



NR Cam: A New Active Low Mass-ratio Contact Binary with a Potential Third Companion

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Received 2025 May 19; revised 2025 June 26; accepted 2025 July 8; published 2025 August 1

Abstract

This study presents a detailed photometric and spectroscopic analysis of the W UMa-type binary NR Cam, using data from the Transiting Exoplanet Survey Satellite (TESS) and ground-based observations. The light curves exhibit significant variable, with a negative correlation between the brightness of the two maxima—a characteristic of W UMa-type binaries typically attributed to magnetic activity. To explain this behavior, we incorporated a starspot model into our Wilson–Devinney analysis. Our results confirm that NR Cam is a W-subtype, moderately contact binary with a low mass ratio of $q = 5.75(\pm 0.03)$ and a fill-out factor of $f = 33.4(\pm 3.1)\%$. We also analyzed the orbital period variation using all available times of minima. The resulting $O - C$ diagram reveals a long-term decreasing trend in the orbital period at a rate of $dP/dt = -5.18(\pm 0.02) \times 10^{-8} \text{ day yr}^{-1}$, superimposed with a periodic oscillation characterized by an amplitude of $A_3 = 0.0019(\pm 0.0001) \text{ day}$ and an oscillation period of $P_3 = 7.776(\pm 0.003) \text{ yr}$. The long-term decrease is likely due to mass transfer between the binary components, with an estimated mass transfer rate of $dM_2/dt = 1.33(\pm 0.01) \times 10^{-8} M_{\odot} \text{ yr}^{-1}$. The periodic oscillations are likely driven by the light-travel time effect caused by a tertiary companion, with a minimum mass of $M_3 = 0.0956(1) M_{\odot}$ and a maximum separation of $3.841(6) \text{ au}$. Additionally, we considered the possibility that the periodic variation could result from changes in the gravitational quadrupole moment due to magnetic activity cycles, as described by the Applegate mechanism. Our findings confirm that NR Cam is an active binary system, where magnetic activity plays a significant role in its orbital evolution. These results contribute to our understanding of the magnetic dynamics and evolutionary processes in contact binary systems.

Key words: (stars:) binaries (including multiple): close – (stars:) binaries: eclipsing – (stars:) starspots

1. Introduction

W Ursae Majoris (W UMa-type) contact binaries are close binary systems composed of two late-type main-sequence stars that orbit each other with orbital periods typically ranging from 0.2 to 1.5 days (Kopal 1955; Gettel et al. 2006). A defining characteristic of such systems is that the two component stars share a common convective envelope (Rucinski et al. 1993), resulting in efficient thermal and mass exchange between them. Their photometric light curves are distinguished by the EW-type variation, typically exhibiting two minima of nearly equal depth, corresponding to the primary and secondary eclipses (Binnendijk 1965).

W UMa-type contact binaries are further categorized into A-subtype and W-subtype based on the relative temperature of the components. In A-subtype systems, the more massive

(primary) component is the hotter star, whereas in W-subtype systems, the less massive (secondary) component paradoxically has a higher surface temperature (Binnendijk 1970). A common photometric feature observed in many W UMa systems is the O’Connell effect (O’Connell 1951), wherein the two maxima in the light curve display a noticeable asymmetry. This phenomenon is generally attributed to localized magnetic activity, such as cool or hot starspots, on the surfaces of the components (Applegate 1992).

In addition to photometric variability, orbital period variations in W UMa systems reveal complex dynamical behavior. Long-term period increases or decreases can result from mass transfer or angular momentum loss within the system. Periodic oscillations may be induced by cyclic magnetic activity (Applegate 1992) or gravitational influences from a third companion (Irwin 1952; Kreiner et al. 2001). Irregular period changes may also occur due to transient or stochastic astrophysical processes, such as magnetic field

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Table 1
The Observation Log of NR Cam by TESS

Sector	Observation Start Time	Observation End Time	Time Span (BJD)	Exposure Time (s)
sector20	2019.12.25	2020.01.20	2458842–2458868	120
sector26	2020.06.09	2020.07.04	2459010–2459035	120
sector40	2021.06.25	2021.07.23	2459390–2459418	120
sector47	2021.12.31	2022.01.27	2459579–2459606	120
sector53	2022.06.13	2022.07.08	2459743–2459768	120
sector60	2022.12.23	2023.01.18	2459936–2459962	120
sector73	2023.12.07	2024.01.03	2460285–2460312	120
sector74	2024.01.03	2024.01.30	2460313–2460339	120

restructuring, episodic mass exchange, or interactions with circumstellar material (Li & Zhang 2006). Magnetic coupling between the components has also been proposed as a driver of both periodic modulation and erratic orbital behavior (Yuan & Qian 2007).

Studying W UMa-type contact binaries not only enhances our understanding of close binary star dynamics and magnetic activity cycles but also provides empirical constraints on theoretical models of stellar structure, angular momentum evolution, and binary formation pathways.

One such system is NR Camelopardalis (NR Cam), also cataloged as GSC 04531-00265, TYC 4531-265-1, and NSVS 713007. NR Cam was first recognized as a variable star with the identifier NSV 03754 in the New catalog of Suspected Variable (NSV). Its variability was confirmed through data from the Northern Sky Variability Survey (NSVS), based on observations from the ROTSE1 telescope, and formally published by Otero & Wils (2005). They reported an orbital period of 0.255885 days and clear evidence of a strong O’Connell effect, characterized by asymmetry between the two maxima in the light curve.

The first detailed photometric investigation was conducted by Shoup et al. (2014), who presented their findings at the 224th American Astronomical Society meeting. They obtained multi-band (*BVR*) light curves and color curves. Using the Wilson–Devinney (W–D) code, they modeled the system and concluded that NR Cam is a contact binary system, with both components sharing a common convective envelope. The surface temperatures of the stars were estimated to be approximately 4500 K and 4200 K, and the orbital inclination was determined to be $68.0 \pm 0.6^\circ$. A strong O’Connell effect was also observed and attributed to magnetically induced starspot activity.

