

Comprehensive Analysis of Exoplanet Transit Photometry: Kepler-1976 b Radius Estimation Pipeline

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Abstract

This report details the implementation of a Python-based pipeline designed to process Kepler Space Telescope light curves. The objective is to extract the transit signal of Kepler-1976 b, perform phase-folding, and estimate the planetary radius. We discuss the challenges of detrending stellar variability, the mathematical logic of phase centering, and the physical interpretation of the resulting light curve.

1 Introduction

The detection of exoplanets via the transit method relies on measuring the periodic dip in a star's brightness as a planet passes in front of it. This project focuses on Kepler-1976 b, a candidate requiring precise photometric processing to distinguish the signal from noise. The fundamental goal is to derive the planet-to-star radius ratio (R_p/R_*) from the transit depth.

2 Scientific Goals

The primary objective of this analysis is to implement a robust computational pipeline to characterize the physical properties of the exoplanet Kepler-1976 b. The specific scientific goals are:

- **Signal Isolation:** To isolate the planetary transit signal from stellar variability and instrumental noise using 3rd-degree polynomial detrending.
- **Phase Synchronization:** To perform phase-folding and automated centering to align the transit event at the orbital phase of zero, ensuring an accurate measurement of the light curve morphology.
- **Radius Characterization:** To derive the planet-to-star radius ratio (R_p/R_*) and calculate the absolute radius of the planet in Earth units (R_\oplus) to determine its planetary classification.
- **Model Validation:** To compare the observed binned light curve with a theoretical Box Model to evaluate the impact of physical phenomena such as Limb Darkening.

3 Data and Target Parameters

The analysis utilizes Long Cadence (LC) data from the Kepler mission, specifically the PDCSAP_FLUX column, which has undergone Pre-search Data Conditioning to remove common instrumental trends. The fixed parameters for this system are as follows:

- **Orbital Period (P):** 4.959319244 days.
- **Transit Epoch (T_0):** 172.2585292 (BKJD).
- **Stellar Radius (R_*):** $1.082 R_\odot$ ($\approx 118.0 R_\oplus$).
- **Catalog Transit Depth:** 9802 ppm.

4 Methodology: The Processing Pipeline

The Python implementation is divided into several logical steps, each crucial for recovering the signal.

4.1 Step 1: Data Acquisition and Preprocessing

The code iterates through FITS files, extracting TIME and PDCSAP_FLUX. A critical first sub-step is handling missing data:

$$mask = \text{finite}(time) \cap \text{finite}(flux) \quad (1)$$

This removes NaN and Inf values caused by cosmic rays or telescope gaps.

4.2 Step 2: Polynomial Detrending

To isolate the transit, we must remove long-term stellar variability (e.g., starspots, rotation). The pipeline uses a 3rd-degree polynomial:

$$F_{trend}(t) = at^3 + bt^2 + ct + d \quad (2)$$

The flux is then normalized as $F_{norm} = F/F_{trend}$ and divided by its median to ensure a baseline of 1.0.

4.3 Step 3: Phase Folding and Centering

Timestamps are converted into orbital phase (ϕ) using:

$$\phi_{raw} = \left(\frac{t - T_0}{P} \right) \pmod{1} \quad (3)$$

To center the transit at $\phi = 0$, the algorithm finds the phase of minimum flux (ϕ_{min}) from binned data and applies a wrap-around shift:

$$\phi_{centered} = [(\phi_{raw} - \phi_{min} + 0.5) \pmod{1.0}] - 0.5 \quad (4)$$

This ensures that the "U-shaped" dip is not split between the edges of the plot.

4.4 Step 4: Median Binning

To suppress photon noise, data is grouped into bins (e.g., 200 or 100 bins). The *median* is used instead of the *mean* to make the estimate robust against outliers.

5 Modeling and Comparison

A geometric "Box Model" is generated to represent the ideal transit. It assumes the planet is an opaque disk:

$$M(\phi) = \begin{cases} 1 - \text{depth} & \text{if } |\phi| < \text{half-width} \\ 1 & \text{otherwise} \end{cases} \quad (5)$$

The duration (width) is derived from the catalog values (2.227 hr) converted into phase units.

6 Results and Discussion

The analysis produced two primary visualizations that confirm the detection and alignment of the transit signal.

