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PyPLUTO: a Data Analysis Python Package for the PLUTO Code

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Summary

In recent years, numerical simulations have become indispensable for addressing complex astrophysical problems. The so-called magnetohydrodynamics (MHD) framework represents a key tool for investigating the dynamical evolution of astrophysical plasmas. This formalism consists of a set of partial differential equations (Chiuderi & Velli, 2015) that enforce the conservation of mass, momentum, and energy, along with Maxwell's equations for the evolution of the electromagnetic fields. Due to the high nonlinearity of the MHD equations (regardless of their specifications, e.g., classical/relativistic or ideal/resistive), a general analytical solution is not possible, making numerical approaches crucial. Numerical simulations usually produce large sets of data files, and their scientific analysis relies on dedicated software tools designed for data visualization (Ahrens et al., 2005; Childs et al., 2012). However, to encompass all code output features, specialized tools focusing on the numerical code may represent a more versatile and integrated solution. Here, we present PyPLUTO, a Python package tailored for efficient loading, manipulation, and visualization of outputs produced with the PLUTO code (Mignone et al., 2007; Mignone, Zanni, et al., 2012). PyPLUTO uses memory mapping to optimize data loading and provides general data manipulation and visualization routines. PyPLUTO also supports the particle modules of the PLUTO code, enabling users to load and visualize particles, such as cosmic rays (Mignone et al., 2018), Lagrangian (Vaidya et al., 2018), or dust (Mignone et al., 2019) particles, from hybrid simulations. A dedicated Graphical User Interface (GUI, shown in Fig. 1) simplifies the generation of single-subplot figures, making PyPLUTO a powerful yet user-friendly toolkit for astrophysical data analysis.

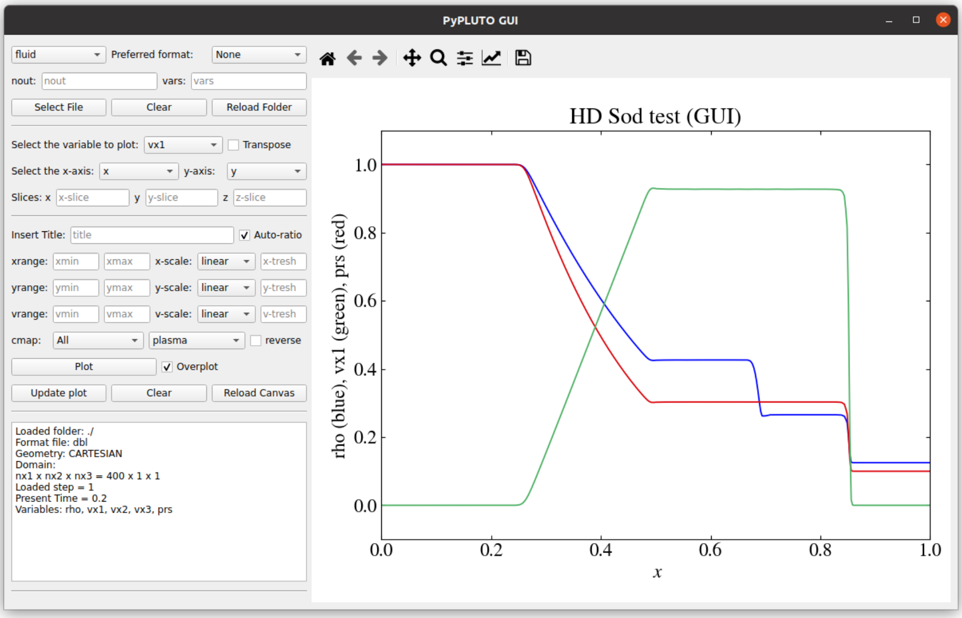

Figure 1: Interactive visualization of shock tube test results (i.e., density, pressure, and velocity profiles) with the GUI.

