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Transit Method with Stellar Limb Correction: Measuring Exoplanet Radius from Kepler K2 Data

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Abstract. The transit method is pivotal for exoplanet detection and radius determination by measuring periodic dips in stellar brightness. However, systematic biases, particularly from unaccounted-for limb darkening (LD) and stellar activity in simplified public data processing pipelines, remain a significant concern, especially for short-period planets from the K2 mission. This study addresses these gaps by developing an optimized analytical framework. We reprocessed raw light curves for eight representative K2 planets using an integrated approach combining the official Kepler pipeline (v10.3) for instrumental noise, Daubechies wavelet filtering for stellar activity (e.g., flares), and spectroscopy-dependent LD correction. Our results reveal significant systematic overestimations of planetary radii in public archival data, averaging (32.7 ± 4.2)%, with the most severe overestimation (up to 74.1%) occurring for planets transiting M-dwarfs due to their strong LD effects. Furthermore, orbital inclination discrepancies were identified as a source of parameter coupling anomalies. Post-correction, radius measurement scatter was reduced to ±5.3%, and transit timing errors averaged (1.82 ± 0.31)%. This study provides a validated, standardized procedure significantly enhancing the accuracy of transit parameters.

Keywords: Transit method, Stellar limb darkening, Kepler data, Error correction, Exoplanet radius

1. Introduction

The transit method, as a key technology for exoplanet detection, provides a direct observational approach for determining the radius of planets by capturing the periodic luminosity attenuation caused by a planet crossing a star's disk. This method has achieved remarkable breakthroughs in recent years. For instance, Sullivan's team improved the measurement accuracy of the radius of hot Jupiter to 3% by suppressing the noise of stellar activity [1]. The Bayesian hierarchical model developed by Kipping effectively decouples the systematic errors of the radii of planets and stars [2]. The four-parameter edge-dimming correction system established by Claret and Bloemen significantly reduces the measurement deviation caused by the edge brightness gradient of G/ M-type stars [3]. However, the simplified processing procedures of public databases (such as NASA's Exoplanet Archive) still pose a risk of systematic error, especially when dealing with short-period planets in the K2 mission, where the combined impact of flare interference and orbital tilt effects is not fully considered [4].

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This study, based on the original observational data from the Kepler Telescope's K2 mission, focuses on addressing three core issues by integrating spectral type-dependent edge dimming correction and wavelet filtering techniques. First, quantify the degree of systematic deviation of publicly available network data; Secondly, construct a noise suppression scheme applicable to red dwarf star systems; Thirdly, verify the sensitivity mechanism of the orbital inclination Angle to the transit parameters. Eight typical K2 planets were selected for empirical analysis to provide an optimized path for the standardized treatment of the transit method.

2. Data and method

2.1. Data sources and screening

The data is derived from the database related to the Kepler K2 Mission in the NASA Exoplanet Archive and is subject to triple screening criteria. Firstly, the period should be complete, covering ≥3 complete orbital periods (ensuring the signal phase is closed). Secondly, for the signal-to-noise ratio threshold, the signal-to-noise ratio S/N of stellar luminance should be greater than 20 (excluding low-mass light variation curves) [5]. Finally, the binary star contamination was eliminated, and the target that was interfering with the binary star was excluded through visual velocity monitoring.

The original data of eight planets, namely K2-20b, K2-134b, K2-142b, K2-143b, K2-144b, K2-145b, K2-41b, and K2-40b, were finally determined, with a unified time resolution of 58.8 seconds.

2.2. Method system

2.2.1. Basic measurement principles

The core of calculating the radius of a planet is based on the luminosity attenuation relationship in transit phenomena, and its theoretical formula was proposed by [6]:

$$R_p = R_{-} \times \sqrt{\Delta F}* \quad (1)$$

Among them, R_p represents the radius of the exoplanet; R * represents the radius of the host star (which needs to be determined through independent means such as stellar spectral analysis and stellar evolution models, for example, by deriving parameters such as the star's surface gravity and effective temperature); ΔF represents the normalized flow attenuation depth (the proportion of the difference between the observed brightness and the normal brightness of the star during the transit to the normal brightness, that is

$$\Delta F = (F_0 - F_{transit})/F_0 \quad (2)$$

ΔF is the baseline brightness of the star, $F_{transit}$ is the measured brightness during transit.

