




Erebus: An exoplanet secondary-eclipse photometry data reduction pipeline

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Summary

The James Webb Space Telescope (JWST) is uniquely suited to probing the mid-infrared wavelengths of light, enabling exoplanet research to be performed that was previously impossible. By observing rocky exoplanet photometry at 15 microns using its Mid-Infrared Instrument (MIRI) astrophysicists can infer the presence or absence of an atmosphere by comparing the dip in brightness as an exoplanet passes behind its star (the secondary eclipse) against theoretical values determined using surface and atmospheric models.

Erebus is a pipeline for analyzing time-series secondary-eclipse photometry data from MIRI with a focus on detrending pixel-level detector systematic effects in order to determine the magnitude of these lightcurve dips (eclipse depths). Erebus performs aperture photometry to retrieve the brightness of the star system over time (the lightcurve) and uses a Markov Chain Monte Carlo to fit for the eclipse depth while detrending against inter-pixel systematics found using frame-normalized Principal Component Analysis (FN-PCA). By performing PCA on the normalized time-series of image frames, all astrophysical signals (seen as uniform increases/decreases in brightness across the entire detector) are removed leaving behind only inter-pixel systematic effects to be detrended against. Erebus is configured using simple yaml files describing the physical parameters of the planets and the specifications of each run, and outputs an h5 file containing all relevant information as well as creating informative plots. Alternatively, Erebus provides utility functions for analyzing MIRI detector systematics using FN-PCA which can then be used as a part of another data reduction pipeline. An example plot from using Erebus to analyze an eclipse of the planet TRAPPIST-1b can be seen in Figure 1.

Statement of need

The existing literature on detrending and analyzing secondary-eclipse MIRI photometry varies in its methods and source code availability. Erebus provides a uniform method for analyzing this data that is specifically tailored around the MIRI instrument, while being easy to use and open source to further enable collaboration as more JWST 15 micron data is released.

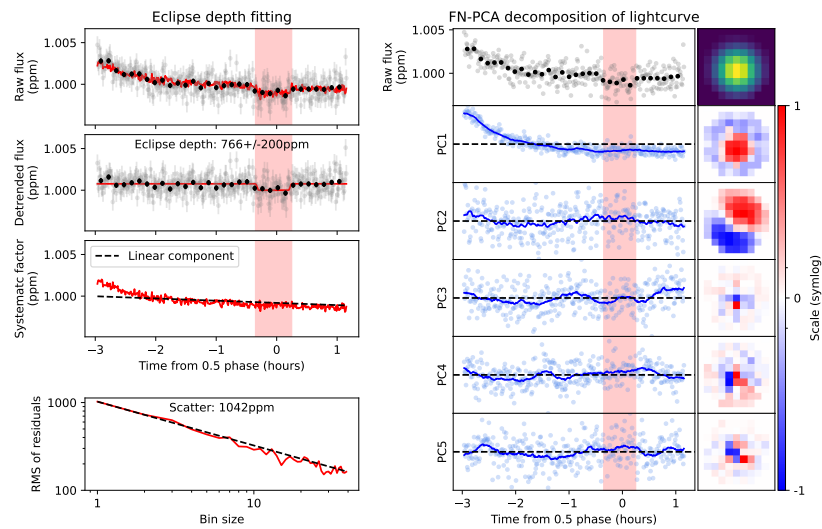


Figure 1: Example of frame normalized principal component analysis detrending fit for the planet TRAPPIST-1b using Erebus. The panels on the left show the raw and detrended lightcurves and the systematic model, as well as a goodness of fit metric comparing RMS of residuals to bin size. The panels on the right show the decomposition of the time-series image data into principal components used to detrend the lightcurve. This plot is automatically generated by the software.

Documentation

Erebus documentation can be found at <https://nicholasconnors.github.io/erebus/latest/>. It includes information on the API, the settings available in all yaml configuration files, and example Jupyter notebooks for how to use the software.

Uses in scientific literature

Erebus was used to perform a uniform reanalysis of existing MIRI 15 micron rocky exoplanet photometry in Connors et al (in prep). It was made in preparation for the 500 hour rocky worlds Director's Discretionary Time survey scheduled for JWST which will observe dozens of planets at 15 microns during secondary eclipses.

Similar tools

Open source tools similar to Erebus include:

- jwst (Bushouse et al., 2022) and Eureka! (Bell et al., 2022): General-purpose end-to-end pipelines for reduction of JWST data including a broader range of instruments.
- TransitSpectroscopy (Nestor Espinoza, 2022): A Python package with routines for reduction of both exoplanet transit and secondary eclipse observations, with support for spectroscopy and photometry.
- juliet (Néstor Espinoza et al., 2019): A tool for fitting exoplanet transit photometry. Also supports fitting radial velocity data.

Unlike jwst or Eureka!, Erebus does not provide an end-to-end reduction of JWST MIRI data, and must be ran on data that was pre-processed with either software (up to Stage 2). Erebus differs from similar softwares in how it performs detrending of the exoplanet lightcurve using frame-normalized principal component analysis, and its specific focus on exoplanet secondary eclipse observations.