Statement of Need

The PLUTO code (Mignone et al., 2007) is a widely used, freely distributed computational fluid dynamics code designed to solve the classical and (special) relativistic MHD equations in different geometries and spatial dimensions. The original code is written in C (while the upcoming GPU version provides a complete C++ rewrite) and it contains several numerical methods adaptable to different contexts. Data post-processing is a crucial step in analyzing the results of any numerical simulation. Other packages addressing related needs (e.g., plutoplot) provide valuable functionality for working with PLUTO data, including loading and visualization. However, they may not support all data formats or offer integration for data manipulation and advanced plotting tasks. In this work, we present PyPLUTO, a Python package designed to efficiently load, manipulate, and visualize the output from the PLUTO code. The initial version of PyPLUTO (written by Bhargav Vaidya) is available here. PyPLUTO has since been completely rewritten and is now maintained at a new repository. The package retains its core strengths while offering user-friendly methods for generating publication-quality plots with high customization. In addition to its enhanced flexibility, PyPLUTO offers strong computational efficiency, enabling the rapid handling of large datasets typical of state-of-the-art numerical simulations. Through this balance between customization, performance, and ease of use, PyPLUTO represents a key tool to effectively communicate scientific results while minimizing the effort required for post-processing.

Main Features

PyPLUTO is a package written in Python (version $ $3.10) with the additions of NumPy (Harris et al., 2020), Matplotlib (Hunter, 2007), SciPy (Virtanen et al., 2020), pandas (team, 2020), h5py (Collette, 2013), and PyQT6 (although the last two are optional). The package, which can be installed through pip, primarily consists of three main classes:

- The Load class loads and manipulates the PLUTO output files containing fluid-related quantities.
- The LoadPart class loads and manipulates the PLUTO output files containing particle-related quantities.
- The Image class produces and handles the graphical windows and the plotting procedures.

Additionally, a separate PyPLUTOApp class launches a GUI able to load and plot 1D and 2D data in a single set of axes. PyPLUTO has been implemented to be supported by Windows, MacOS, and Linux, through both standard scripts and more interactive tools (e.g., IPython or Jupyter). The style guidelines follow the PEP8 conventions for Python code, enforced through the Black package (Langa & Black, 2020), and focus on clarity and code readability. Finally, by leveraging the capabilities of the sphinx package, PyPLUTO features extensive docstrings, providing a helpful reference for both users and developers.

Benchmark Examples

PyPLUTO provides a set of benchmarks that are immediately accessible after the package is installed. These consist of test problems that can be applied to relevant astrophysical applications and showcase the full range of PyPLUTO's features. Here we report two examples demonstrating the package's capabilities.

Disk-planet Interaction

This test problem examines particle acceleration near an X-type magnetic reconnection region (Puzzoni et al., 2021). In the last decades, magnetic reconnection (Bugli et al., 2025; Mattia et al., 2023) has proven to be a key physical process to explain the population of non-thermal particles in solar flares, relativistic outflows, and neutron star magnetospheres. This sort of test provides valuable insights into particle acceleration mechanisms in high-energy astrophysical environments by enabling the investigation of particle trajectories and energy distribution near the X-point. This test simulates the interaction of a planet embedded in a disk (Mignone, Flock, et al., 2012) and represents an ideal scenario for understanding the formation and evolution of planetary systems. In particular, forming spiral density waves and disk gaps represents some key observational signatures of planet formation and planet-disk interaction (Melon Fuksman et al., 2021; Muley et al., 2024). In the left panel of Fig. 2, we show an adaptation of Figure 10 of (Mignone, Flock, et al., 2012), featuring two separate zoom-ins around the planet's location.

- The first zoom (upper-right subplot) shows an enlarged view of the density distribution using the same color map and logarithmic scale as the global plot.
- The second zoom (lower-left subplot) highlights the changes in toroidal velocity due to the planet's presence by employing a different color map (to enhance the sign change) and a linear color scale.

These zoomed views offer deeper insights into the physical processes at play and demonstrate the utility of PyPLUTO for analyzing complex astrophysical systems.

Particles Accelerated near an X-point

This test problem examines particle acceleration near an X-type magnetic reconnection region (Puzzoni et al., 2021). In the last decades, magnetic reconnection (Bugli et al., 2025; Mattia et al., 2023) has proven to be a key physical process to explain the population of non-thermal particles in solar flares, relativistic outflows, and neutron star magnetospheres. This sort of test provides valuable insights into particle acceleration mechanisms in high-energy astrophysical environments by enabling the investigation of particle trajectories and energy distribution near the X-point.