Subsequently, Tavakkoli et al. (2015) performed an independent light curve analysis based on new CCD observations in *B*, *V*, and *R* bands. they derived a revised ephemeris,

given by Equation (1):

$$Min.I = HJD2451589.74645(112) + 0.255886072(69) \times E \quad (1)$$

Their modeling identified NR Cam as a W-subtype contact binary, with a mass ratio of $q = 1.062 \pm 0.001$ and a fill-out factor of only $f = 0.6\%$, indicating a shallow overcontact configuration. The orbital inclination was determined to be $66.13 \pm 0.08^\circ$, which is slightly lower than the value reported by Shoup et al. (2014). Tavakkoli et al. (2015) further estimated the absolute physical parameters of the system, including $M_1 = 0.92(\pm 0.20)M_\odot$, $R_1 = 0.79(\pm 0.07)R_\odot$ and $M_2 = 0.98(\pm 0.20)M_\odot$, $R_2 = 0.81(\pm 0.07)R_\odot$, by assuming main-sequence status and applying Kepler’s third law. Additionally, they analyzed the evolution of the O’Connell effect over a 14 yr timespan by measuring the brightness difference between phases 0.25 and 0.75 (*MaxI* – *MaxII*), revealing changes in the location and strength of surface spot activity.

Although several previous studies provided a valuable baseline model, subsequent photometric and spectroscopic analysis—including the work presented in this study—reveals inconsistencies with their conclusions. In the present work, we incorporate high-cadence, high-precision light curves from the Transiting Exoplanet Survey Satellite (TESS) observations (Ricker et al. 2015) in conjunction with new ground-based photometry to derive more accurate physical and geometrical parameters. This approach allows for refined modeling of the system’s structure and spot activity, and offers deeper insights into the evolutionary status of NR Cam.

2. Photometric and Spectroscopic Observations

2.1. TESS Photometric Data

The primary mission of TESS is the detection of exoplanets via the transit method. However, over the course of its operation, TESS has also collected high-precision photometric data for a large number of variable stars, greatly enhancing the study of eclipsing binaries (Yang et al. 2022, 2023; Li et al. 2024; Tang et al. 2025). This data has been crucial for investigating their orbital dynamics, magnetic activity, and starspot evolution. NR Cam, as part of this effort, was observed across eight TESS sectors—Sector 20, 26, 40, 47, 53, 60, 73, and 74—with a 2 minutes cadence in each sector. Detailed observational information for these sectors is listed in Table 1.

In this study, we adopted the *SAP_FLUX* (Simple Aperture Photometry) light curves, which were downloaded from the Mikulski Archive for Space Telescopes (MAST) database.⁷ Although the *PDCSAP_FLUX* (Pre-search Data Conditioning SAP flux) is often considered cleaner due to the removal of

⁷ <https://mast.stsci.edu/portal/Mashup/Clients/Mast/Portal.html>

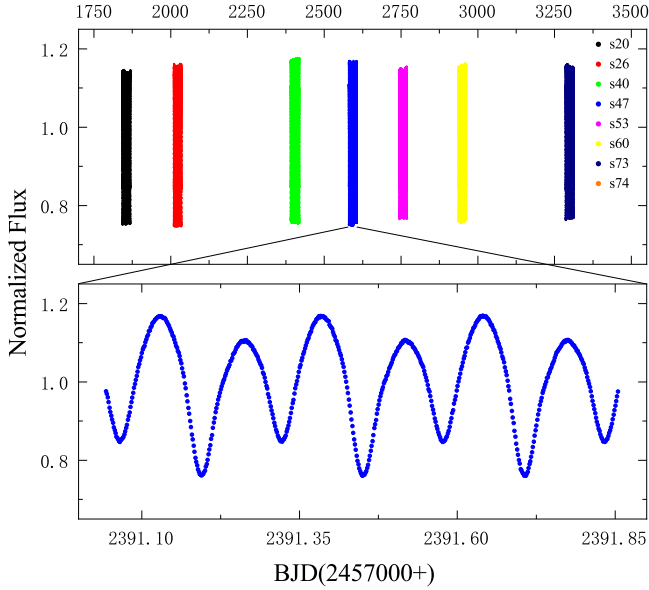


Figure 1. TESS photometric data of normalized flux.

systematic trends via Co-trending Basis Vectors, we chose to use the *SAP_FLUX* because it retains the original photometric measurements without filtering or excluding any data segments. In our comparative analysis of *SAP_FLUX* and *PDCSAP_FLUX* for multiple targets, we found no significant difference in data quality or long-term trends. However, *PDCSAP_FLUX* processing occasionally removes flux points marked as discontinuous, which can result in loss of potentially valuable information. Since our study focuses on orbital period variations, where the completeness of time-series data is crucial, the *SAP_FLUX* is better suited for preserving all observational features relevant to this analysis. The raw flux data were processed using the Lightcurve (Lightcurve Collaboration et al. 2018) and pltgui⁸ Python packages, and then converted to normalized flux for consistency across all sectors. The normalized TESS light curves of NR Cam from all eight sectors are displayed in Figure 1. A segment of the light curve was randomly selected and shown in the lower panel of Figure 1. It is evident that both the maxima and minima exhibit notable variations across different sectors, indicating dynamic surface activity and possibly evolving spot configurations over time.

2.2. Ground-based Photometric Observations

We conducted two sets of ground-based photometric observations of NR Cam using the 60 and 85 cm telescopes at the Xinglong Observatory of the National Astronomical Observatories, Chinese Academy of Sciences (NAOC), both telescopes are equipped with Andor DZ936 2K CCD cameras.

Table 2

Coordinates of NR Cam, the Comparison, and the Check Stars

Target	Star	α 2000 (h m s)	δ 2000 ($^{\circ}$ ' ")	MagV
Variable	NR Cam	07 54 30.57	+78 06 45.34	10.97
The check	TIC141759666	07 50 50.57	+78 08 04.19	10.84
The comparison	TIC141759639	07 51 04.44	+78 02 00.62	10.64
The comparison	TIC141759680	07 51 19.52	+78 11 37.11	10.43
The comparison	TIC446158756	07 57 42.36	+78 02 05.33	9.96

The first observation was carried out on 2022 January 1 using the 60 cm telescope, during which complete light curves in the *B*, *V*, *R_c* and *I_c* bands were obtained. The exposure times for each band were 40 s, 25 s, 15 s, and 15 s, respectively, with a total of 167 CCD frames acquired per band. The second observation was conducted on 2025 January 14 using the 85 cm telescope, focusing on the eclipse phase of NR Cam in the same four photometric bands. The exposure times were slightly adjusted to 30 s (*B*), 20 s (*V*), 15 s (*R_c*), and 10 s (*I_c*), and 123 CCD frames were collected in each band.

All CCD frames were processed using our self-developed automated pipeline, Quick Light-Curve Pipeline (QLCP),⁹ which performs standard image calibration including bias subtraction, flat-field correction, and image alignment (Zheng et al. 2024). The image alignment step compensates for the small tracking errors of the telescope by matching star positions across all frames, ensuring consistent aperture placement during photometric extraction. The photometry itself was carried out using Source-Extractor (Bertin & Arnouts 1996), which identifies stellar sources and measures their instrumental magnitudes.

