The Journal of Open Source Software

Wind-AE: A Python package for atmospheric escape with metals and X-rays

Madelyn I. Broome [1*], **John H. McCann** [1*], **and Ruth Murray-Clay** [1*]

1 University of California Santa Cruz, Dept. of Astronomy & Astrophysics, Santa Cruz, US * These authors contributed equally.

DOI: 10.xxxxxx/draft

Software

- Review
- Repository
- Archive

Editor:

Submitted: 27 September 2025
Published: unpublished

Summary

Throughout their lives, close-in exoplanets are strongly irradiated by their host stars. In the first few hundred million years of life, though, atomic species in a planet's upper atmosphere are photoionized by the young hot stars' strong X-ray and extreme UV radiation. This ionizing radiation from the star heats the planets' upper atmospheres to up to 10,000 K and causes the gas to expand, accelerate from sub- to supersonic speeds (a.k.a., a Parker wind), and outflow from the planet – essentially photoevaporating part or all of the planet's atmosphere in a process called atmospheric escape. Understanding the atmospheric mass loss histories of these planets is essential to understanding the evolution of exoplanets close to their host stars. However, mass loss rates are not directly observable. They can only be inferred from models. To that end, we have developed `Wind-AE`: a fast, 1D, steady-state Parker wind forward relaxation model based on (Murray-Clay et al., 2009) that can model irradiation by multifrequency X-ray/extreme-UV (XUV) stellar spectra and the interactions of these high energy photons with "metals" (atomic species).

Statement of Need

`Wind-AE` is a Python wrapper around an update of the widely-cited (Murray-Clay et al., 2009) C code. The update to the model physics primarily includes the ability to model multifrequency XUV photons interacting with metals in the planets' upper atmospehres. Modeling impact of the presence of metals and X-rays is important because the two have the ability to dramatically change the mass loss rates and wind radial structure for certain planets. `Wind-AE` is unique for its combination of X-ray/metal physics and speed. Speed is of particular interest to users in the broader exoplanet communities for whom `Wind-AE` presents a variety of uses including as a simple plug-and-play model that quickly returns mass loss rates and as a model that can be easily integrated with more sophisticated models to: simulate observability of atmospheric escape (as in (Pai Asnodkar et al., 2024)), simulate the evolution of planets' atmospheres over time (as in Tang et al. 2025 (submitted)), to investigate open questions about the demographics of exoplanets (as in (Loyd et al., 2025)), and make grids of mass loss rates (as in Broome et al. (2025)).

Because of the inherent sensitivity of the relaxation method (it requires a good initial guess that is close in parameter space to the goal solution to converge), a Python wrapper that contains algorithms for ramping smoothly through parameter space makes `Wind-AE` far more reliable, flexible, and user friendly. Python-based user interfaces are far more accessible than C to the majority astronomers, from researchers to undergraduate students who have used this code.

Comparison to Similar Packages

For detailed scientific comparisons of other 1D open source atmospheric escape models, see Appendix A of our paper. Broadly speaking, `Wind-AE` runs faster than many models that perform more detailed physical calculations and makes what we consider to be more physically realistic assumptions than many models of comparable or faster speed.

- ATES is a comparably rapid model that includes X-ray radiation from the star, but differs from `Wind-AE` in that it approximates the stellar spectrum as a power law, only models atomic hydrogen and helium in the atmosphere, and calculates the ionization balance post facto (Caldiroli et al., 2021).
- p-winds is an isothermal Parker wind model which is approximately 10 times faster than `Wind-AE`, but serves a slightly different purpose as users set the mass loss rate to obtain the wind's structure. `p-winds` models extreme-UV radiation (EUV), but does not model X-rays. By solving for the temperature as a function of radius, `Wind-AE` is able to obtain more realistic outflow profiles, but at the cost of speed. ((Dos Santos et al., 2022)).
- Sunbather wraps `p-winds` and Cloudy (a spectral synthesis code (Ferland et al., 2017)) to create transit models that include metals (Linssen et al., 2024).
- TPCI leverages Cloudy and the hydrodynamic code PLUTO ((Mignone et al., 2012)) for more thorough X-ray and EUV-irradiated simulations, but slightly more expensive calculations ((Salz et al., 2015)).
- pyTPCI is a Python wrapper for TPCI (**?**).
- AIOLIS models diffusion (a physical process whose impact on atmospheric escape is still being investigated) and the lower atmosphere in more detail and in a time-dependent manner, so it takes of order 100 times longer [schulik:2022].
- CETIMB includes more detailed lower atmosphere physics and is therefore about 500 times slower (Koskinen et al., 2022).
- CHAIN integrates CLOUDY and (**?**). Like TPCI, via Cloudy, CHAIN has slightly more nuanced heating and cooling calculations and does model X-rays (though the published grid is EUV only (Kubyshkina & Fossati, 2021)), so is also more expensive.

