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Bowshockpy: A generator of synthetic observations for jet-driven bowshocks

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Summary

Collimated jets are a common phenomenon in the Universe, appearing in a variety of astrophysical objects with accretion disks, such as black holes, planetary nebulae, and young stellar objects (YSOs). These astrophysical jets sometimes present knotty structures, which have long been suggested to be the result of a velocity variations of the flow within the jet beam (Rees, 1978). In the case of jets from YSOs, interpreting the knots as "internal working surfaces" produced by time-variable ejection, provided an explanation for the multiple bow-shaped shocks typically observed in Herbig-Haro jets: the overpressure in the internal working surface drives material sideways, which interacts with the ambient to form the bowshocks shells (Masson & Chernin, 1993; Raga et al., 1990; Stone & Norman, 1993). Current observations probing the molecular components of jets from YSOs are detecting bowshock shells with sufficient high angular and spectral resolution to reveal in details of their morphology and kinematics. The characterization of these bowshock using models provides valueable informaton of the interaction of the jet with the environment (Blázquez-Calero et al., under review). Bowshockpy is a Python package that generates synthetic spectral cubes, PV diagrams, and moment images for a simple analytical jet-driven bowshock model, using the prescription for protostellar jets presented in Tabone et al. (2018).

Statement of need

Jets from YSOs are thought to play a crucial role in the formation of a star by removing angular momentum from the disk and, therefore, allowing accretion onto the forming star. Additionally, jets are invoked in order to explain the low star formation efficiency at both core and cloud scales (Frank et al., 2014). Thus, characterizing the physical properties of protostellar jets and their interaction with their surrounding medium is of major importance in order to understand the star formation process. Recent observations at mm wavelengths with radio interferometers, specially the Atacama Large Milimeter Array (ALMA), enable us to study in great detail the molecular component in jets (mainly in CO and SiO emisson). Sensitive observations at high and spectral resoltion with ALMA reveal the presence of shell-like structures connecting the fast knots in the jet. While knots in the jets are usually interpreted as internal working surfaces (Tafalla et al., 2017) that expel jet material sideways by pressure forces, the shells are thought to be bowshocks that arise from the interaction of this jet material with the surrounding gas (Lee et al., 2017; Plunkett et al., 2015). Characterizing these bowshocks through models an numerical simulations (Ostriker et al., 2001; Tabone et al., 2018) can give information on the interaction of the jet with the surrounding gas, such as quantifying the velocity and mass-rate at which jet material is expeled sideways from the internal working surface, the mass-rate of ambient material incorporated into the bowshock and the ambient density (Blázquez-Calero et al., under review).

Bowshockpy is an implementation of the analytical momentum conserving bowshock model of

Tabone et al. (2018), which has been validated with hydrodynamical numerical simulations. The software computes the observed column densities of the bowshock shell and, assuming local thermodynamic equilibrium conditions, simulates the CO intensities of low-J rovibrational transitions, providing mock observations of the CO emission that radio telescopes would be able to detect at milimeter wavelengths. This software provides spectral cubes, PV diagrams, and moment images of the bowshock shell fairly quick in an personal computer, allowing the modelization of observed bowshocks using just a few user-defined model and observer/instrumental parameters. To our knowledge, there is no software publicly available that allows the creation of synthetic observations of an analytical jet-driven bowshock model. We note that, although this software has been initially aimed to be used in jet-driven bowshocks in YSO objects, its applicability would be equally valid for molecular jets from protoplanetary nebulae.

Description

We summarize here the key principles and characteristics of the analytic, momentum-conserving bowshock model presented in Ref. Tabone et al. (2018), which we use as a basis for comparison with our data. Originally developed to describe the leading bowshock at the jet head(Masson & Chernin, 1993; Ostriker et al., 2001), this model was recently extended by Tabone et al. (2018) to describe bowshocks formed by internal working surfaces (IWS) within a jet propagating into a slower-moving ambient medium.

In the framework of momentum conserving bowshock, velocity variations within a highly supersonic jet induces the formation of a two-shock structure called internal working surface (Raga et al., 1990). Then, the overpressured shocked jet material is driven sideways, interacting with slower surrounding material, forming a curved bowshock. By modeling the bowshock as a stationary, thin shell of well-mixed material, its shape and velocity field can be derived self-consistently from the conservation of mass and momentum.

Summary: Few parameters that define the bowshock, we obtain the CO spectral cube, pv's, and moments.

- Explain the bowshock model. Foundations (references). Morphology and kinematics given in Ostriker and Tabone. Parameters that define a bowshock.
- Surface density (ref of your paper?)
- Mass in each pixel. CIC interpolation
- Once we have the mass in each cell of the spectral cube through equation, we can calculate the intensity of the line of interest, assuming the excitation properties and performing the radiative transfer. In this thesis, we are interested in the CO emission from a bowshock model, assuming LTE conditions and perform for the radiative transfer (eqs from). In order to compare it with radio observations, we convolved the model images with the synthetized beam of the observations.
- Outputs: Cube, pv's and moments, but also important parameters such as mdot0, mdotamb, and the ambient density.

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