To enhance the accuracy and reliability of the differential photometry, we selected a set of three nearby non-variable stars as comparison stars, and additionally, one check star to independently verify the stability of the comparison system. Using multiple non-variable comparison stars allows random photometric noise and observational scatter to be averaged out, thereby improving the overall signal stability. This approach reduces the impact of stochastic fluctuations that may affect any individual comparison star, and is widely adopted in ensemble photometry methods for high-precision time-series analysis (Gilliland & Brown 1988; Honeycutt 1992). These stars were consistently used across both observation runs, and their equatorial coordinates and V-band magnitudes are listed in Table 2. Figure 2 displays the differential light curves obtained with the 60 and 85 cm telescopes, both exhibiting the characteristic EW-type profile typical of W UMa-type eclipsing binaries. A small gap is visible near phase 0.8 in the 2022 light curves from the 60 cm telescope. This was caused by a brief equipment malfunction that led to a

⁸ <https://gitee.com/drjiezhang/pltgui>

⁹ <https://gitee.com/drjiezhang/qlcp>

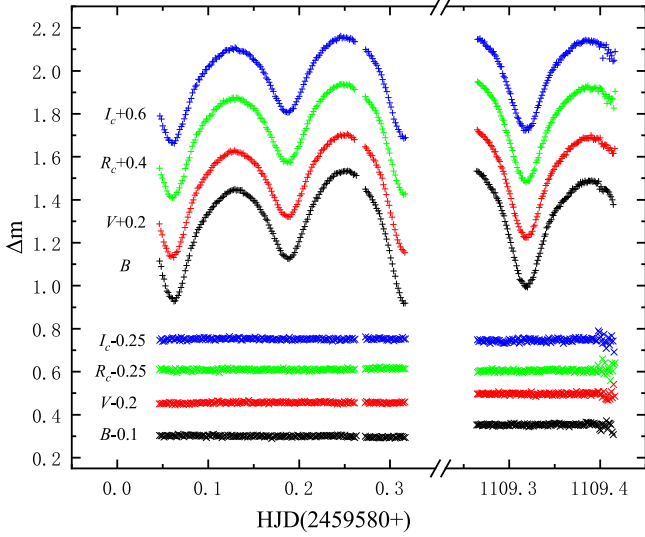


Figure 2. Differential magnitude diagrams of NR Cam and the comparison star observed on 2022 January 1 (60 cm telescope at Yunnan Observatories) and 2025 January 14 (85 cm telescope at the National Astronomical Observatories) in the B , V , R_c , and I_c bands. The magnitude differences between the comparison and check stars are $B-0.1$, $V-0.2$, $R_c-0.25$, and $I_c-0.25$.

17 minutes interruption in the observation. However, the missing data segment is narrow in phase coverage and does not affect the overall morphology or scientific interpretation of the light curves.

2.3. Ground-based Spectroscopic Observations

Spectroscopic observations of NR Cam were conducted on 2022 January 18 using the 2.16 m telescope at the Xinglong Observatory of the National Astronomical Observatories, Chinese Academy of Sciences (NAOC). The instrument used was the Beijing Faint Object Spectrograph and Camera (BFOSC), equipped with a 2048×2048 pixel CCD. Observations were carried out using the E9+G10 grating combination, providing a wavelength coverage from 3300 Å to 10000 Å with a slit width of $1''.6$. This setup yields a spectral resolution of approximately $R \sim 3000\text{--}3500$, based on the instrumental dispersion of $0.38\text{--}0.86\text{Å pixel}^{-1}$ (Zhao et al. 2018). A total of 18 spectra were obtained, including two exposures of 1200 s and 16 exposures of 1500 s each. All spectral images were processed using standard procedures in the IRAF software package, including bias subtraction, flat-field correction, cosmic-ray removal, spectral extraction, wavelength calibration, and flux normalization. Wavelength calibration was performed using spectra from an Fe–Ar lamp.

To derive the atmospheric parameters of the primary component, we selected the spectrum closest to orbital phase 0.5, corresponding to the secondary component being in eclipse. At this phase, the observed spectrum predominantly represents the contribution from the primary star. The selected

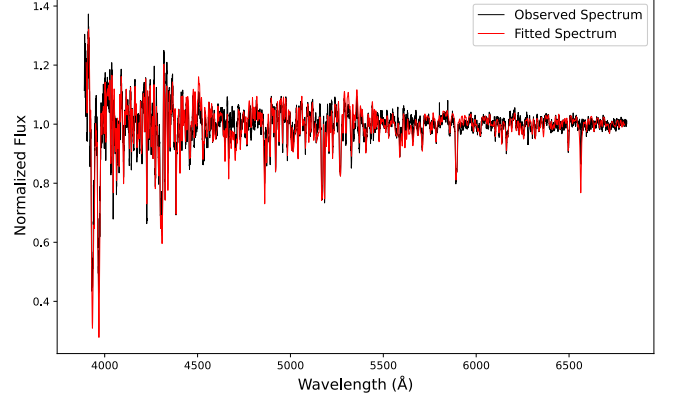


Figure 3. The normalized spectrum and fitted spectrum at phase = 0.53276331.

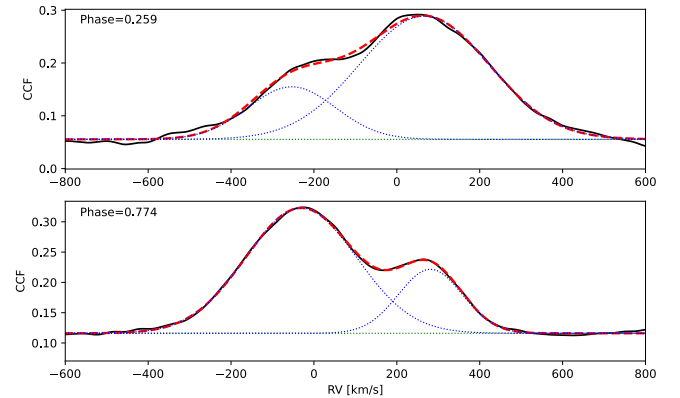


Figure 4. One of the CCF contour fitting graphs. The red dashed line represents the double Gaussian fit, while the blue dashed line represents a single Gaussian component.

spectrum at phase 0.53 was modeled using the University of Lyon Spectroscopic Analysis Software (ULySS) package (Koleva et al. 2009), with spectral synthesis based on the Elodie 3.1 interpolator. As shown in Figure 3, the black curve represents the observed spectrum, while the red curve is the best-fit model. The fitting yielded the following atmospheric parameters for the primary star: effective temperature $T_{\text{eff}} = 5570 \pm 9$ K, the mean logarithm of the gravitational acceleration $\log g = 4.12 \pm 0.02$ dex, and the mean metallicity $[\text{Fe}/\text{H}] = 0.32 \pm 0.01$.

