The 16th Cambridge Workshop on Cool Stars, Stellar Systems and the Sun
ASP Conference Series, Vol. 448, Electronic Edition
Christopher M. Johns-Krull, Matthew K. Browning, and Andrew A. West, eds.

Generation of Knots in a Randomly Pulsed Protostellar Jet: Synthesis of the X-ray Emission

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Abstract. X-rays from protostellar jets have been discovered first in HH 2 and HH 154 and are now considered as a general feature of jets. HH 154 is among the best studied X-ray emitting jet: up to now it is the only jet whose X-ray source proper motion has been measured. By observing this jet in X-rays, a complex morphology of the detected source has been revealed. Here we discuss the results of modeling a randomly ejected pulsed jet traveling into an initially homogeneous medium. Our model allows us to directly compare the model predictions and the observations.

1. Introduction

X-rays from shocks in protostellar jets have been discovered taking advantage of both Chandra and XMM/Newton X-ray telescopes, with data collected in 2000 by Pravdo et al. (2001) in HH 2 and by Favata et al. (2002) in HH 154. The detected X-ray emission is now considered as a possible general feature of jets, as reviewed by Bonito et al. (2010a) (see Table 1 for a summary of the physical properties observed in all the X-ray emitting jets discovered so far). HH 154 is among the best studied X-ray emitting jet, being observed with both XMM/Newton (Favata et al. 2002) and Chandra (Bally et al. 2003) and being the first and so far only jet whose X-ray source proper motion has been measured (Favata et al. 2006). The X-ray luminosity of jets has been studied first analytically by Raga et al. (2002) and through detailed numerical model by our group (Bonito et al. 2004, 2007, 2010b,a). Bonito et al. (2007) performed for the first time a wide exploration of the parameter space describing the jet/ambient physical parameters and synthesized the X-ray emission to reproduce the observations of protostellar jets. The observations of Favata et al. (2006) showed a complex morphology of the X-ray moving source detected in HH 154. Here we present the synthesis of the X-ray emission derived from the model of a randomly ejected pulsed jet ramming through an initially homogeneous ambient medium and the comparison between the model predictions and the observations.

2. The Model

The knotty morphology observed in the X-ray source of HH 154 (Favata et al. 2006) suggests a pulsed jet propagating through the ambient medium. To reproduce the observations, we performed detailed numerical simulations of a randomly ejected pulsed jet using the FLASH code (Fryxell et al. 2000). In our model the protostellar jet consists of several bullets, each described as an impulse lasting 0.5 yr, ejected along the jet axis with random values of the velocity. We take into account the main physical effects describing the jet/ambient interaction, i.e. fluid dynamics and energetics include the thermal conduction and the radiative losses. We performed an exploration of the ejection rate parameter by considering three ejection rates corresponding to time intervals between two consecutive blobs: $dt = 0.5, 2$, and 8 yr.

In Fig. 1 we show a cut along the jet axis of the density distribution of the pulsed jet model for the $dt = 0.5$ yr case (see also Bonito et al. 2010b). The red line superimposed on the figure indicates the initial jet density: the initially homogeneous ambient medium becomes quickly inhomogeneous due to blobs interactions.