Acknowledgements

Erebus was built using [astropy](#) (Astropy Collaboration et al., 2013, 2018, 2022), [emcee](#) (Foreman-Mackey et al., 2013), [NumPy](#) (Harris et al., 2020), [batman](#) (Kreidberg, 2015), [sklearn](#) (Pedregosa et al., 2011), [matplotlib](#) (Hunter, 2007), [h5py](#) (Collette, 2013), [SciPy](#) (Virtanen et al., 2020), [corner](#) (Foreman-Mackey, 2016), [uncertainties](#), and [pydantic](#).

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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., N'otche, 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. *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., Van der Plas, 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. *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. *558*, A33. <https://doi.org/10.1051/0004-6361/201322068>
- Bell, T. J., Ahrer, E.-M., Brande, J., Carter, A. L., Feinstein, A. D., Guzman Caloca, G., Mansfield, M., Zieba, S., Piaulet, C., Benneke, B., Filippazzo, J., May, E. M., Roy, P.-A., Kreidberg, L., & Stevenson, K. B. (2022). Eureka!: An end-to-end pipeline for JWST time-series observations. *Journal of Open Source Software*, *7*(79), 4503. <https://doi.org/10.21105/joss.04503>
- Bushouse, H., Eisenhamer, J., Dencheva, N., Davies, J., Greenfield, P., Morrison, J., Hodge, P., Simon, B., Grumm, D., Droettboom, M., Slavich, E., Sosey, M., Pauly, T., Miller, T., Jedrzejewski, R., Hack, W., Davis, D., Crawford, S., Law, D., ... Williams, T. (2022). *JWST calibration pipeline* (Version 1.8.2). Zenodo. <https://doi.org/10.5281/zenodo.7229890>
- Collette, A. (2013). *Python and HDF5*. O'Reilly.
- Espinoza, Nestor. (2022). *TransitSpectroscopy* (Version 0.3.11). Zenodo. <https://doi.org/10.5281/zenodo.6960924>
- Espinoza, Néstor, Kossakowski, D., & Brahm, R. (2019). juliet: a versatile modelling tool for transiting and non-transiting exoplanetary systems. *490*(2), 2262–2283. <https://doi.org/10.1093/mnras/stz2688>
- Foreman-Mackey, D. (2016). Corner.py: Scatterplot matrices in python. *Journal of Open Source Software*, *1*(2), 24. <https://doi.org/10.21105/joss.00024>
- Foreman-Mackey, D., Hogg, D. W., Lang, D., & Goodman, J. (2013). <Tt>emcee</tt>: The MCMC hammer. *Publications of the Astronomical Society of the Pacific*, *125*(925), 306–312. <https://doi.org/10.1086/670067>

- 100 Harris, C. R., Millman, K. J., Walt, S. J. van der, Gommers, R., Virtanen, P., Cournapeau, D.,
101 Wieser, E., Taylor, J., Berg, S., Smith, N. J., Kern, R., Picus, M., Hoyer, S., Kerkwijk,
102 M. H. van, Brett, M., Haldane, A., Río, J. F. del, Wiebe, M., Peterson, P., ... Oliphant,
103 T. E. (2020). Array programming with NumPy. *Nature*, 585(7825), 357–362. <https://doi.org/10.1038/s41586-020-2649-2>
104
- 105 Hunter, J. D. (2007). Matplotlib: A 2D graphics environment. *Computing in Science &*
106 *Engineering*, 9(3), 90–95. <https://doi.org/10.1109/MCSE.2007.55>
- 107 Kreidberg, L. (2015). batman: BAsic Transit Model cAlculationN in Python. 127(957), 1161.
108 <https://doi.org/10.1086/683602>
- 109 Pedregosa, F., Varoquaux, G., Gramfort, A., Michel, V., Thirion, B., Grisel, O., Blondel, M.,
110 Prettenhofer, P., Weiss, R., Dubourg, V., Vanderplas, J., Passos, A., Cournapeau, D.,
111 Brucher, M., Perrot, M., & Duchesnay, E. (2011). Scikit-learn: Machine learning in Python.
112 *Journal of Machine Learning Research*, 12, 2825–2830.
- 113 Virtanen, P., Gommers, R., Oliphant, T. E., Haberland, M., Reddy, T., Cournapeau, D.,
114 Burovski, E., Peterson, P., Weckesser, W., Bright, J., van der Walt, S. J., Brett, M., Wilson,
115 J., Millman, K. J., Mayorov, N., Nelson, A. R. J., Jones, E., Kern, R., Larson, E., ... SciPy
116 1.0 Contributors. (2020). SciPy 1.0: Fundamental Algorithms for Scientific Computing in
117 Python. *Nature Methods*, 17, 261–272. <https://doi.org/10.1038/s41592-019-0686-2>

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