Artificial intelligence in radiative hydrodynamics for astrophysics

G. Radureau[1] , C. Busschaert[1]

[1] CEA, DAM, DIF, F–91297, Arpajon, France

Radiative hydrodynamics (RHD) describes the coupling between a hypersonic, high-temperature plasma and its radiation, a key process in astrophysical environments and stellar evolution. Depending on the optical regime, different models are employed: cooling functions in the optically thin limit, diffusion in the optically thick regime, and more general frameworks such as M1-gray and M1-multigroup models (Dubroca & Feugeas, 1999; Turpault, 2005), which provide a unified description across regimes. Within the POLAR project, we investigate plasma–radiation interactions in magnetic cataclysmic variables, with a particular focus on cooling instabilities, combining numerical simulations and laboratory astrophysics experiments. On the simulation side, we aim to validate and improve models of cooling instabilities by refining simplified cooling functions to better reproduce key observations (Busschaert et al., 2013; Bonnet-Bideau et al., 2015). We compare these simulations with the more general M1 framework, and mitigate its high computational cost using artificial intelligence methods for efficient closure relations and data-driven extrapolation (Radureau et al., 2025, 2026). On the experimental side, laboratory astrophysics relies on scaling laws based on dimensionless numbers such as the Boltzmann and Mihalas numbers; however, recent work has shown that more general scalings can be constructed without enforcing strict conservation of these dimensionless quantities (Tranchant et al., 2025). In this context, we explore AI-based dimensionless learning approaches (Xie et al., 2022) to approximate these generalized scaling relations. We will present an overview of these machine learning developments and the resulting physical insights within the POLAR project at the SF2A conference.

Keywords— Radiative Hydrodynamics, Artificial Intelligence, Scaling Laws

References

Bonnet-Bidaud, J.M., Mouchet, M., Busschaert, C., Falize, É. & Michaut, C., 2015 *A&A*, **579**, p. A24
Busschaert, C., Michaut, C., Falize, É. & Nguyen, H.C., 2013 *High Energy Density Physics*, **9**, p. 42-46
Dubroca, B. & Feugeas, J., 1999, *CRAS - Series I - Mathematics*, vol. **329**, p. 915-920
Radureau, G., Michaut, C. & Comport, A.I., 2025 *Phys. Rev. E*, **111**, p. 035301
Radureau, G., Michaut, C. & Comport, A.I., under review
Tranchant, V., Charpentier, N., Van Box Som, L., Ciardi, A., & Falize, É., 2025 *Scientific Reports*, **15**, p. 10806
Turpault, R., 2005, *JQSRT*, vol. **94**, p. 357-371
Xie, X., Samaei, A., Guo, J., Liu, W.K. & Gan, Z., 2022 *Nature Communications*, **16**, p. 7562