In the right panel of Fig. 2, we show an adaptation of the top panel of Figures 13-14 from (Mignone et al., 2018). The main plot displays the distribution of test particles, color-coded by their velocity magnitudes, with magnetic field lines overlaid as solid and dashed lines. The inset panel shows the energy spectrum at the initial ($t = 0$, in blue) and final ($t = 100$, in red) time. In this scenario, the absence of a guide field ($\vec{E} \cdot \vec{B} = 0$) results in a symmetric distribution along the y-axis from the combined effects of the gradient, curvature, and $\vec{E} \times \vec{B}$ drifts in the vicinity of the X-point, where the electric field is the strongest. This plot provides a clear visual representation of particle motion and energy changes, demonstrating how PyPLUTO can be used to investigate complex processes such as particle acceleration in astrophysical sources.

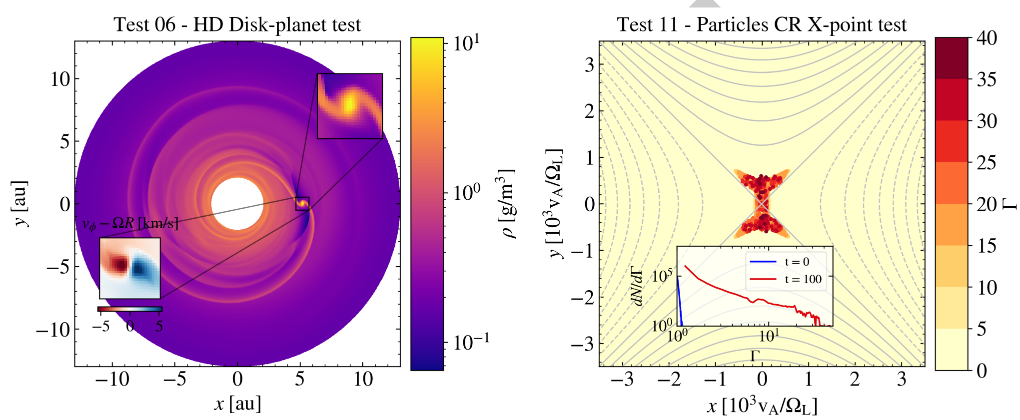

Figure 2: Left panel: example of inset zooms of the planet region of the disk-planet test problem. The main plot and the right zoom show the density on a logarithmic scale, while the left zoom highlights the toroidal velocity on a linear scale. Right panel: example of an X-point region with magnetic field lines overlaid (as contour lines of the vector potential, solid lines). The main plot shows the test-particle distribution, color-coded by velocity magnitudes, while the inset plot displays the particle energy spectrum at the beginning (in blue) and end (in red) of the simulation.

Ongoing research using PyPLUTO

Research applicable with PyPLUTO includes the development of numerical algorithms (Berta et al., 2024; Mattia & Mignone, 2022; Melon Fuksman et al., 2025) and numerical simulations of astrophysical objects, such as jets (Costa et al., 2025; Mattia et al., 2023, 2024; Mattia & Fendt, 2022; Sciaccaluga et al., 2025), star clusters (Härer et al., 2025), and protoplanetary disks (Melon Fuksman et al., 2024a, 2024b), as well as physical processes, such as particle acceleration (Wang et al., 2024) and magnetic reconnection (Bugli et al., 2025).

Conclusion and Future Perspectives

The PyPLUTO package is designed as a powerful yet flexible tool to facilitate the data analysis and visualization of the output from PLUTO simulations, focusing on user-friendliness while allowing the necessary customization to produce publication-quality figures. To overcome current limitations and further enhance the package's capabilities, particular focus will be devoted to:

- introducing specific routines for rendering 3D data to provide users with tools for visualizing volumetric data;
- supporting interactive visualization and comparison of multiple simulation outputs, allowing the users to track temporal evolution directly with the GUI;

- expanding the graphical interface to support particle data, including dynamic visualization of particle distributions and trajectories.

Alongside these improvements, PyPLUTO development will focus on encompassing the latest features of the PLUTO code, such as new Adaptive Mesh Refinement strategies and extensions to more general metric tensors. PyPLUTO is a public package that can be downloaded alongside the CPU and GPU versions of the PLUTO code. Regular updates will be released with improvements and bug fixes. Additionally, a repository containing the PyPLUTO development versions will be available for users who wish to exploit the code's latest features in advance.