Subsequently, these parameters were used to generate a synthetic template spectrum using Kurucz's atmospheres model. We employed the cross-correlation function (CCF) technique to measure the radial velocities (RVs) of both components of NR Cam. The CCFs were computed between the observed spectra and the synthetic template, and double-Gaussian fitting was applied to determine the peak positions corresponding to the radial velocity of each star. As shown in Figure 4, the CCFs near orbital phases 0.25 and 0.75 clearly exhibit two distinct peaks, indicating the motion of both

Table 3
The Resulting RVs for Both Components

BJD(+2459598)	Phase	RV_1 (km s ⁻¹)	RV_2 (km s ⁻¹)
0.13346	0.720	277.18(±1.05)	-41.07(±0.76)
0.14744	0.774	275.73(±0.38)	-36.10(±0.26)
0.16329	0.836	250.88(±0.54)	-28.06(±0.37)
0.18079	0.905	206.61(±3.04)	-10.17(±1.42)
0.19826	0.973	74.89(±28.18)	19.55(±0.42)
0.21576	0.041	-85.63(±1.73)	29.61(±1.27)
0.23325	0.110	-186.42(±10.40)	43.00(±4.98)
0.25408	0.191	-247.74(±2.32)	59.92(±1.50)
0.27153	0.259	-259.01(±2.46)	60.76(±1.53)
0.28903	0.328	-228.45(±2.38)	59.75(±1.44)
0.30653	0.396	-145.09(±7.97)	48.81(±4.74)
0.32403	0.464	-17.63(±1.19)	31.69(±0.75)
0.34152	0.533	115.94(±5.65)	11.49(±0.85)
0.35902	0.601	200.44(±2.23)	-17.61(±1.28)
0.37652	0.670	266.56(±0.66)	-30.00(±0.35)
0.39402	0.738	287.93(±0.61)	-31.73(±0.37)
0.41151	0.806	280.83(±0.76)	-23.04(±0.42)
0.42900	0.875	237.75(±2.05)	-10.79(±1.03)

components. The fitted Gaussian profiles (dashed curves) allow for precise determination of the RVs. Barycentric corrections were applied to all measured velocities, and the resulting RVs for both components are summarized in Table 3.

3. Orbital Period Analysis

To investigate the orbital period variations of NR Cam, we collected 95 times of light minimum from archival literature. In addition, a second-order least squares fitting was applied to the eclipsing portion of the TESS curves (Figure 1) and ground-based light curves (Figure 2) to determine new times of minima. As a result, two new minima were obtained from 60 cm telescope observations, one minimum from 85 cm telescope observations, and an additional 736 minima were derived from the TESS data. All times of minima along with their associated uncertainties are listed in the first two columns of Table 4.

Using the initial period of 0^d255886072, as given by Tavakkoli et al. (2015) in Equation (1), we calculated the preliminary $O - C$ values for all available times of light minimum. A revised linear ephemeris was then determined as follows:

$$Min.I(BJD) = 2460335.922142(67) + 0^d25588545(1) \times E \quad (2)$$

Here, 2460335.922142 is the corrected epoch, and 0^d25588545 represents the refined orbital period. The $(O - C)_1$ values, calculated using Equation (2), are presented in Table 4. The corresponding $(O - C)_1$ diagram is shown in the upper panel of Figure 5. It is evident that the $(O - C)_1$ curve exhibits an

overall downward parabolic trend superimposed with a cyclic variation.

For contact binaries, a parabolic trend in the $(O - C)$ diagram typically indicates a secular change in the orbital period, often attributed to mass transfer between the components. Meanwhile, periodic variations may arise from the light-travel time effect (LTTE) induced by the presence of a tertiary companion, or from cyclic magnetic activity. Tokovinin et al. (2006) demonstrated that the detection rate of tertiary companions is inversely correlated with the orbital period of the binary. For systems with periods shorter than 3 days, the tertiary detection rate reaches as high as 96%, suggesting that most close binaries are part of triple or higher-order systems. Based on this, we suggest that the periodic variation observed in NR Cam may be caused by the LTTE induced by a third companion.

To model these effects, we fit the $(O - C)_1$ values using the following combined quadratic and LTTE model:

$$(O - C)_1 = \Delta T + \Delta P \times E + Q \times E^2 + A \times \left[\frac{1 - e^2}{1 + e \cos v} \sin(v + \omega) + e \sin \omega \right] \quad (3)$$

In this formula, ΔT , ΔP , and Q represent corrections to the epoch, the orbital period, and the orbital period change rate, respectively. The last term describes the LTTE (Irwin 1952), where $A = a_{12} \sin i / c$, and P_3 , e , ω , and v are the orbital parameters of the eclipsing binary around the center of mass of the triple system. The fitting was performed using the Levenberg–Marquardt algorithm Yang (2009), and the fitted parameters along with their uncertainties are listed in Table 5.

From the quadratic term in Equation (3), it can be inferred that the orbital period of NR Cam exhibits a long-term decrease at a rate of $dP/dt = -5.18(\pm 0.02) \times 10^{-8}$ day yr⁻¹. In addition, the fitted LTTE parameters indicate a modulation amplitude of $A = 0.0019(\pm 0.0001)$ day and a tertiary orbital period of $P_3 = 7.776(\pm 0.003)$ yr. After removing the parabolic trend from the $(O - C)_1$ curve, the residuals, denoted as $(O - C)_2$, are represented in the middle panel of Figure 5 and detailed in Table 4. The final residuals after removing all trends are also listed in Table 4 and shown in the lower panel of Figure 5.