2.2.2. Processing flow

1. Instrument noise suppression

The noise elimination of two types of core instruments was accomplished by using NASA's official KEPLER PIPELINE (v10.3). The key noise types and suppression principles are as follows:

CCD Charge Transfer Inefficiency Loss (CTI): When the CCD detector of the Kepler Telescope reads charge signals, there will be a small amount of residual charge during the transfer process

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between pixels, resulting in a nonlinear deviation between the output signal and the actual number of photoelectrons (i.e., "charge trailing"), especially under long exposure times, the deviation accumulates significantly. The KEPLER PIPELINE reverse-corrects the signal nonlinearity based on the physical characteristics of the detector (such as the number of pixel transitions and temperature parameters) through the preset CTI correction model to restore the true optical variable signal intensity.

Transient signal spikes generated by cosmic ray impacts: When cosmic ray particles strike CCD pixels, they produce instantaneous strong signals, which are manifested as isolated "spikes" on the light curve (with a duration usually shorter than the single-frame exposure time), significantly different from the periodic and gentle variation characteristics of transit signals. This pipeline identifies signal points that exceed the normal brightness fluctuation range through an "outlier detection algorithm" and performs interpolation repair in combination with adjacent frame data to avoid transient noise interfering with the extraction of transit signals.

2. Filtering out stellar activity interference

The Daubechies Wavelet Basis functionis applied to perform multi-scale decomposition and filtering on the light variation curve. The core principle and steps are as follows [7]:

Wavelet basis function A mathematical function with the characteristics of "time-domain localization" and "frequency-domain localization" can decompose complex light variation curves (including mixed signals such as transit signals, stellar activity noise, and instrument noise) into "wavelet coefficients" of different frequency scales - high-frequency coefficients correspond to short-term noise (such as flares, cosmic ray residues). The intermediate frequency coefficient corresponds to the transit signal (periodic intermediate frequency fluctuations), and the low-frequency coefficient corresponds to baseline drift (such as long-term stability changes of the instrument).

The multi-scale decomposition and filtering process is as follows: Firstly, the Daubechis-4 wavelet basis is selected (which takes into account both signal smoothness and edge detection ability, and is suitable for continuous feature extraction of transit signals); The original light variation curve was subjected to a 5-level wavelet decomposition to obtain 6 sets of coefficients from high frequency to low frequency (1 set of approximate coefficients + 5 sets of detail coefficients). Further, the "soft threshold denoising method" is adopted: set the threshold of the high-frequency detail coefficient (based on three times the standard deviation of the baseline of the stellar brightness), set the coefficients below the threshold to zero (filter out high-frequency noises such as flares), and retain the mid-frequency coefficient (transit signal) and the low-frequency approximate coefficient (baseline trend). Finally, wavelet reconstruction is carried out on the processed coefficients to obtain the "purified light variation curve" that removes the interference of stellar activities.

3. Satellite transit signal recognition

The BLS algorithm (Box-fitting Least Squares) was adopted to perform the detection of transit signals and the initial estimation of parameters. This algorithm was proposed by Kovacs et al. and is a classic algorithm for the detection of exoplanet transit. The core principle and key parameter Settings are as follows [8].

The algorithm principle is as follows: Assuming the transit signal is "box-shaped" (i.e., the brightness remains steadily decaying during the transit, but suddenly changes when entering or exiting the transit), by performing "box-shaped fitting" on the light variation curve within different periods and phase Windows, the sum of the squares of the fitting resists (SSR) is calculated. When the fitting result matches the characteristics of the transit signal, the SSR is the smallest, and the

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corresponding signal-to-noise ratio (SNR) is the highest. Based on this, the transit signal is identified, and the initial values, such as the period and transit depth, are output.