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References

Ahrens, J. P., Geveci, B., & Law, C. (2005). ParaView: An end-user tool for large-data visualization. In *Visualization handbook* (pp. 717–731). Unknown Publisher. https://doi.org/10.1016/B978-012387582-2/50038-1

Berta, V., Mignone, A., Bugli, M., & Mattia, G. (2024). A 4^{th}-order accurate finite volume method for ideal classical and special relativistic MHD based on pointwise reconstructions. *Journal of Computational Physics*, *499*, 112701. https://doi.org/10.1016/j.jcp.2023.112701

Bugli, M., Lopresti, E. F., Figueiredo, E., Mignone, A., Cerutti, B., Mattia, G., Del Zanna, L., Bodo, G., & Berta, V. (2025). Relativistic reconnection with effective resistivity: I. Dynamics and reconnection rate. *Astronomy and Astrophysics*, *693*, A233. https://doi.org/10.1051/0004-6361/202452277

Childs, H., Brugger, E., Whitlock, B., Meredith, J., Ahern, S., Pugmire, D., Biagas, K., Miller, M., Harrison, C., Weber, G. H., Krishnan, H., Fogal, T., Sanderson, A., Garth, C., Bethel, E. W., Camp, D., Rübel, O., Durant, M., Favre, J. M., & Navrátil, P. (2012). VisIt: An end-user tool for visualizing and analyzing very large data. In *High performance visualization–enabling extreme-scale scientific insight* (pp. 357–372). https://doi.org/10.1201/b12985

Chiuderi, C., & Velli, M. (2015). *Basics of Plasma Astrophysics*. https://doi.org/10.1007/978-88-470-5280-2

Collette, A. (2013). *Python and HDF5*. O'Reilly.

Costa, A., Bodo, G., Tavecchio, F., Rossi, P., Coppi, P., Sciaccaluga, A., & Boula, S. (2025). How do recollimation-induced instabilities shape the propagation of hydrodynamic relativistic jets? *arXiv e-Prints*, arXiv:2503.18602. https://doi.org/10.48550/arXiv.2503.18602

Härer, L., Vieu, T., & Reville, B. (2025). Stellar-wind feedback and magnetic fields around young compact star clusters: 3D magnetohydrodynamics simulations. *Astronomy and Astrophysics*, *698*, A6. https://doi.org/10.1051/0004-6361/202554057

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. *Nature*, *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

Langa, Ł., & Black, contributors to. (2020). *Black: The uncompromising python code formatter*. https://black.readthedocs.io/en/stable/

Mattia, G., Del Zanna, L., Bugli, M., Pavan, A., Ciolfi, R., Bodo, G., & Mignone, A. (2023). Resistive relativistic MHD simulations of astrophysical jets. *Astronomy and Astrophysics*, *679*, A49. https://doi.org/10.1051/0004-6361/202347126

Mattia, G., Del Zanna, L., Pavan, A., & Ciolfi, R. (2024). Magnetic dissipation in short gamma-ray-burst jets: I. Resistive relativistic MHD evolution in a model environment. *Astronomy and Astrophysics*, *691*, A105. https://doi.org/10.1051/0004-6361/202451528

Mattia, G., & Fendt, C. (2022). Jets from Accretion Disk Dynamos: Consistent Quenching Modes for Dynamo and Resistivity. *The Astrophysical Journal*, *935*(1), 22. https://doi.org/10.3847/1538-4357/ac7d59

Mattia, G., & Mignone, A. (2022). A comparison of approximate non-linear Riemann solvers for Relativistic MHD. *Monthly Notices of the Royal Astronomical Society*, *510*(1), 481–499. https://doi.org/10.1093/mnras/stab3373

Melon Fuksman, D., Flock, M., & Klahr, H. (2024a). Vertical shear instability in two-moment radiation-hydrodynamical simulations of irradiated protoplanetary disks. I. Angular momentum transport and turbulent heating. *Astronomy and Astrophysics*, *682*, A139. https://doi.org/10.1051/0004-6361/202346554

