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-infra red 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 presense or absense 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.

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 siduals 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.

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 siduals 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.

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

30 open source to further enable collaboration as more JWST 15 micron data is released.

Documentation

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

Uses in scientific literature

36 Erebus was used to perform a uniform reanalysis of existing MIRI 15 micron rocky exoplanet
37 photometry in Connors et al (in prep).

Similar tools

39 Open source tools similar to Erebus include:

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

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

Acknowledgements

References