4. Spectroscopic and Photometric Study

4.1. TESS Light-curve Variation

NR Cam exhibits significant variability in its light curve morphology, particularly evident through the O’Connell effect, where the two maxima are unequal in brightness. To investigate these variations, the phases of all TESS photometric data were calculated using the revised ephemeris of Equation (2), and the folded phase-flux diagram is presented in Figure 6. In this figure, different colors correspond to different

Table 4
The Light Minimum Times of NR Cam

$BJD(+2450000)$	Error	E	$(O - C)_1$	$(O - C)_2$	Ref	Min	Reference
9581.062059	0.000098	-2950	0.001931	0.002520	0.000620	I	This study-60
9581.188892	0.000149	-2949.5	0.000822	0.001410	-0.000490	II	This study-60
10690.319628	0.000093	1385	-0.003108	-0.001670	-0.000390	I	This study-85
4891.703581	0.000900	-21276	-0.004026	0.000500	0.001460	I	(1)
4947.483081	0.000400	-21058	-0.007513	-0.003110	-0.001990	I	(2)
4947.356981	0.000600	-21058.5	-0.005670	-0.001270	-0.000150	II	(2)
5277.703976	0.000300	-19767.5	-0.006543	-0.002800	-0.001030	II	(3)
4910.379781	0.000200	-21203	-0.007450	-0.002970	-0.001950	I	(4)
...	...	...	...	...	...	...	...
10338.479359	0.000762	10	-0.001143	-0.000050	0.000160	I	(32)
10338.735107	0.000751	11	-0.001280	-0.000180	0.000030	I	(32)
10338.991056	0.000741	12	-0.001216	-0.000120	0.000090	I	(32)
10339.247004	0.00074	13	-0.001154	-0.000060	0.000160	I	(32)
10339.502869	0.000757	14	-0.001174	-0.000080	0.000140	I	(32)

References. (1) Diethelm (2009); (2) Hubscher et al. (2010); (3) Diethelm (2010); (4) Hubscher & Monninger (2011); (5) Diethelm (2011); (6) Nelson (2011); (7) Parimucha et al. (2011); (8) Brat et al. (2011); (9) Samolyk (2011); (10) Hubscher et al. (2012); (11) Nelson (2012); (12) Diethelm (2013); (13) Hübscher et al. (2013); (14) Nelson (2013); (15) Hübscher & Lehmann (2013); (16) Hoňková et al. (2013); (17) Nagai (2013); (18) Honkova et al. (2013); (19) Hoňková et al. (2015); (20) Tavakkoli et al. (2015); (21) Hubscher (2016); (22) Parimucha et al. (2016); (23) Nelson (2017); (24) Hübscher (2017); (25) Juryšek et al. (2017); (26) Nagai (2017); (27) Pagel (2018); (28) Pagel (2019); (29) Paschke (2020); (30) Lehký et al. (2021); (31) Pagel (2022); (32) TESS.

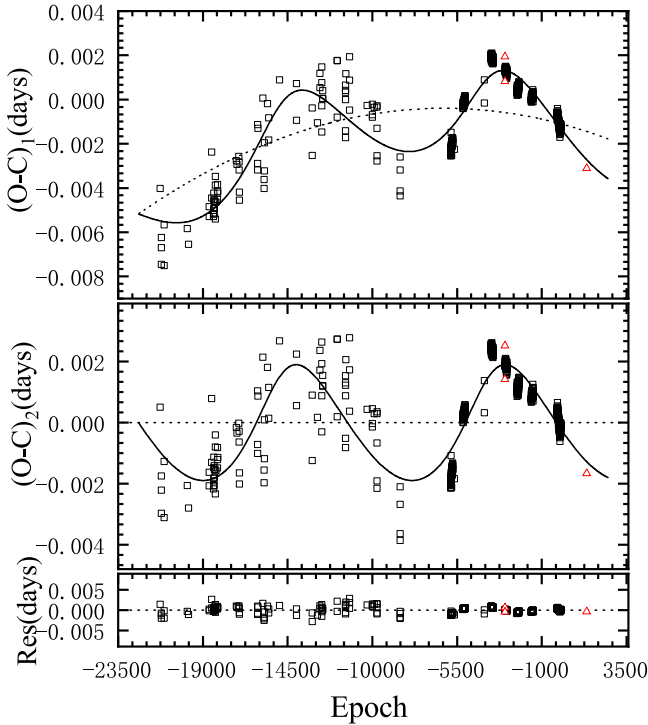


Figure 5. Upper panel: $(O - C)_1$ values calculated using formula (2). The solid and dotted lines are plotted using formula (3); Middle panel: $(O - C)_2$ diagram after removing the parabolic trend; Lower panel: Residual diagram after eliminating all trends.

Table 5
Orbital Parameters of Light-travel Time Effect for NR Cam

Parameter	NR Cam
T (BJD)	2460335.920554(110)
P (day)	0.255885(3)
Q ($\times 10^{-11}$ days)	-1.815(6)
A (day)	0.001927(2)
e	0.2644(9)
T_s (BJD)	2460529.75271(1082.38227)
ω (arc)	0.8467(29)
P_{mod} (yr)	7.776(3)
$a_{12}\sin i$ (au)	0.3337(4)
$f(m)(M_\odot)$	0.00061(1)
$M_3(i_3 = 90^\circ)(M_\odot)$	0.0956(1)
$M_3(i_3 = 60^\circ)(M_\odot)$	0.1112(1)
$M_3(i_3 = 30^\circ)(M_\odot)$	0.2011(2)

TESS sectors. The diagram clearly reveals continuous and prominent changes in both the primary and secondary maxima throughout the TESS observing span.

To further analyze these variations, we fitted the light curve maxima near phases 0.25 (Max I) and 0.75 (Max II) for each TESS sector using second-order polynomial fitting. The temporal evolution of the relative fluxes of Max I and Max II as a function of Barycentric Julian Date (BJD) is shown in Figure 7. It is apparent that the two maxima exhibit a negative

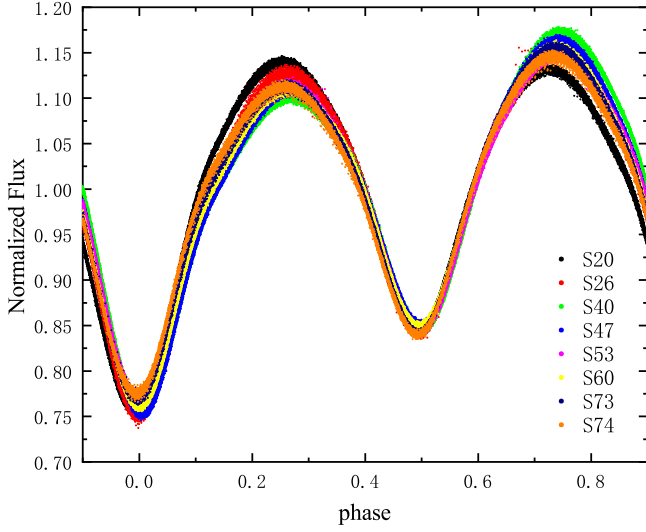


Figure 6. The TESS phase-flux diagram that varied with time.

