploration of the parameters space, we can conclude that only a narrow range of values match with the observations (see Fig. 1, crosses and black dot) yielding a strong diagnostic power of the physical conditions of the jet.

In the next future we will analyse proprietary HST and *Chandra* observations of HH 154, approved in AO6. These observations will allow us to study the X-ray blob and its proper motion and evolution, so critical for the physical implications, e.g. interaction with ambient inhomogeneities, self-interaction, etc. We plane to compare the L_X variability obtained from our simulations with what found from new XMM-*Newton* data.

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