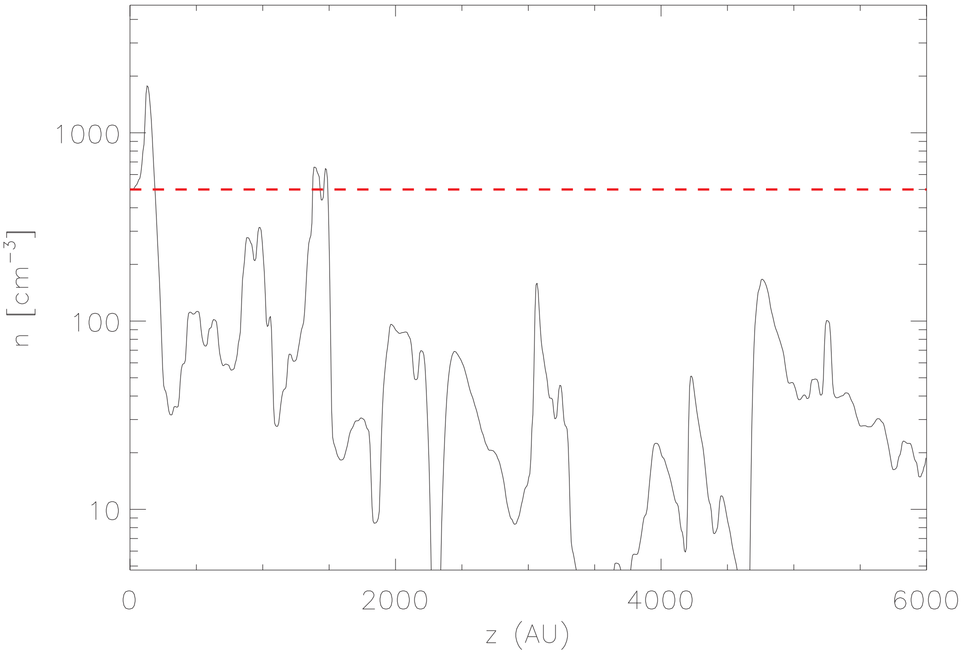

Figure 1. Example of a cut along the jet axis of the density distribution of one of our pulsed jet model.

We also investigated the effects due to the presence of the thermal conduction. In Fig. 2 we compare the 2D distribution of the temperature of the model with thermal conduction after 90 yr (right panel) and the pure radiative case after 350 yr (left panel). As discussed in Bonito et al. (2010b), the thermal conduction plays a crucial role in damping out hydrodynamic instabilities in the cocoon contributing to the jet braking.

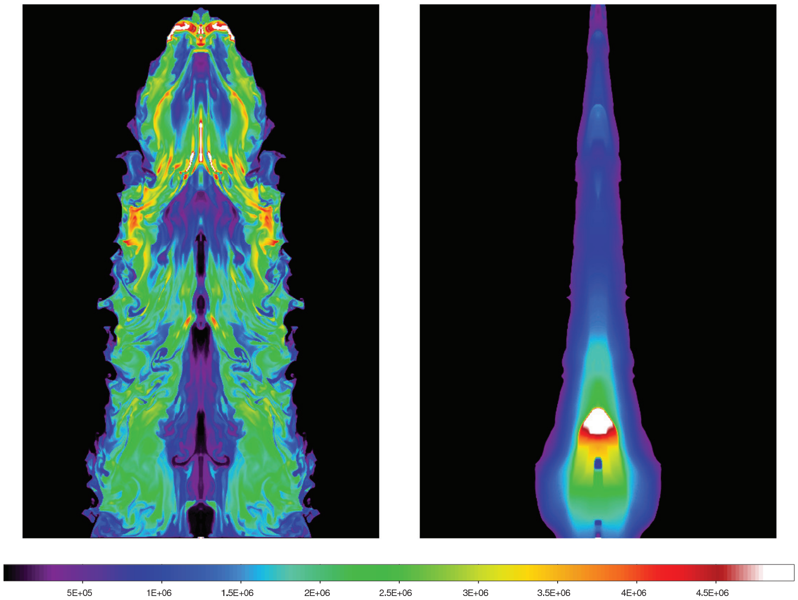

Figure 2. Comparison between models either with (right panel) or without (left panel) the thermal conduction.

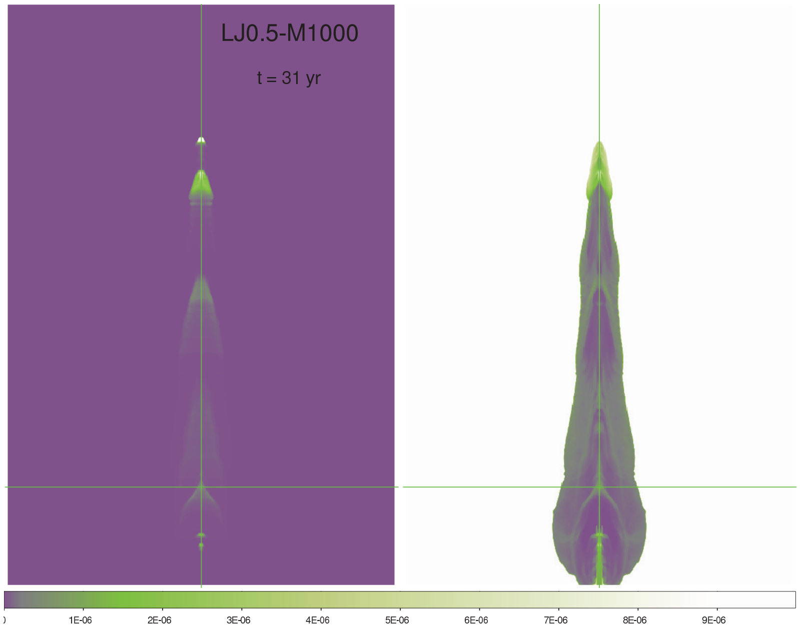

Figure 3. X-ray image (left panel) and density distribution (right panel) derived from the model.