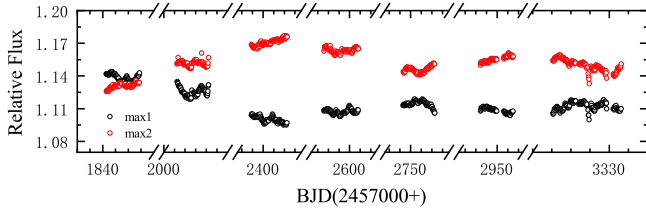


Figure 7. Max I and Max II change relationship diagram.

correlation: when the brightness of Max I increases, the brightness of Max II decreases, and vice versa. Such an anticorrelated behavior between the two maxima is a characteristic of highly active W UMa-type contact binaries. Previous studies (Debski 2020; Hu et al. 2020; Meng et al. 2023; Jeong et al. 2024) have demonstrated that in many overcontact systems, variations in the O’Connell-O’Connell effect are closely linked to magnetic activity, such as the formation, migration, and evolution of large cool starspots on the stellar surfaces.

The dynamically evolving spot patterns naturally lead to the observed negative correlation between the maxima, as the distribution of stellar surface brightness is modulated by spot coverage. The results for NR Cam suggest that it is an extremely magnetically active contact binary, likely experiencing strong stellar magnetic cycles. These findings highlight the necessity of incorporating starspot models in the subsequent light-curve analysis to accurately characterize the system’s physical properties and to account for the observed light curve asymmetries.

4.2. Radial Velocity Curve and Light-curve Analysis

We simultaneously analyzed the BVR_{cI_c} light curves observed with the 60 cm telescope and the radial velocity

(RV) curves using the W-D program (Wilson & Devinney 1971; Wilson 1979, 1990, 2008, 2012; Van Hamme & Wilson 2007; Wilson et al. 2010). The atmospheric parameters derived in Section 2.3 for the primary star, including $T_{\text{eff}} = 5570 \pm 9$ K, $\log g = 4.12 \pm 0.02$ dex, and $[\text{Fe}/\text{H}] = 0.32 \pm 0.01$, were adopted in the fitting process. We set the gravity-darkening coefficients to $g_1 = g_2 = 0.32$ (Lucy 1967) and the bolometric albedo values to $A_1 = A_2 = 0.5$ (Rucinski 1973). The bolometric and limb-darkening coefficients were derived through internal calculations based on the logarithmic law, following the results of (van Hamme 1993). Based on the study of Shoup et al. (2014) and Tavakkoli et al. (2015), which both indicate that NR Cam is in a contact configuration, we adopted Model 3 (the overcontact model) for our analysis. As discussed in the previous section, NR Cam is an extremely magnetically active binary, so we introduced a starspot model into the analysis. Specifically, we added a cool spot on the primary component.

Initially, we performed a simultaneous fitting of the light curves in all four photometric bands together with the RV curves. However, the theoretical light curves in VR_{cI_c} bands showed poor agreement with the observations at the primary minimum. This discrepancy suggests that the model’s current parameters do not fully account for the observed data. Consequently, we performed independent solutions for each of the four light curves, while still modeling each of them simultaneously with the RV curves. The fitting results are presented in Table 6. The solutions for the light curves in different bands show slight variations. We calculated the mean values of the parameters, which are presented in the last column of Table 6, with uncertainties given as standard deviations. The fitting curves for the radial velocity and four bands light curves are shown in Figures 8 and 9, where the observed data are compared with the theoretical light curves. It is clear from these figures that the theoretical curves match the observed data very well, particularly for the primary minima, which are well fitted in all bands. This is the best fit achievable with the current model, and thus, these results are adopted as the final solution for NR Cam. Figure 10 shows the geometric configuration at phase 0.25, with the red regions indicating the positions and sizes of the starspots.

Based on the fitting results for the two maxima from TESS data shown in Figure 7, we observed that the relative difference between the two maxima changes across sectors and exhibits a negatively correlated variation. In order to constrain the starspot parameters on the surface of NR Cam, we used the averaged light curve results from the 60 cm telescope observations as the baseline parameters for the TESS light curve solution. Since the relative maximum difference does not change significantly within a single sector, we randomly selected a segment of the light curve from each of the eight TESS sectors for W-D analysis. For these fits, the mass ratio q was fixed to the spectroscopic value obtained

Table 6
The Luminosity Solution Determined by Calculating the Light Curves of NR Cam in Four Bands, Observed with a 60 cm Aperture Telescope

Parameter	B	V	R_c	I_c	Mean
Mode	3	3	3	3	3
i [°]	73.05(34)	73.05(36)	73.35(57)	73.10(120)	73.14(1)
q [m_2/m_1]	5.69(7)	5.78(5)	5.75(8)	5.76(15)	5.75(3)
T_1 [K]	5570	5570	5570	5570	5570
T_2/T_1	0.8777(41)	0.8614(44)	0.8485(97)	0.8370(270)	0.8562(3)
$\Omega_1 = \Omega_2$	9.752(81)	9.904(56)	9.908(94)	9.870(160)	9.859(3)
$L_1/(L_1 + L_2)$	0.3604(83)	0.3356(77)	0.3180(130)	0.3070(320)	0.3303(3)
$L_2/(L_1 + L_2)$	0.6396(83)	0.6644(77)	0.6820(130)	0.6930(320)	0.6698(3)
r_1 (pole)	0.2365(9)	0.2338(8)	0.2326(15)	0.2348(29)	0.2344(1)
r_1 (side)	0.2478(10)	0.2446(9)	0.2431(18)	0.2457(34)	0.2453(3)
r_1 (back)	0.2942(20)	0.2878(18)	0.2841(35)	0.2895(74)	0.2889(22)
r_2 (pole)	0.5109(41)	0.5061(28)	0.5023(46)	0.5046(80)	0.5060(1)
r_2 (side)	0.5637(64)	0.5563(42)	0.5508(70)	0.5540(120)	0.5562(23)
r_2 (back)	0.5897(83)	0.5805(54)	0.5742(88)	0.5780(150)	0.5806(29)
The degree of contact (f)	0.390(130)	0.326(88)	0.270(150)	0.350(250)	0.334(31)
θ_s (radian)	2.85525	2.82397	2.78175	2.87283	2.83345(3460)
ψ_s (radian)	5.33169	5.14116	5.10876	5.27243	5.21351(9171)
r_s (radian)	1.69363	1.66829	1.74552	1.69519	1.70066(2802)
T_s/T	0.85593	0.85889	0.86782	0.81871	0.85034(1878)