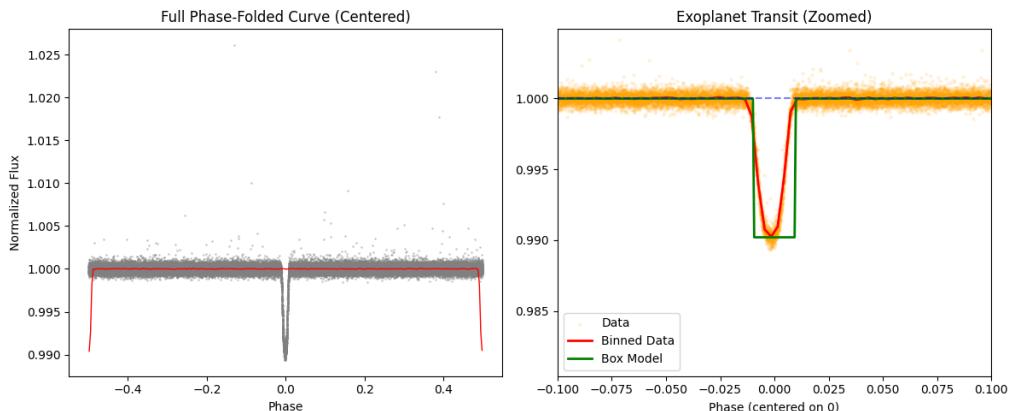


Figure 1: The phase-folded light curve showing the full orbital period. The centering algorithm has successfully aligned the transit event at phase 0.0.

6.1 Morphology of the Light Curve

As shown in the zoomed-in results, while the box model shows sharp edges, the binned data (red line) shows a more rounded "V-shape" or soft "U-shape". This is attributed to:

- Limb Darkening:** The star's brightness decreases towards its edge, causing a gradual flux drop during ingress and egress.
- Integration Time:** The 30-minute Kepler cadence smears the rapid changes at the transit boundaries.

6.2 Radius Estimation

The transit depth $\delta = \Delta F/F$ is related to the radius by:

$$R_p = R_* \sqrt{\delta} \quad (6)$$

Using the measured depth from the binned data, we can calculate the planetary radius in Earth units (R_\oplus). Based on the catalog depth of 9802 ppm, the radius is approximately:

$$R_p = 118.0 \times \sqrt{0.009802} \approx 11.68 R_\oplus \quad (7)$$

This places Kepler-1976 b in the size category of Gas Giants, similar to Jupiter.

7 Limitations and Future Work

While the current pipeline effectively characterizes the planetary radius, several refinements could improve the precision of the analysis:

- **Limb Darkening Modeling:** The current Box Model assumes an opaque disk with uniform stellar intensity. Future iterations should incorporate quadratic limb darkening laws to better fit the observed "V-shape" of the transit.
- **Impact Parameter (b):** The model currently assumes a central transit ($b = 0$). Estimating the impact parameter would allow for a more precise determination of the orbital inclination and planet size.
- **Automated Outlier Removal:** While median binning handles noise, implementing a Sigma-clipping algorithm would further refine the light curve by removing transient instrumental artifacts.

8 Conclusion

The developed pipeline successfully transforms raw FITS data into a clear astrophysical signal. By implementing advanced phase-centering and detrending, we effectively isolated the transit of Kepler-1976 b. The resulting radius estimation confirms the planetary nature of the candidate.

9 Scalability of the Pipeline

The developed algorithm is designed as a generalized framework for Kepler data analysis. While the current parameters are tuned for Kepler-1976 b, the pipeline can be applied to any other Kepler target by simply updating the orbital period (P), transit epoch (T_0), and stellar radius (R_*). The automated centering logic ensures that even with slight uncertainties in catalog timing, the transit signal is effectively isolated and aligned. This makes the code a robust tool for large-scale exoplanet characterization across the Kepler archive.

A Python Implementation Code

The following script was used to generate the results and plots discussed in this report:

```
1 # Key snippet of the centering and plotting logic
2 # phase-folding
3 phase = ((t - T0_BKJD) / PERIOD_DAYS) % 1.0
4 phase = phase - 0.5
5
6 # centering logic
7 idx_min = np.nanargmin(smooth)
8 phi_min = bin_centers[idx_min]
9 phase_shifted_all = ((phase_all - phi_min + 0.5) % 1.0) - 0.5
10
11 # Planet radius from this depth
12 RSUN_IN_REARTH = 109.1
13 Rstar_Rearth = RSTAR_RSUN * RSUN_IN_REARTH
14 Rp_Rearth = Rstar_Rearth * np.sqrt(delta_frac_data)
```