Acknowledgements

MIB, RMC, and JHM acknowledge funding support from NSF CAREER grant 1663706. MIB and RMC acknowledge support from NASA'S Interdisciplinary Consortia for Astrobiology Research (NNH19ZDA001N-ICAR) under grant number 80NSSC21K0597.

We would like to thank Jorge Fernandez-Fernandez, Emerson Tao, and Artem Aguichine for beta testing `Wind-AE`.

References

Caldiroli, A., Haardt, F., Gallo, E., Spinelli, R., Malsky, I., & Rauscher, E. (2021). Irradiation-driven escape of primordial planetary atmospheres. I. The ATES photoionization hydrodynamics code. *655*, A30. https://doi.org/10.1051/0004-6361/202141497

Dos Santos, L. A., Vidotto, A. A., Vissapragada, S., Alam, M. K., Allart, R., Bourrier, V., Kirk, J., Seidel, J. V., & Ehrenreich, D. (2022). p-winds: An open-source Python code to model planetary outflows and upper atmospheres. *659*, A62. https://doi.org/10.1051/0004-6361/202142038

Ferland, G. J., Chatzikos, M., Guzmán, F., Lykins, M. L., van Hoof, P. A. M., Williams, R. J. R., Abel, N. P., Badnell, N. R., Keenan, F. P., Porter, R. L., & Stancil, P. C. (2017). The 2017 Release Cloudy. *53*, 385–438. https://doi.org/10.48550/arXiv.1705.10877

Koskinen, T. T., Lavvas, P., Huang, C., Bergsten, G., Fernandes, R. B., & Young, M. E. (2022). Mass Loss by Atmospheric Escape from Extremely Close-in Planets. *The Astrophysical Journal*, *929*, 52. https://doi.org/10.3847/1538-4357/ac4f45

Kubyshkina, D. I., & Fossati, L. (2021). Extending a Grid of Hydrodynamic Planetary Upper Atmosphere Models. *Research Notes of the American Astronomical Society*, *5*, 74. https://doi.org/10.3847/2515-5172/abf498

Linssen, D., Shih, J., MacLeod, M., & Oklopčić, A. (2024). The open-source sunbather code: Modeling escaping planetary atmospheres and their transit spectra. *688*, A43. https://doi.org/10.1051/0004-6361/202450240

Loyd, R. O. P., Schreyer, E., Owen, J. E., Rogers, J. G., Broome, M. I., Shkolnik, E. L., Murray-Clay, R., Wilson, D. J., Peacock, S., Teske, J., Schlichting, H. E., Duvvuri, G. M., Youngblood, A., Schneider, P. C., France, K., Giacalone, S., Batalha, N. E., Schneider, A. C., Longo, I., … Ardila, D. R. (2025). Hydrogen escaping from a pair of exoplanets smaller than Neptune. *Nature*, *638*(8051), 636–639. https://doi.org/10.1038/s41586-024-08490-x

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 Supplementary*, *198*(1), 7. https://doi.org/10.1088/0067-0049/198/1/7

Murray-Clay, R. A., Chiang, E. I., & Murray, N. (2009). Atmospheric Escape From Hot Jupiters. *The Astrophysical Journal*, *693*(1), 23–42. https://doi.org/10.1088/0004-637X/693/1/23

Pai Asnodkar, A., Wang, J., Broome, M., Huang, C., Johnson, M. C., Ilyin, I., Strassmeier, K. G., & Jensen, A. (2024). PEPSI's non-detection of escaping hydrogen and metal lines adds to the enigma of WASP-12 b. *Monthly Notices of the Royal Astronomical Society*, *535*, 1829–1843. https://doi.org/10.1093/mnras/stae2441

Salz, M., Banerjee, R., Mignone, A., Schneider, P. C., Czesla, S., & Schmitt, J. H. M. M. (2015). TPCI: the PLUTO-CLOUDY Interface . A versatile coupled photoionization hydrodynamics code. *576*, A21. https://doi.org/10.1051/0004-6361/201424330