Melon Fuksman, D., Flock, M., & Klahr, H. (2024b). Vertical shear instability in two-moment radiation-hydrodynamical simulations of irradiated protoplanetary disks. II. Secondary instabilities and stability regions. *Astronomy and Astrophysics*, *682*, A140. https://doi.org/10.1051/0004-6361/202346555

Melon Fuksman, D., Flock, M., Klahr, H., Mattia, G., & Muley, D. (2025). Multidimensional half-moment multigroup radiative transfer: Improving moment-based thermal models of circumstellar disks. *Astronomy and Astrophysics*, *701*, A97. https://doi.org/10.1051/0004-6361/202554994

Melon Fuksman, D., Klahr, H., Flock, M., & Mignone, A. (2021). A Two-moment Radiation Hydrodynamics Scheme Applicable to Simulations of Planet Formation in Circumstellar Disks. *The Astrophysical Journal*, *906*(2), 78. https://doi.org/10.3847/1538-4357/abc879

Mignone, A., Bodo, G., Massaglia, S., Matsakos, T., Tesileanu, O., Zanni, C., & Ferrari, A. (2007). PLUTO: A Numerical Code for Computational Astrophysics. *The Astrophysical Journal Supplement Series*, *170*(1), 228–242. https://doi.org/10.1086/513316

Mignone, A., Bodo, G., Vaidya, B., & Mattia, G. (2018). A Particle Module for the PLUTO Code. I. An Implementation of the MHD-PIC Equations. *The Astrophysical Journal*, *859*(1), 13. https://doi.org/10.3847/1538-4357/aabccd

Mignone, A., Flock, M., Stute, M., Kolb, S. M., & Muscianisi, G. (2012). A conservative orbital advection scheme for simulations of magnetized shear flows with the PLUTO code. *Astronomy and Astrophysics*, *545*, A152. https://doi.org/10.1051/0004-6361/201219557

Mignone, A., Flock, M., & Vaidya, B. (2019). A Particle Module for the PLUTO Code. III. Dust. *The Astrophysical Journal Supplement Series*, *244*(2), 38. https://doi.org/10.3847/1538-4365/ab4356

Mignone, A., Zanni, C., Tzeferacos, P., van Straalen, B., Colella, P., & Bodo, G. (2012). The PLUTO Code for Adaptive Mesh Computations in Astrophysical Fluid Dynamics. *The Astrophysical Journal Supplement Series*, *198*(1), 7. https://doi.org/10.1088/0067-0049/198/1/7

Muley, D., Melon Fuksman, D., & Klahr, H. (2024). Three-temperature radiation hydrodynamics with PLUTO: Thermal and kinematic signatures of accreting protoplanets. *Astronomy and Astrophysics*, *687*, A213. https://doi.org/10.1051/0004-6361/202449739

Puzzoni, E., Mignone, A., & Bodo, G. (2021). On the impact of the numerical method on magnetic reconnection and particle acceleration - I. The MHD case. *Monthly Notices of the Royal Astronomical Society*, *508*(2), 2771–2783. https://doi.org/10.1093/mnras/stab2813

Sciaccaluga, A., Costa, A., Tavecchio, F., Bodo, G., Coppi, P., & Boula, S. (2025). The polarization of the synchrotron radiation from a recollimated jet: Application to high-energy BL Lacs. *Astronomy and Astrophysics*, *699*, A296. https://doi.org/10.1051/0004-6361/202554490

team, T. pandas development. (2020). *Pandas-dev/pandas: pandas* (latest). Zenodo. https://doi.org/10.5281/zenodo.3509134

Vaidya, B., Mignone, A., Bodo, G., Rossi, P., & Massaglia, S. (2018). A Particle Module for the PLUTO Code. II. Hybrid Framework for Modeling Nonthermal Emission from Relativistic Magnetized Flows. *The Astrophysical Journal*, *865*(2), 144. https://doi.org/10.3847/1538-4357/aadd17

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

Wang, J.-S., Reville, B., Rieger, F. M., & Aharonian, F. A. (2024). Acceleration of Ultra-high-energy Cosmic Rays in the Kiloparsec-scale Jets of Nearby Radio Galaxies. *The Astrophysical Journal Letters*, *977*(1), L20. https://doi.org/10.3847/2041-8213/ad9589