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X-ray structures from outflowing Young Stellar Objects interacting with the Interstellar Medium

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Abstract. Young stellar objects (YSOs) are strongly related to winds and outflows. Changes in the morphology and emission properties of those outflows can be the result of their interaction with the Interstellar Medium. The available tools developed into the computational field put at hand a better understanding of the structures that may form on scenarios with growing degrees of complexity. In this work we consider the propagation of a continuously driven supersonic protostellar jet through an inhomogeneous ambient described as an isothermal medium at the base of the launching site and a denser layer far from the YSO. The hydrodynamic evolution, including thermal conduction and radiative cooling is solved, and from the obtained temperature and density distributions we synthetize the outcoming emission in the X-ray band. We then consider the interstellar absorption and the response of the current X-ray telescopes in order to investigate the conditions leading to detectable X-rays.

Resumen. Los objetos estelares jóvenes suelen presentar vientos y flujos colimados. A partir de su interacción con el medio interestelar pueden resultar cambios en su morfología y propiedades de emisión. Las herramientas computacionales actuales ponen a nuestro alcance el estudio de situaciones como esta, con creciente complejidad. En este trabajo consideramos la propagación de un flujo protoestelar contínuo y supersónico a través de un medio con una discontinuidad, siendo más denso en una región lejana a la base desde donde se lanza el flujo. Seguimos su evolución hidrodinámica incluyendo enfriamiento radiativo y conducción térmica, y de las distribuciones obtenidas para la densidad y temperatura, derivamos la emisión saliente en rayos X. Luego consideramos la absorción interestelar y respuesta instrumental de los telescopios de rayos X para indagar las condiciones necesarias para detectar dicha emisión.

1. The model and simulation scheme

We consider the propagation of a continuously driven supersonic protostellar jet with density $n_j = 500$ cm^{-3} and temperature $T_j = 10^4$ K through an isothermal medium at the base of the launching site and a dense layer far from the YSO. This system can be a realistic representation of the observed medium around the protostar L1630MIR-51 that seems to have blown material in direction of the ionization front IC 434. The latter appears as a bright *wall* in the deep Wide Field Camera 3 images, while the origin of the Herbig Haro objects in the vicinity could be ejections from this YSO.

The initial conditions in our model are set to describe pressure equilibrium between the jet and the ambient, and between the ambient and the wall. The basic parameters for this configuration are three:

$$\begin{aligned} M_j \quad &: \text{initial jet Mach number,} \\ \nu_a = n_a/n_j \quad &: \text{initial ambient-to-jet density contrast, and} \\ \nu_w = n_w/n_j \quad &: \text{the initial wall-to-jet density contrast,} \end{aligned}$$

while for for other flow properties defining the scenario we have used characteristic values, similar to Bonito et al. (2004).

The hydrodynamic evolution, including thermal conduction and radiative cooling is solved assuming a perfect, fully ionized, gas with specific heats ratio $\gamma = 5/3$. The usual mass and momentum equations of conservation are considered along with the following energy equation

$$\frac{\partial \rho E}{\partial t} + \nabla \cdot (\rho E + p)\mathbf{v} = -\nabla \cdot q - n_e n_H P(T) \tag{1}$$

with

$$p = (\gamma - 1)\rho\epsilon, \qquad E = \epsilon + \frac{1}{2}|\mathbf{v}|^2, \tag{2}$$

where p is the pressure, E the total gas specific energy (internal energy, ϵ, and kinetic energy) respectively, ρ is the mass density, t the time, $\mathbf{v}$ the plasma velocity, q the heat flux, and $P(T)$ is the radiative losses function per unit emission measure which takes into account free-free, bound-free, bound-bound and 2 photons emission (Raymond & Smith 1977, Mewe et al. 1985, Kaastra & Mewe 2000). The other quantities have the typical meaning. An interpolation expression for the thermal conductive flux allows for a smooth transition between the Spitzer and saturated conduction regimes (Dalton & Balbus 1993).

Any magnetic field is regarded as negligible. We have fixed the initial jet radius $r_j = 100$ AU. The wall is located at $z = 10^4$ AU, and the computational domain is axisymmetric with $(r \times z) \simeq (1500 \times 15000)$ AU. Reflection boundary conditions are imposed along the jet axis, inflow boundary conditions at the base for $r < r_j$, and outflow boundary conditions elsewhere. The calculations are performed with the FLASH code (Fryxell et al. 2000), which incorporates an adaptive grid scheme to handle compressible plasmas with shocks, and uses the message passing interface library to achieve parallelization.

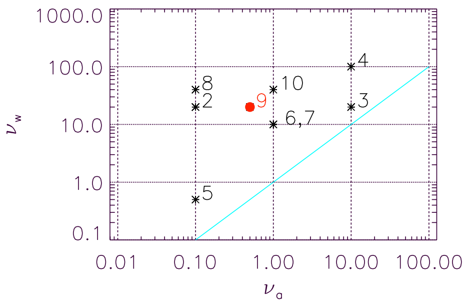

Figure 1. One plane of the explored parameter space. From the resulting temperature the configurations 7 and 10 produce too hot front shocks.

