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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). 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 the case of YSO jets, interpreting the knots as "internal working surfaces" produced by a time-variable ejection provides an explanation for the multiple bow-shaped shocks typically observed in optical jets: the overpressure in the internal working surface drives material sideways, which then 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 YSO jets –with high angular and spectral resolution– are now resolving shells connecting the jet knots, revealing their morphology and kinematics in great detail (Lee et al., 2017; López-Vázquez et al., 2024; Plunkett et al., 2015). Modeling bowshock shells offers valuable insight into how jets interact with the environment (Blazquez-Calero et al., under rev.).

`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). The software computes the intensities of low-J rotational transitions of the CO molecule, providing mock observations of the CO emission that radio telescopes as the Atacama Large Milimeter Array (ALMA) are able to detect 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 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 expel jet material sideways by pressure forces (Tafalla et al., 2017), 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; 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 (Blazquez-Calero et al., under rev.).

The necessity of `Bowshockpy` relies on the importance of providing a public open-source tool for modelling bowshock shells, with particular focus on the CO emission observable at millimeter wavelengths by radio telescopes as ALMA. 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), there is no public software designed for these puposes. The analytical momentum-conserving bowshock jet-driven model implemented in `Bowshockpy` (Ostriker et al., 2001; Tabone et al., 2018), enables fast computation and, despite its assumptions (mainly, negligible pressure gradients and full mixing between jet and ambient material), its validity has been tested by more realistic hydrodynamcal simulations (Tabone et al., 2018).

# Code description

`Bowshockpy` computes synthetic spectral cubes, position-velocity diagrams, and moment images for an analytical jet-driven bowshock model, using the prescription for YSO jets presented in Ostriker et al. (2001) and Tabone et al. (2018). In this scenario, velocity variations within the beam of a highly collimated and highly supersonic jet induces the formation of internal working surfaces, from which jet material is ejected sideways. This jet material interacts with the ambient material, forming the bowshock shell. The analytical prescription implemented in `bowshockpy` assumes mass and momentum conservation (negligible preasure gradients), full mixing between the jet and ambient material, and a negligible size of the internal working suface.

These are the steps followed by `Bowshockpy` in order to obtain the CO 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 (see Ostriker et al. (2001) and Tabone et al. (2018)). These model parameters are characteristic length scale, the distance between the working surface and the source, the velocity of the internal working surfce, velocity of the material surrounding jet, and the velocity at which the material is ejected from the internal working surface .
- Given the total mass of the bowshock shell, one can obtain its surface density. 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, and the position angle of the bowshock axis. Together with some parameters defining the properties of the spectral cube, as the pixel size and channel width, bowshockpy computes, in projection, the mass of the bowshock shell at each pixel and velocity channel of the spectral cube.
- `Bowshockpy` can also calculate the intensities of low-J rotational CO transtions. Assuming a CO abundance, bowshockpy calculates first the column densities at each pixel and channel of the spectral cube. Given the excitation temperature and assuming Local Thermodinamic Equilibrium, the opacities are computed. Finally, `bowshockpy` performs the radiative transfer in order to compute the intensities.

The output spectral cubes, position velocity diagrams, and moments maps (integrated intensity, peak intensity, mean velocity field and vthe velocity dispersion) are saved in `FITS` format.

The code is available at GitHub and licensed under the MIT License. It can be install 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). For more detailed information about `Bowshockpy` and its features, see the extensive documentation hosted at ReadtheDocs, where examples and notebooks showing its usage are presented.


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