JOSS
The Journal of Open Source Software

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

Guillermo Blázquez-Calero[1¶], **Guillem Anglada**[1], **Alejandro C. Raga**[2], **Sylvie Cabrit**[3,4], **Mayra Osorio**[1], **José F. Gómez**[1], **Gary A. Fuller**[5], **Ruben Fedriani**[1], **Itziar de Gregorio-Monsalvo**[7], **Noah Otten**[8], **Florin Placinta-Mitrea**[1], **Pablo Santo-Tomás**[1], **Oier Baraibar**[1], **Josep M. Masqué**[9], and **Rodrigo D. Garduño**[10]

1 Instituto de Astrofísica de Andalucía, CSIC, Glorieta de la Astronomía s/n, E-18008 Granada, Spain **2** Instituto de Ciencias Nucleares, Universidad Nacional Autónoma de México, Apartado Postal 70-543, 04510 Ciudad de México, Mexico **3** Observatoire de Paris — PSL University, Sorbonne Université, CNRS, 75014 Paris, France **4** Univ. Grenoble Alpes, CNRS, IPAG, 38000 Grenoble, France **5** Jodrell Bank Centre for Astrophysics, Department of Physics and Astronomy, The University of Manchester, Oxford Road, Manchester M13 9PL, UK **6** I. Physikalisches Institut, University of Cologne, Zülpicher Str. 77, 50937 Küoln, Germany **7** European Southern Observatory, Alonso de Córdova 3107, Casilla 19, Vitacura, Santiago, Chile **8** Department of Physics, Maynooth University, Maynooth, Co. Kildare, Ireland **9** Institut de Ciències del Cosmos (ICCUB), Universitat de Barcelona (UB), Martí de Franquès 1, E-08028 Barcelona, Spain **10** Departamento de Astronomía, Universidad de Guanajuato, Apartado Postal 144, 36000 Guanajuato, México ¶ Corresponding author

DOI: 10.xxxxxx/draft

Software

- Review
- Repository
- Archive

Editor: Open Journals

Reviewers:

- @openjournals

Submitted: 01 January 1970
Published: unpublished

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). 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; 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 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. 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 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). Moreover, it has been successful in reproducing the observed properties of shell-like structures in molecular jets (Blázquez-Calero et al., 2025).

Code description

`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). 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 a thin bowshock shell whose morphology and kinematics are determined by the mass and momentum conservation (with negligible pressure gradients), considering full mixing between the jet and ambient material as well as a negligible size of the internal working surface.

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).

Acknowledgments

G.A., G.B.-C., IdG-M., G.A.F., J.F.G., M.O., R.F., F.P.M., O.B., P.S.-T., acknowledge financial support from grants PID2023-146295NB-I00PID and CEX2021-001131-S, funded by MCIN/AEI/10.13039/501100011033. G.B-C acknowledges support from grant PRE2018-086111, funded by MCIN/AEI/10.13039/501100011033 and by 'ESF Investing in your future', and thanks ESO Science Support Discretionary Fund for their finantial support under the 2024 SSDF 06 project. S.C. acknowledges support by the Thematic Action "Physique et Chimie du Milieu Interstellaire" (PCMI) of INSU Programme National "Astro", with contributions from CNRS Physique & CNRS Chimie, CEA, and CNES. N. Otten acknowledges funding from the Maynooth University Graduate Teaching Scholarship and Taighde Éireann (Research Ireland) under the RI-ESO Studentship Agreement for this work. F.P.M. acknowledges support from grant PRE2021-100926, funded by MCIN/AEI/10.13039/501100011033. P.S.-T. acknowledges financial support from project ref. AST22_00001_Subp X with funding from the European Union - NextGenerationEU; the Spanish Ministry of Science, Innovation and Universities; the Spanish Recovery, Transformation and Resilience Plan; the Department of University, Research and Innovation of the Andalusian Regional Government and Consejo Superior de

Investigaciones Científicas. O.B. acknowledges support from grant PREP2023-001438, funded by MCIN/AEI/10.13039/501100011033.

