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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, post-AGB stars, and young stellar objects (YSOs). Astrophysical jets often exhibit knotty structures, which have long been suggested to be internal shocks resulting from velocity variations within the jet flow (Kofman & Raga, 1992; Raga & Kofman, 1992; Rees, 1978). In fact, numerical simulations show that supersonic variations in the ejection velocity lead to the formation of two-shock structures known as "internal working surfaces", which travel downstream of the jet flow (Biro & Raga, 1994). The overpressure in the internal working surface drives material sideways that interacts with the ambient, producing the bow-shaped shocks typically observed in jets from YSO (Masson & Chernin, 1993; Raga et al., 1990; Stone & Norman, 1993). Modeling bowshock shells offers valuable insight into how jets interact with the ambient medium, enabling us to characterize jet properties that are essential for understanding how stars form (Blázquez-Calero et al., 2025).

BowshockPy is an open-source Python package that generates synthetic spectral cubes, position-velocity diagrams, and moment images of an analytical jet-driven bowshock model, using the prescription for YSO jets presented in Ostriker et al. (2001) and Tabone et al. (2018). BowshockPy assumes a thin bowshock shell whose morphology and kinematics are determined by the mass and momentum conservation (ignoring pressure gradients), considering full mixing between the jet and ambient material as well as a negligible size of the internal working surface. The software calculates the column densities of the bowshock shell and can determine the intensities of low-J rotational transitions of linear molecules (such as CO). The intensities are obtained using the rigid rotor approximation (valid for low-J transitions, where vibrational excitation and centrifugal distortion effects are negligible), and assuming local thermodynamic equilibrium. This provides mock observations of the molecular line emission that radio telescopes as the Atacama Large Millimeter Array (ALMA) are able to image at millimeter wavelengths.

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 YSO 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 ALMA, enable us to study in great detail the molecular component in jets. Sensitive observations at high spatial and spectral resolution with ALMA reveal the presence of shell-like structures connecting the fast knots in the jet. While knots in the jets have been interpreted as internal working surfaces that eject jet material sideways by pressure forces (Santiago-García et al., 2009), the shells could be bowshocks that arise from the interaction of this jet material with the surrounding gas (Lee et al., 2017; López-Vázquez et al., 2024; Plunkett et al., 2015). Characterizing these bowshocks through models and numerical simulations (Ostriker et al., 2001; Rabenanahary et al., 2022; Rivera-Ortiz et al., 2023; Tabone et al., 2018; Tafalla et al., 2017, 2026) can provide quantitative information on the interaction of the jet with the surrounding gas, such as the velocity and mass-rate at which jet material is ejected sideways from the internal working surface, the mass-rate of ambient material incorporated into the bowshock, and the ambient density (Blázquez-Calero et al., 2025). This information helps to understand the dynamical properties of jets and how it injects mass and momentum to the environment, both of which are crucial for understanding how stars forms.

The necessity of `BowshockPy` relies on the importance of providing a public open-source tool for modeling bowshock shells, with particular focus on the line emission of low-J rotational transitions of linear molecules (such as CO), observable at millimeter wavelengths by radio interferometers as ALMA.

State of the field

Although there are numerous publications that have modeled many different aspects of bowshocks from YSO jets (Burns et al., 2016; Correia et al., 2009; Lee et al., 2000; Rabenanahary et al., 2022; Rivera-Ortiz et al., 2023; Schultz et al., 2005; Smith et al., 2003; Tafalla et al., 2026), there is no public software designed for these purposes. The simple analytical momentum-conserving bowshock model implemented in `BowshockPy` (Ostriker et al., 2001; Tabone et al., 2018), which assumes a thin shell of fully mixed jet and ambient material, enables fast computation. The model results have been compared with more detailed hydrodynamical simulations, obtaining a good agreement in the bowshock morphology and kinematics (Tabone et al., 2018).

Software design

`BowshockPy` is a Python 3 software designed with the purpose of generating in a simple and quick way model images of bowshocks that can be directly compared with observations. `BowshockPy` computes synthetic spectral cubes, position-velocity diagrams, and moment maps (integrated intensity, peak intensity, mean velocity field, and velocity dispersion) for an analytical jet-driven bowshock model, based on the prescription for YSO jets presented in Ostriker et al. (2001) and Tabone et al. (2018). These are the steps followed by `BowshockPy` in order to obtain the line intensity spectral cubes:

- From the mass and momentum conservation equations, the morphology and kinematics of the bowshock shell can be obtained as a function of a few free parameters (Ostriker et al., 2001; Tabone et al., 2018). These model parameters are a characteristic length scale, the distance between the working surface and the source, the velocity of the internal working surface, the velocity of ambient material surrounding the jet, and the velocity at which the material is ejected from the internal working surface. The surface density at each point of the bowshock is computed as a function of the shell integrated mass (Blázquez-Calero et al., 2025). At this stage, we have all the parameters that define the model in its own reference frame. The rest of the workflow depends on the observer reference frame.

- In order to perform the mock observations, some parameters dependent of the observer reference frame are used, mainly: the inclination angle of the bowshock axis with respect to the line-of-sight, the observer distance to the source, the systemic velocity of the ambient cloud, and the position angle of the bowshock axis.
- Together with some parameters defining the properties of the spectral cube, such as the pixel size and channel width, `BowshockPy` computes the mass of the bowshock shell at each pixel and velocity channel of the spectral cube.
- From the masses at each pixel and channel of the spectral cube, `BowshockPy` computes the column densities of the emitting molecule assuming a given abundance. In addition, it can calculate the opacities under local thermodynamic equilibrium for a low-J rotational transition of a linear molecule in the rigid rotor approximation (that is, under the assumption of negligible vibrational excited states and negligible centrifugal distortion effects), and perform the radiative transfer to obtain the intensities. If the user needs a different model to determine the intensities, `BowshockPy` allows them to apply custom models to the calculated column densities.

There are two ways to utilize `BowshockPy`: It can either be run from the terminal using an input file containing all the model parameters, or it can be imported as a package to use its functions and classes. The computed spectral cubes, position velocity diagrams, and moments maps are saved in `FITS` format. For more detailed information about `BowshockPy` and its features, see the extensive documentation hosted at ReadtheDocs, where examples and a notebook tutorial showing its usage are presented.

The code is available at GitHub and licensed under the MIT License. It can be installed via PyPI, and it depends on the Python open-source libraries `NumPy` (Harris et al., 2020), `SciPy` (Virtanen et al., 2020), `Matplotlib` (Hunter, 2007), `Photutils` (Bradley et al., 2022), and `Astropy` (Astropy Collaboration et al., 2013, 2018, 2022).

Research impact Statement

`BowshockPy` has proven to be highly valuable for modeling jet-driven bowshock shells. It has been used in Blázquez-Calero et al. (2025), which showed that the bowshock model is able to reproduce the morphology and kinematics of the observed shell-like structures in a molecular jet. Its capability to generate images that can be directly compared with observations at a low computational cost makes it a very useful tool for the scientific community specialized in jets from YSO, particularly for interpreting sensitive radio interferometric observations with high spatial and spectral resolution.

AI usage disclosure

No AI tools were used in the creation of this software. Generative AI tools were used only occasionally to correct the spelling and improve the clarity of some parts of the text in this paper.

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