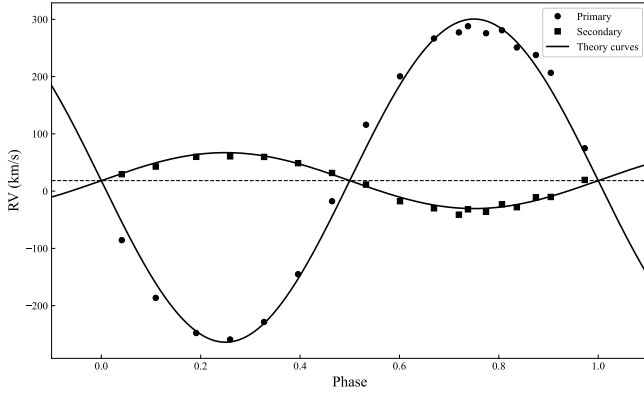


Figure 8. Radial velocity curve of NR Cam.

from RV solutions. Figure 11 presents the fitted curves of the observed and theoretical light curves across all eight sectors, showing excellent agreement with the observational data. A diagram of the starspot geometry at phase 0.25 is also shown in Figure 11, with the red regions indicating the locations and sizes of the starspots. The solution derived from the TESS light curves is consistent with the results obtained from the ground-based data, as shown in Table 7. The fitting results indicate that NR Cam is a W-subtype contact binary system with moderate, characterized by a fill-out factor of $f = 33.4(\pm 3.1)\%$ and a low mass ratio $q = 5.75(\pm 0.03)$.

5. Discussion and Conclusions

We conducted a detailed photometric and spectroscopic analysis of NR Cam using the W-D program. The results

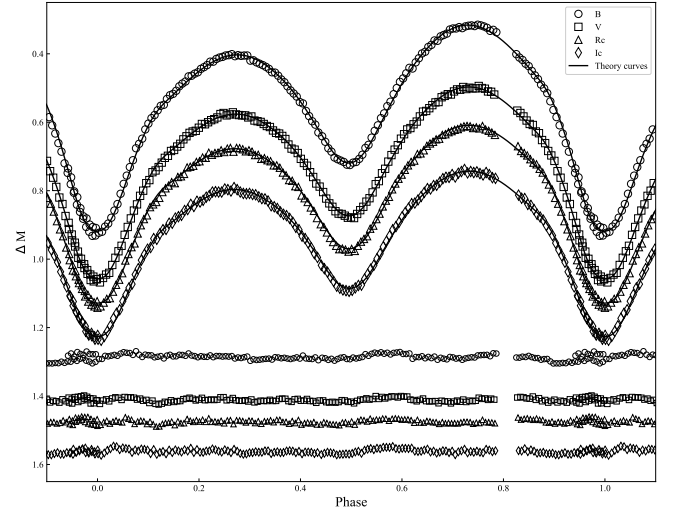


Figure 9. Light curve orbital solution for four bands.

indicate that NR Cam is a W-subtype contact binary system with a low mass ratio of $q = 5.75(\pm 0.03)$ and a moderate degree of contact, characterized by a fill-out factor of $f = 33.4(\pm 3.1)\%$. These results differ significantly from those of Tavakkoli et al. (2015), who classified NR Cam as a shallow contact binary with a fill-out factor of only $f = 0.6\%$ and two nearly identical components ($q = 1.062(\pm 0.001)$), based solely on single-band light curve modeling. In contrast, our solution incorporates both multi-band light curves and double-lined radial velocity data. The mass ratio in our model is directly derived from orbital dynamics, independent of surface features or modeling assumptions. This spectroscopic

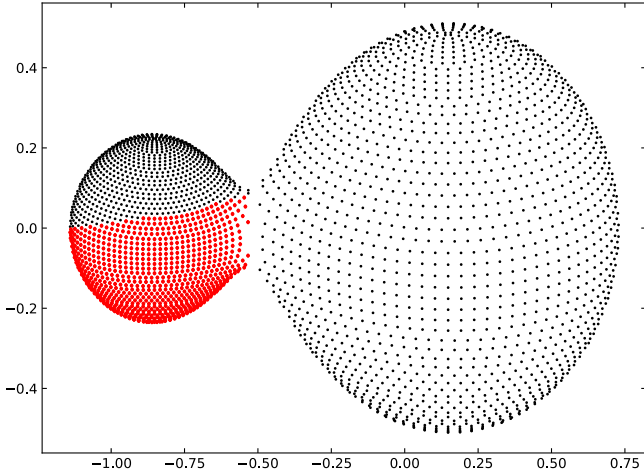


Figure 10. 0.25-phase geometry diagram.

constraint eliminates common degeneracies in photometric modeling and ensures a more physically consistent and reliable solution. Based on the radial velocity curves and light curves, the W-D program calculated the absolute parameters of the two components, which are listed in Table 8.

Using all available times of minima, the $O - C$ diagram was constructed and analyzed. The analysis of the orbital period variations of NR Cam reveals a long-term decreasing trend in its orbital period, with a rate of $dP/dt = -5.18(\pm 0.02) \times 10^{-8} \text{ day yr}^{-1}$. Since NR Cam is a moderately contact binary, the observed decrease in period can likely be attributed to the transfer of mass from the more massive component to the less massive one. According to the results presented in Table 8, the absolute mass of the primary star is $0.163M_{\odot}$, while the secondary star has a mass of $0.937M_{\odot}$. Under the assumption of conservative mass transfer, and taking into account the mass transfer conservation formula (Singh & Chaubey 1986):

$$\frac{\dot{P}}{P} = 3\dot{M}_2 \left(\frac{1}{M_1} - \frac{1}{M_2} \right). \quad (4)$$

The mass transfer rate of NR Cam was ultimately calculated to be $dM_2/dt = 1.33(\pm 0.01) \times 10^{-8} M_{\odot} \text{ yr}^{-1}$. After removing the long-term decreasing trend, a periodic oscillation was also detected in the orbital period, with an amplitude of $A_3 = 0.0019(\pm 0.0001) \text{ day}$ and an oscillation period of $P_3 = 7.776(\pm 0.003) \text{ yr}$. For contact binaries, periodic oscillations are commonly attributed to either the LTTE (Irwin 1952) or cyclic magnetic activity (Applegate 1992). Assuming that the periodic variation is caused by the LTTE induced by a third companion, we can calculate the mass function of the third companion using the following

formula:

$$\begin{aligned} f(m) &= \frac{4\pi^2}{GP_3^2} \times (a_{12} \sin i)^3 \\ &= \frac{(M_3 \sin i)^3}{(M_1 + M_2 + M_3)^2} \end{aligned} \quad (5)$$