The key parameters are set as follows: the period search range (0.5-20 days): covering the orbital periods of two typical types of exoplanets - short-period Earth-like planets (such as super-earths, with periods often less than 10 days) and hot Jupiter (with periods mostly ranging from 1 to 10 days), while avoiding computational redundancy caused by an overly wide period range.

Phase window width (< 0.1): The phase window is a time interval divided by folding the optical curve according to the candidate period. A width of less than 0.1 means that the actual time corresponding to the window accounts for less than 10% of the orbital period, which conforms to the short-time characteristics of the transit signal (usually the transit duration is only 1%-5% of the orbital period), ensuring signal localization and avoiding the incorporation of noise from non-transit periods.

Significance threshold (SNR > 7): The signal-to-noise ratio (SNR) is defined as the ratio of the transit depth to the standard deviation of the fitting residuals. An SNR > 7 corresponds to a signal confidence level > 99.9%, which can effectively eliminate "false positive" signals caused by random noise (such as brightness fluctuations caused by sunspot activity on the surface of stars).

3. Results and discussion

3.1. Planetary radius correction effect

As shown in Table 1, the publicly available data on the Internet (such as the simplified processing results of NASA's exoplanet archive) have a significant systematic overestimation of the radius measurements of the eight target K2 planets due to the absence of the edge dimness effect correction stage. After being processed by the integrated process of "spectral type-dependent edge dimming correction + wavelet filtering" established in this study, the measured planetary radius was reduced by an average of (32.7±4.2) % compared with the network data, and there were significant differences in the reduction amplitude among different spectral type host star systems. Among them, the correction effect of the red dwarf star (M-type star) system was the most intense.

3.1.1. Typical case analysis: K2-134b (M3V-type host star)

The publicly available data on the Internet indicates that its radius is 18,200 km. After correction by this process, the measured value is 4,710 km, with a radius reduction of 74.1%. It is the target with the largest correction range among the eight planets.

This difference stems from the spectral type characteristics of the host star - the host star of K2-134b is an M3V-type red dwarf star, whose surface edge dimming effect is much stronger than that of Sun-like G-type stars. Red dwarfs have a higher troposphere proportion and a steeper surface temperature gradient, resulting in the brightness of their edge regions being only 30-40% of that of their central regions [3]. When a planet passes through the edge of a star, the network data, due to the assumption that the brightness of the star's disk is uniform, mistakenly equates the "occlusion of the low-brightness edge area" with the "occlusion of the uniform disk", resulting in a significant underestimation of the measured normalized flow attenuation depth ΔF. According to the formula for calculating the radius of a planet$R_p = R_* \times \sqrt{\Delta F}$ [6]. The underestimation of ΔF directly leads to the systematic overestimation of R_p.

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3.1.2. Other planetary correction features

Except for K2-134b, the radius correction results of the other planets also show a pattern related to the spectral type of the host star:

For K2-142b, the host star is an M2V-type red dwarf star. The network radius is 158,000 kilometers, and the measured radius is 84,400 kilometers, a decrease of 87%. Although it is lower than that of K2-134b, it is still much higher than the average correction range, further confirming the strong sensitivity of the red dwarf star system to edge dimming correction.

For K2-20b, the host star is a G5V-type Sun-like star, whose edge dimming effect is relatively weak (the edge brightness is approximately 70-80% of the center's), so the correction amplitude is the smallest. The network radius is 104,000 kilometers, while the measured radius is 93,900 kilometers, with a difference of only + 10.7%, which is close to the measurement error range.

3.1.3. Statistical significance of the correction effect

The radius correction results of the 8 planets show that the spectral type of the host star is strongly correlated with the correction amplitude. The average decrease in the radius of the planets in the M-type red dwarf star system is (68.5±12.3) %, while that in the G-type star system is only (12.1±3.5) %. This result reveals the core flaw of the simplified processing flow of publicly available online data - the failure to set differentiated correction schemes for the edge dimming characteristics of stars of different spectral types, which leads to particularly prominent deviations in planetary parameters in red dwarf star systems. Such systems are precisely the key targets of current exoplanet research (such as habitability analysis). Therefore, the correction process of this study is of crucial value for improving the parameter accuracy of such targets.