2. Results and emission properties

In order to explore the parameter space we have followed the evolution of the jet for several configurations designed to represent realistic HH flows and keeping $n_w > n_a$ through different combinations. A variety of temperature distributions[1] are achieved after a time interval between ~ 100 and ~ 300 yr, depending on the set of parameters, when the shock front has advanced inside the wall upto a half of its height. We then consider the interstellar absorption for a column density $N_H \sim 10^{22}$ cm^{-2}, and the response of the last generation X-ray telescopes to obtain the focal plane image. Specifically, we use Chandra to compare images and XMM-Newton to compare the results from the spectral analysis, in order to take advantage of the high spatial resolution of the former and the large effective area of the latter.

The best suited case to produce an X-ray source detectable at the assumed distance, $d \sim 400$ pc, is given by $M_j = 40$, $\nu_a = 0.5$, and $\nu_w = 20$. These values correspond to run 9 indicated in red in Figure 1 where we show one of the parameter planes explored. In Figure 2 we show the synthetic image, and the spectrum. The obtained luminosity is $L_X \sim 10^{30}$ erg/s. For the run 9 configuration and ~ 100 yr of advance the X-ray source is located inside the wall and has an almost pointlike morphology.

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[1] The distributions are not shown here but the authors will be pleased to shown them as they were included in the poster for the meeting. Contact: *morellana@fcaglp.unlp.edu.ar*

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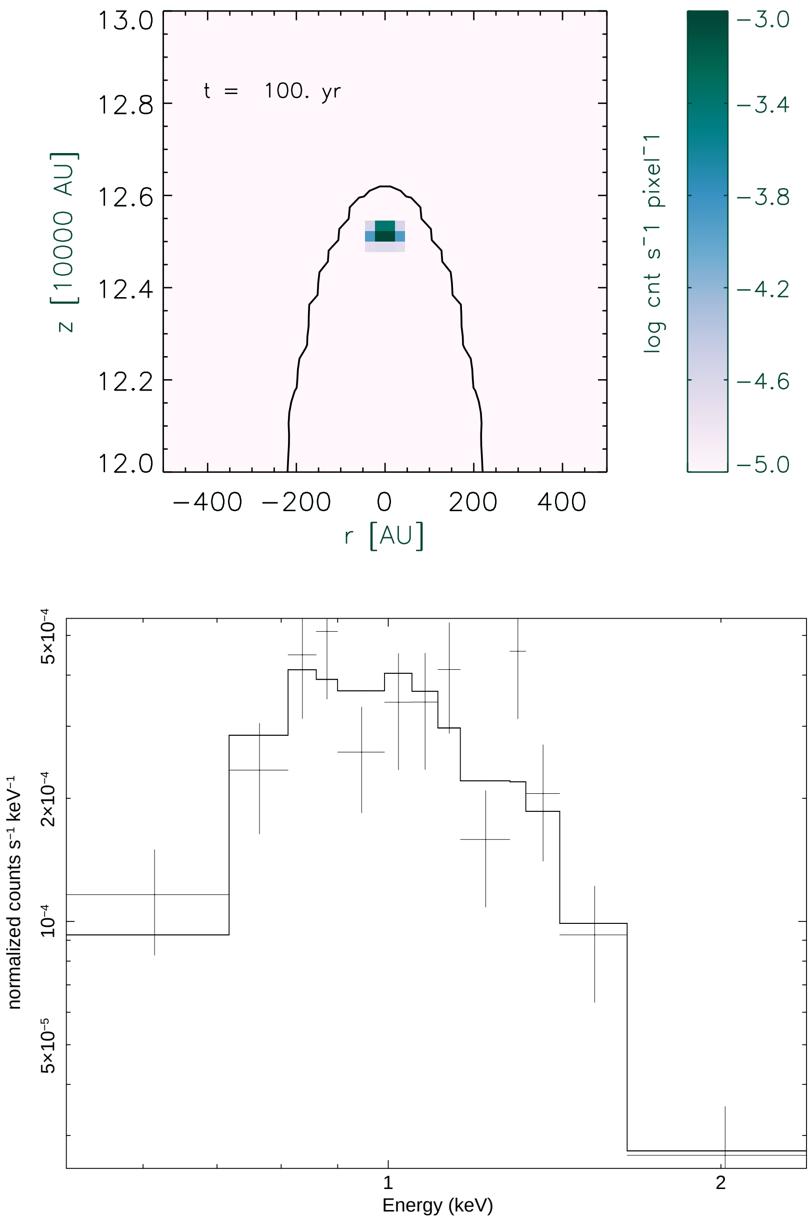

Figure 2. Top: Synthetic X-ray map. Detail showing the source is located behind the shock. The black contour indicates the place of not perturbed gas of the wall. Bottom: The X-ray spectrum using an exposure time 500 ks, binning to have at least 10 counts per bin. The model shows the C-statistic fit, which resulted in $kT = 0.28$ keV.