The Journal of Open Source Software

Wakeflow: A Python package for semi-analytic models of planetary wakes

Thomas Hilder[1¶], **Daniele Fasano**[2], **Francesco Bollati**[3], **and Jacob Vandenberg**[4]

1 School of Physics and Astronomy, Monash University, Australia **2** Dipartimento di Fisica, Università degli Studi di Milano, Italy **3** Dipartimento di Scienza e Alta Tecnologia, Università degli Studi dell'Insubria, Italy **4** School of Mathematics, Monash University, Australia ¶ Corresponding author

DOI: 10.21105/joss.04863

Software

- Review
- Repository
- Archive

Editor: Dan Foreman-Mackey

Reviewers:

- @richteague
- @andizq

Submitted: 19 September 2022
Published: 27 February 2023

Summary

`Wakeflow` is a Python package for generating semi-analytic models of the perturbations induced by planets embedded in gaseous circumstellar disks. These perturbations take the form of a spiral shock wave (Ogilvie & Lubow, 2002), and are often called a "planet wake" in analogy with that produced by a boat in a lake. Using `Wakeflow`, users may calculate the perturbed density and velocity fields of the gas in the disk. These may be used with radiation transfer codes to generate synthetic observations that map both the gas distribution and the gas kinematics. Comparison with real observations, such as from molecular line emission taken with the Attacama Large Millimetre Array, allows researchers to infer the properties of potential planets as well as the disk itself.

Statement of need

Detecting newly formed planets embedded in their disk is a challenging problem in the field of planet formation. A major area of progress in recent years is the detection of planets by the gravitationally induced disturbance in their host disks. This disturbance, caused by the planet wake, manifests as a deviation in velocity from the bulk flow which may be measured through the Doppler shift of molecular lines (e.g. Perez et al., 2015; Pinte et al., 2018). Such kinematic observations have been accurately reproduced through 3D fluid simulations of the planet-disk interaction, allowing for the inference of planet and disk properties (Pinte et al., 2018, 2019). However, these studies are computationally expensive.

`Wakeflow` eases this computational cost by applying the theory of planet wake generation and propagation (Bollati, Lodato, et al., 2021; Goldreich & Tremaine, 1979; Goodman & Rafikov, 2001; Rafikov, 2002) to create semi-analytic models of planet wakes. `Wakeflow` models are readily created in less than a minute on a modern laptop, as opposed to the hours of supercomputer time needed for 3D hydrodynamical simulations. The relatively low computational cost of `Wakeflow` means that researchers can get an idea of whether planet-disk interactions can explain their observations, and the disk and planet parameters needed, before spending computer time on more detailed simulations.

`Wakeflow` can interface with the radiative transfer code `MCFOST` (Pinte et al., 2006, 2009) in order to create synthetic observations of the semi-analytic models for direct comparison with observed continuum or line emission.

`Wakeflow` is partially adapted from a previous Python code also written by us called `Analytical_Kinks` (Bollati, Fasano, et al., 2021). `Wakeflow` is intended to be a more complete, versatile and easy to use version of that code, and it obeys standard Python packaging conventions. In addition, `Wakeflow` can directly interface with `MCFOST` while `Analytical_Kinks` cannot. At the time of writing, no other open source software packages exist to generate the perturbations induced by an embedded planet in a circumstellar disk using the semi-analytic theory of planet wakes.

Existing scientific publications focusing on detecting the kinematic signatures of planets that have used `Wakeflow` or its predecessor `Analytical_Kinks` include Bollati, Lodato, et al. (2021), Calcino et al. (2022) and Teague et al. (2022).

Acknowledgements

`Wakeflow` relies on the following scientific Python packages: `NumPy` (Harris et al., 2020), `Matplotlib` (Hunter, 2007), `SciPy` (Virtanen et al., 2020) and `Astropy` (Astropy Collaboration et al., 2022).

