

# 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 ( $\phi$ ) 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 ( $\phi_{min}$ ) 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.

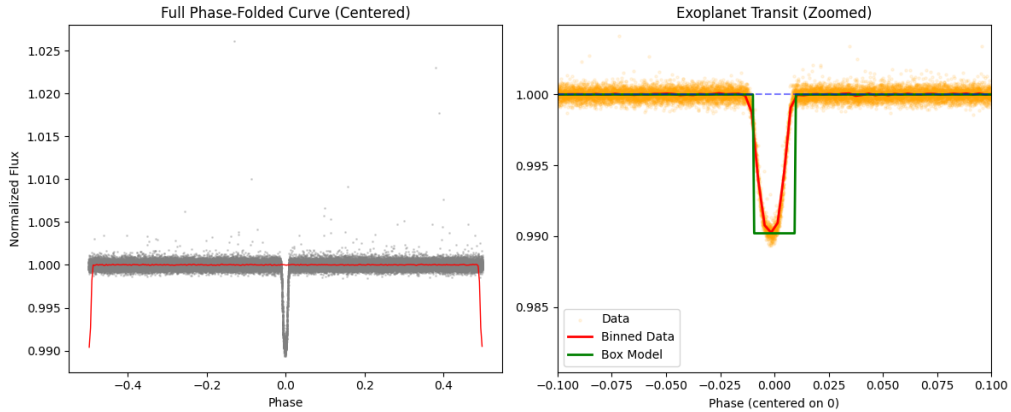


Figure 1: The phase-folded light curve showing the full orbital period. The centering algorithm has successfully aligned the transit event at phase 0.0.

### 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:

1. **Limb Darkening:** The star's brightness decreases towards its edge, causing a gradual flux drop during ingress and egress.
2. **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 - TO_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)
```