3. Results

In the pulsed jet model the interactions between blobs, ejected at different epochs and with different speed, lead to the generation of internal shocks. Fig. 3 shows the generation of a knotty structure both in the density distribution and in the synthesized X-ray image. The derived knotty structure reproduces a multi-structures morphology consistent with the observations.

The X-ray morphology derived from the pulsed jet model shows several structures within the jet: interacting knots, forward, reverse, and steady shocks. As shown in Fig. 4, reverse shocks powered by freshly ejected plasma blobs may explain the formation of apparently stationary shocks as detected at the base of the X-ray emitting jets.

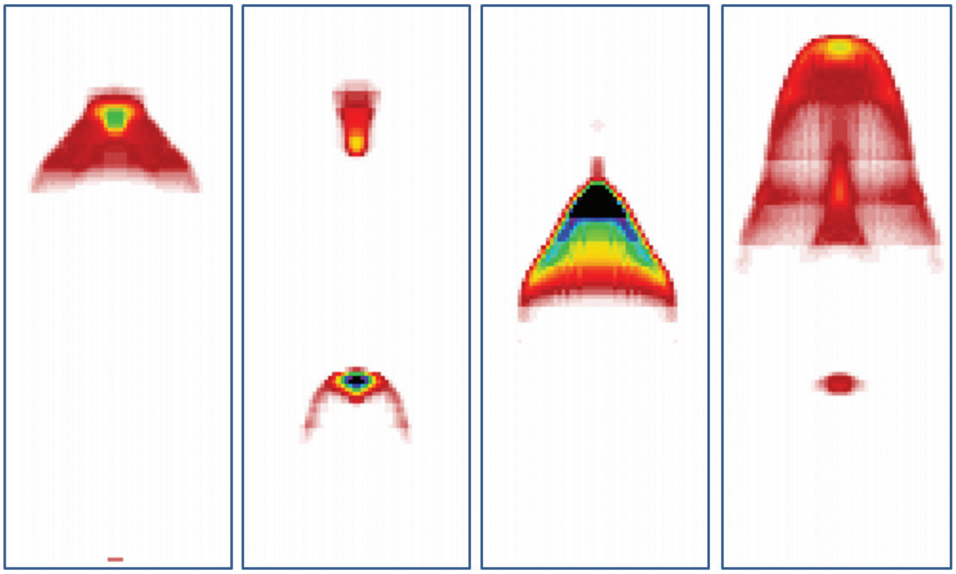

Figure 4. Sequence of four X-ray maps synthesized from the model over a time baseline of 3 yr and with a frequency of 1 yr, at the base of the jet (see Bonito et al. 2010a).

The comparison between our model results and the observations allow us to constrain the ejection rate and to derive predictions on the physical parameters of the jet/ambient system for all the X-ray emitting jets discovered so far. We derive that the most energetic case is the one with ejection rate corresponding to $dt = 0.5$ yr and leads to the highest luminosity and temperature: the higher dt, the lower L_X and T_X. Figure 7 in Bonito et al. (2010a) shows that HH jets with X-ray emission at the base of the jet have properties (L_X and best-fit temperature) that nicely agree with our results. In particular, there is a good agreement for the nearest X-ray emitting jets: HH 154 is well described by a pulsed jet with $dt = 2$ yr, while DG Tau (the weakest X-ray-emitting jet; see Table 1 in Bonito et al. 2010a) is consistent with a jet with low ejection rate (i.e. the case with the lowest luminosities derived).

In general, our model provides the first attempt to describe the characteristics of almost all the X-ray-emitting HH jets detected so far. We also derived detailed predictions on the future X-ray observations of HH 154, as discussed in detail in Bonito et al. (2010a).

Acknowledgments. We acknowledge support by the Marie Curie Fellowship Contract No. MTKD-CT-2005-029768. The software used in this work was in part developed by the DOE-supported ASC/Alliances Center for Astrophysical Thermonuclear

Flashes at the University of Chicago. The calculations were performed on the cluster on the SCAN facility on the INAF-OAPa and at CINECA (Bologna, Italy).

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