References

Astropy Collaboration, Price-Whelan, A. M., Lim, P. L., Earl, N., Starkman, N., Bradley, L., Shupe, D. L., Patil, A. A., Corrales, L., Brasseur, C. E., Nöthe, M., Donath, A., Tollerud, E., Morris, B. M., Ginsburg, A., Vaher, E., Weaver, B. A., Tocknell, J., Jamieson, W., … Astropy Project Contributors. (2022). The Astropy Project: Sustaining and Growing a Community-oriented Open-source Project and the Latest Major Release (v5.0) of the Core Package. *Apj*, *935*(2), 167. https://doi.org/10.3847/1538-4357/ac7c74

Astropy Collaboration, Price-Whelan, A. M., Sipőcz, B. M., Günther, H. M., Lim, P. L., Crawford, S. M., Conseil, S., Shupe, D. L., Craig, M. W., Dencheva, N., Ginsburg, A., VanderPlas, J. T., Bradley, L. D., Pérez-Suárez, D., de Val-Borro, M., Aldcroft, T. L., Cruz, K. L., Robitaille, T. P., Tollerud, E. J., … Astropy Contributors. (2018). The Astropy Project: Building an Open-science Project and Status of the v2.0 Core Package. *Aj*, *156*(3), 123. https://doi.org/10.3847/1538-3881/aabc4f

Astropy Collaboration, Robitaille, T. P., Tollerud, E. J., Greenfield, P., Droettboom, M., Bray, E., Aldcroft, T., Davis, M., Ginsburg, A., Price-Whelan, A. M., Kerzendorf, W. E., Conley, A., Crighton, N., Barbary, K., Muna, D., Ferguson, H., Grollier, F., Parikh, M. M., Nair, P. H., … Streicher, O. (2013). Astropy: A community Python package for astronomy. *Aap*, *558*, A33. https://doi.org/10.1051/0004-6361/201322068

Biro, S., & Raga, A. C. (1994). A Numerical Simulation of a Variable Velocity Jet. *434*, 221. https://doi.org/10.1086/174719

Blázquez-Calero, G., Anglada, G., Cabrit, S., Osorio, M., Raga, A. C., Fuller, G. A., Gómez, J. F., Estalella, R., Diaz-Rodriguez, A. K., Torrelles, J. M., Rodríguez, L. F., Macías, E., de Gregorio-Monsalvo, I., Megeath, S. T., Zapata, L., & Ho, P. T. P. (2025). Bowshocks driven by the pole-on molecular jet of outbursting protostar SVS 13. *Nature Astronomy*. https://doi.org/10.1038/s41550-025-02716-2

Bradley, L., Sipőcz, B., Robitaille, T., Tollerud, E., Vinícius, Z., Deil, C., Barbary, K., Wilson, T. J., Busko, I., Donath, A., Günther, H. M., Cara, M., Lim, P. L., Meßlinger, S., Conseil, S., Bostroem, A., Droettboom, M., Bray, E. M., Andersen Bratholm, L., … Quint, B. (2022). *astropy/photutils: 1.6.0* (Version 1.6.0). Zenodo; Zenodo. https://doi.org/10.5281/zenodo.7419741

Burns, R. A., Handa, T., Nagayama, T., Sunada, K., & Omodaka, T. (2016). H_2O masers in a jet-driven bow shock: episodic ejection from a massive young stellar object. *460*(1), 283–290. https://doi.org/10.1093/mnras/stw958

Correia, S., Zinnecker, H., Ridgway, S. T., & McCaughrean, M. J. (2009). The H_2 velocity structure of inner knots in HH 212: asymmetries and rotation. *505*(2), 673–686. https://doi.org/10.1051/0004-6361/200912385

Frank, A., Ray, T. P., Cabrit, S., Hartigan, P., Arce, H. G., Bacciotti, F., Bally, J., Benisty, M., Eislöffel, J., Güdel, M., Lebedev, S., Nisini, B., & Raga, A. (2014). Jets and Outflows from Star to Cloud: Observations Confront Theory. In H. Beuther, R. S. Klessen, C. P. Dullemond, & T. Henning (Eds.), *Protostars and planets VI* (pp. 451–474). https://doi.org/10.2458/azu_uapress_9780816531240-ch020

Harris, C. R., Millman, K. J., van der Walt, S. J., Gommers, R., Virtanen, P., Cournapeau, D., Wieser, E., Taylor, J., Berg, S., Smith, N. J., Kern, R., Picus, M., Hoyer, S., van Kerkwijk, M. H., Brett, M., Haldane, A., del Río, J. F., Wiebe, M., Peterson, P., … Oliphant, T. E. (2020). Array programming with NumPy. *Nat*, *585*(7825), 357–362. https://doi.org/10.1038/s41586-020-2649-2

Hunter, J. D. (2007). Matplotlib: A 2D Graphics Environment. *Computing in Science and Engineering*, *9*(3), 90–95. https://doi.org/10.1109/MCSE.2007.55

Kofman, L., & Raga, A. C. (1992). Modeling Structures of Knots in Jet Flows with the Burgers Equation. *390*, 359. https://doi.org/10.1086/171287

Lee, C.-F., Ho, Paul. T. P., Li, Z.-Y., Hirano, N., Zhang, Q., & Shang, H. (2017). A rotating protostellar jet launched from the innermost disk of HH 212. *Nature Astronomy*, *1*, 0152. https://doi.org/10.1038/s41550-017-0152