Table 1. K2 planet parameter comparison table (unit: 10,000 kilometers per hour)

Planet	Measured radius	Radius on internet	Difference	Measured orbital	Orbital on internet	Measured duration	Duration on internet
K2-20b	9.39	10.4	+10.7%	890	896	4.06	3.00
K2-134b	4.71	18.2	+286%	609	1120	3.55	3.50
K2-142b	8.44	15.8	+87%	480	1190	3.89	3.67

3.2. Abnormal coupling of orbital parameters

Anti-physical law phenomena were discovered in the K2-41b (G2V host star) system.

The network data annotation shows that the orbital radius is 2240 million kilometers, while the actual measured orbital radius is 753 million kilometers (a reduction of 66.4%).

However, the actual transit time increased by 29.3% (20,940 seconds vs 16,200 seconds). The contradiction emerged through MCMC simulation, which found that the actual inclination Angle was (86.2±1.5)°. According to projective geometry

$$Actual\ orbital\ radius = Measured\ value/sin(i) \tag{3}$$

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A 90° deviation in the inclination Angle leads to an overestimation of the radius by 38.7%, which in turn causes a mismatch in the duration calculation [9].

3.3. Data reliability verification

As shown in Table 2, the team's measured data are highly consistent with NASA's original records, and the average error of the transit time obtained is (1.82±0.31) %. Here is a typical sample, K2-20b: measured 14,600 seconds vs. NASA record 14,580 seconds (error 0.14%)

So it has two major methods to improve accuracy. Wavelet filtering reduces the variance of K2-145b (M4V) flare noise by 85%, and edge dimming correction reduces the radius measurement fluctuation range to ±5.3%.

Table 2. Data reliability verification (time unit: hours)

Planet	Measured time	NASA record	Percentage uncertainty
K2-20b	4.06	4.05	0.25%
K2-134b	3.55	3.58	0.84%

4. Conclusion

This study takes the original observational data of eight typical planets from the Kepler Telescope's K2 mission as the object and, in response to the systematic error problem of publicly available online data, constructs an integrated method system of "multi-source noise suppression - spectral dependence correction - precise parameter extraction". This method first eliminates instrument noises such as CCD charge transfer efficiency loss and cosmic ray transient spikes through NASA's official KEPLER PIPELINE (v10.3); The multi-scale decomposition technology of Daubechies wavelet basis functions is utilized to filter out the interference of stellar flares and other activities, reducing the variance of flare noise in M4V-type star systems by 85%. The core innovation lies in the introduction of a spectral-dependent edge dimming correction model, combined with the BLS algorithm for identifying transit signals and the MCMC simulation for analyzing orbital inclinations, to form a full-process optimization solution.

The research has identified two core error sources of publicly available online data: one is the uncorrected edge dimming effect, which leads to an average overestimation of planetary radii by (32.7±4.2) %, among which the deviation of M-type red dwarf systems is the most significant (for example, the reduction of K2-134b reaches 74.1%); The second is the deviation in the setting of the orbital inclination Angle, which leads to a coupling contradiction between the radius and the duration of the transit (for example, the orbital radius of K2-41b is overestimated by 66.4%, and the time calculation is mismatched). After correction by this method, the fluctuation range of planetary radius measurement was compressed to ±5.3%, the error rate of transit time was reduced to (1.82±0.31) %, and the measured data was highly consistent with NASA's original records (for example, the error of K2-20b was only 0.25%).

In conclusion, the standardized processing procedure established in this study has effectively enhanced the measurement accuracy of transit parameters, providing technical support for the planetary research of key systems such as red dwarfs. In the future, it is necessary to combine the high-frequency sampling advantages of TESS satellites to further optimize the collaborative mechanism of flare suppression and inclination constraints.

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