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. *The Astrophysical Journal*, *935*(2), 167. https://doi.org/10.3847/1538-4357/ac7c74

Bollati, F., Fasano, D., & Hilder, T. (2021). Analytical_kinks. In *GitHub repository*. GitHub. https://github.com/DanieleFasano/Analytical_Kinks

Bollati, F., Lodato, G., Price, D. J., & Pinte, C. (2021). The theory of kinks - I. A semi-analytic model of velocity perturbations due to planet-disc interaction. *Monthly Notices of the Royal Astronomical Society*, *504*(4), 5444–5454. https://doi.org/10.1093/mnras/stab1145

Calcino, J., Hilder, T., Price, D. J., Pinte, C., Bollati, F., Lodato, G., & Norfolk, B. J. (2022). Mapping the Planetary Wake in HD 163296 with Kinematics. *Astrophysical Journal, Letters*, *929*(2), L25. https://doi.org/10.3847/2041-8213/ac64a7

Goldreich, P., & Tremaine, S. (1979). The excitation of density waves at the Lindblad and corotation resonances by an external potential. *The Astrophysical Journal*, *233*, 857–871. https://doi.org/10.1086/157448

Goodman, J., & Rafikov, R. R. (2001). Planetary Torques as the Viscosity of Protoplanetary Disks. *The Astrophysical Journal*, *552*(2), 793–802. https://doi.org/10.1086/320572

Harris, C. R., Millman, K. J., Walt, S. J. van der, Gommers, R., Virtanen, P., Cournapeau, D., Wieser, E., Taylor, J., Berg, S., Smith, N. J., Kern, R., Picus, M., Hoyer, S., Kerkwijk, M. H. van, Brett, M., Haldane, A., Río, J. F. del, 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 & Engineering*, *9*(3), 90–95. https://doi.org/10.1109/MCSE.2007.55

Ogilvie, G. I., & Lubow, S. H. (2002). On the wake generated by a planet in a disc. *Monthly Notices of the Royal Astronomical Society*, *330*(4), 950–954. https://doi.org/10.1046/j.1365-8711.2002.05148.x

Perez, S., Dunhill, A., Casassus, S., Roman, P., Szulágyi, J., Flores, C., Marino, S., & Montesinos, M. (2015). Planet Formation Signposts: Observability of Circumplanetary

Disks via Gas Kinematics. *Astrophysical Journal, Letters*, *811*(1), L5. https://doi.org/10.1088/2041-8205/811/1/L5

Pinte, C., Harries, T. J., Min, M., Watson, A. M., Dullemond, C. P., Woitke, P., Ménard, F., & Durán-Rojas, M. C. (2009). Benchmark problems for continuum radiative transfer. High optical depths, anisotropic scattering, and polarisation. *Astronomy and Astrophysics*, *498*(3), 967–980. https://doi.org/10.1051/0004-6361/200811555

Pinte, C., Ménard, F., Duchêne, G., & Bastien, P. (2006). Monte Carlo radiative transfer in protoplanetary disks. *Astronomy and Astrophysics*, *459*(3), 797–804. https://doi.org/10.1051/0004-6361:20053275

Pinte, C., Price, D. J., Ménard, F., Duchêne, G., Dent, W. R. F., Hill, T., de Gregorio-Monsalvo, I., Hales, A., & Mentiplay, D. (2018). Kinematic Evidence for an Embedded Protoplanet in a Circumstellar Disk. *Astrophysical Journal, Letters*, *860*(1), L13. https://doi.org/10.3847/2041-8213/aac6dc

Pinte, C., van der Plas, G., Ménard, F., Price, D. J., Christiaens, V., Hill, T., Mentiplay, D., Ginski, C., Choquet, E., Boehler, Y., Duchêne, G., Perez, S., & Casassus, S. (2019). Kinematic detection of a planet carving a gap in a protoplanetary disk. *Nature Astronomy*, *3*, 1109–1114. https://doi.org/10.1038/s41550-019-0852-6

Rafikov, R. R. (2002). Nonlinear Propagation of Planet-generated Tidal Waves. *The Astrophysical Journal*, *569*(2), 997–1008. https://doi.org/10.1086/339399

Teague, R., Bae, J., Andrews, S. M., Benisty, M., Bergin, E. A., Facchini, S., Huang, J., Longarini, C., & Wilner, D. (2022). Mapping the Complex Kinematic Substructure in the TW Hya Disk. *936*(2), 163. https://doi.org/10.3847/1538-4357/ac88ca

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