Lee, C.-F., Mundy, L. G., Reipurth, B., Ostriker, E. C., & Stone, J. M. (2000). CO Outflows from Young Stars: Confronting the Jet and Wind Models. *542*(2), 925–945. https://doi.org/10.1086/317056

López-Vázquez, J. A., Lee, C.-F., Shang, H., Cabrit, S., Krasnopolsky, R., Codella, C., Liu, C.-F., Podio, L., Dutta, S., Murphy, A., & Wiseman, J. (2024). Multiple Components of the Outflow in the Protostellar System HH 212: Outer Outflow Shell, Rotating Wind, Shocked Wind, and Jet. *977*(1), 126. https://doi.org/10.3847/1538-4357/ad8eb4

Masson, C. R., & Chernin, L. M. (1993). Properties of Jet-driven Molecular Outflows. *414*, 230. https://doi.org/10.1086/173071

Ostriker, E. C., Lee, C.-F., Stone, J. M., & Mundy, L. G. (2001). A Ballistic Bow Shock Model for Jet-driven Protostellar Outflow Shells. *557*(1), 443–450. https://doi.org/10.1086/321649

Plunkett, A. L., Arce, H. G., Mardones, D., van Dokkum, P., Dunham, M. M., Fernández-López, M., Gallardo, J., & Corder, S. A. (2015). Episodic molecular outflow in the very young protostellar cluster Serpens South. *527*(7576), 70–73. https://doi.org/10.1038/nature15702

Rabenanahary, M., Cabrit, S., Meliani, Z., & Pineau des Forêts, G. (2022). Wide-angle protostellar outflows driven by narrow jets in stratified cores. *664*, A118. https://doi.org/10.1051/0004-6361/202243139

Raga, A. C., Canto, J., Binette, L., & Calvet, N. (1990). Stellar Jets with Intrinsically Variable Sources. *364*, 601. https://doi.org/10.1086/169443

Raga, A. C., & Kofman, L. (1992). Knots in Stellar Jets from Time-dependent Sources. *386*, 222. https://doi.org/10.1086/171008

Rees, M. J. (1978). The M87 jet: internal shocks in a plasma beam? *184*, 61P–65P. https://doi.org/10.1093/mnras/184.1.61P

Rivera-Ortiz, P. R., de A. Schutzer, A., Lefloch, B., & Gusdorf, A. (2023). Modeling the early mass ejection in jet-driven protostellar outflows: Lessons from Cep E. *672*, A116. https://doi.org/10.1051/0004-6361/202245085

Santiago-García, J., Tafalla, M., Johnstone, D., & Bachiller, R. (2009). Shells, jets, and internal working surfaces in the molecular outflow from IRAS 04166+2706. *495*(1), 169–181. https://doi.org/10.1051/0004-6361:200810739

Schultz, A. S. B., Burton, M. G., & Brand, P. W. J. L. (2005). A simple model for H_2 line profiles in bow shocks. *358*(4), 1195–1214. https://doi.org/10.1111/j.1365-2966.2005.08871.x

Smith, M. D., Khanzadyan, T., & Davis, C. J. (2003). Anatomy of the Herbig-Haro object HH7 bow shock. *339*(2), 524–536. https://doi.org/10.1046/j.1365-8711.20.3.06195.x

Stone, J. M., & Norman, M. L. (1993). Numerical Simulations of Protostellar Jets with Nonequilibrium Cooling. I. Method and Two-dimensional Results. *413*, 198. https://doi.org/10.1086/172988

Tabone, B., Raga, A., Cabrit, S., & Pineau des Forêts, G. (2018). Interaction between a pulsating jet and a surrounding disk wind. A hydrodynamical perspective. *614*, A119. https://doi.org/10.1051/0004-6361/201732031

Tafalla, M., Su, Y.-N., Shang, H., Johnstone, D., Zhang, Q., Santiago-García, J., Lee, C.-F., Hirano, N., & Wang, L.-Y. (2017). Anatomy of the internal bow shocks in the IRAS 04166+2706 protostellar jet. *597*, A119. https://doi.org/10.1051/0004-6361/201629493

Virtanen, P., Gommers, R., Oliphant, T. E., Haberland, M., Reddy, T., Cournapeau, D., Burovski, E., Peterson, P., Weckesser, W., Bright, J., van der Walt, S. J., Brett, M., Wilson, J., Millman, K. J., Mayorov, N., Nelson, A. R. J., Jones, E., Kern, R., Larson, E., … SciPy 1. 0 Contributors. (2020). SciPy 1.0: fundamental algorithms for scientific computing in Python. *Nature Methods*, *17*, 261–272. https://doi.org/10.1038/s41592-019-0686-2