The mass function $f(m)$ and the mass M_3 of the third body for orbital inclinations of $i_3 = 30^\circ, 60^\circ, 90^\circ$ were calculated, and the results are presented in Table 5. The calculated results indicate that the minimum mass of the third body is $M_3 = 0.0956(1)M_{\odot}$, and the maximum separation between the third body and the binary system is $3.841(6) \text{ au}$. A tertiary companion can extract angular momentum from the inner binary system, leading to a reduction in the system's initial angular momentum and orbital period. This process accelerates the evolution of the contact binary (Qian et al. 2006, 2007). Therefore, investigating whether NR Cam hosts a third companion not only provides observational evidence supporting the hypothesis that tertiary bodies are commonly present in contact binary systems (Tokovinin et al. 2006), but also offers valuable insights into the formation and evolution of contact binaries (Pribulla & Rucinski 2006; Rucinski et al. 2007; Pribulla et al. 2020).

Another possible explanation for the observed periodic variation is the variation of the gravitational quadrupole moment due to magnetic activity cycles, as proposed by Applegate (1992). To estimate the energy required to generate the periodic variation, we applied the Brinkworth et al. (2006) model, and the results are shown in Figure 12. In this figure, the red and blue solid lines represent the energy required to produce the periodic variation, while the red and blue dashed lines correspond to the total energy radiated from the two components. It is clearly seen that the total energy radiated by the two components satisfies the energy requirement of the Applegate mechanism. Therefore, the periodic variation in the orbital period can also be explained by the magnetic activity cycles.

We analyzed the TESS observational data of NR Cam and found that its light curve exhibits persistent variation in the brightness of the two maxima, displaying a prominent O'Connell effect and transitioning between positive and negative O'Connell types. A detailed analysis revealed that the variations in the maxima are negatively correlated, a common characteristic of W UMa-type contact binaries, typically attributed to magnetic activity (Li et al. 2022; Jiang & Zheng 2024). To account for this, we introduced a starspot model in the primary star for our W-D analysis. This model enabled us to explore the migration and evolutionary patterns of starspots on the primary component's surface, providing deeper insights into the system's magnetic activity. Chabrier et al. (2007) suggested that rapid rotation or magnetic activity plays a crucial role in the evolution of binary stars. NR Cam

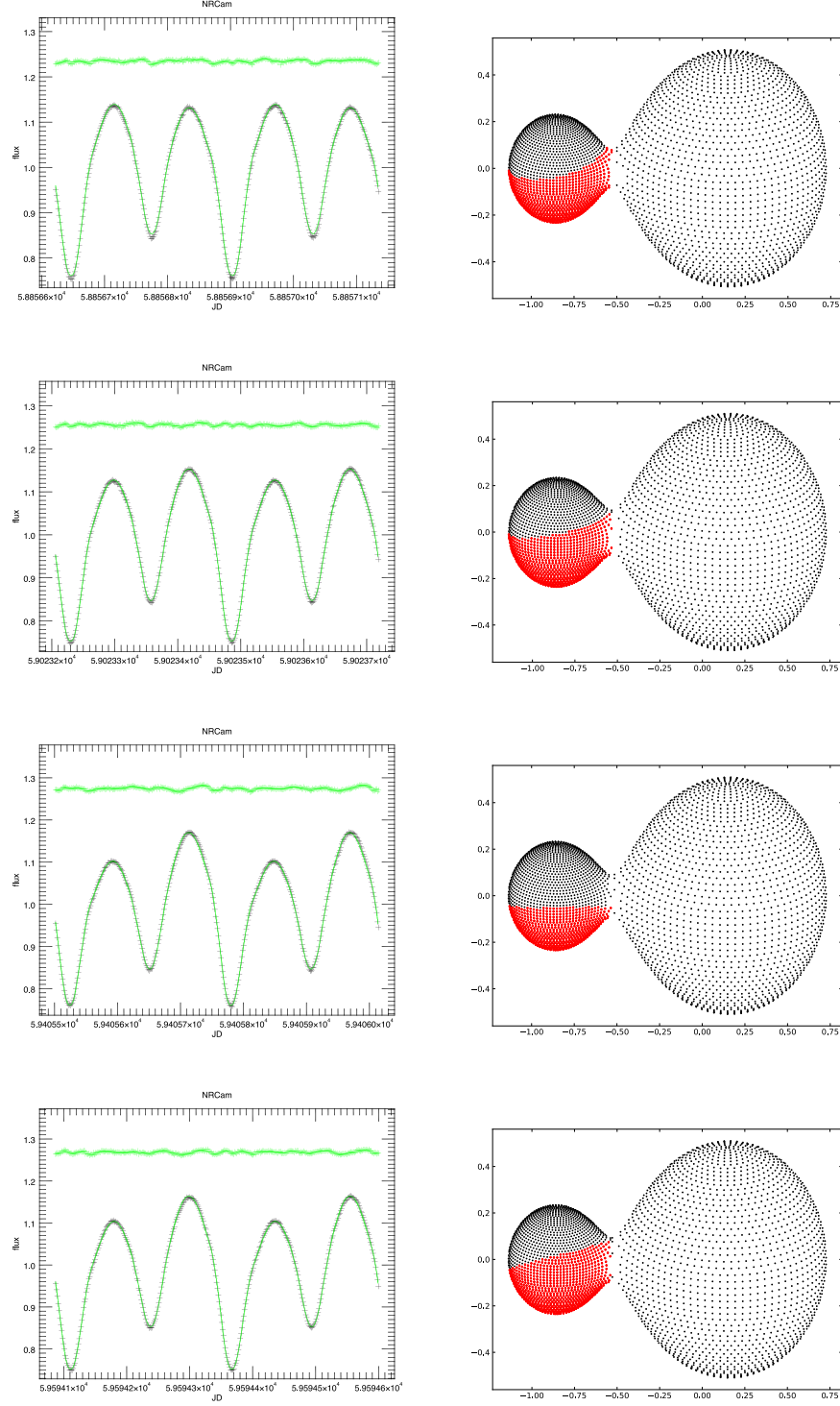


Figure 11. W-D model light curve fits for eight sectors and the corresponding phase 0.25 plots.

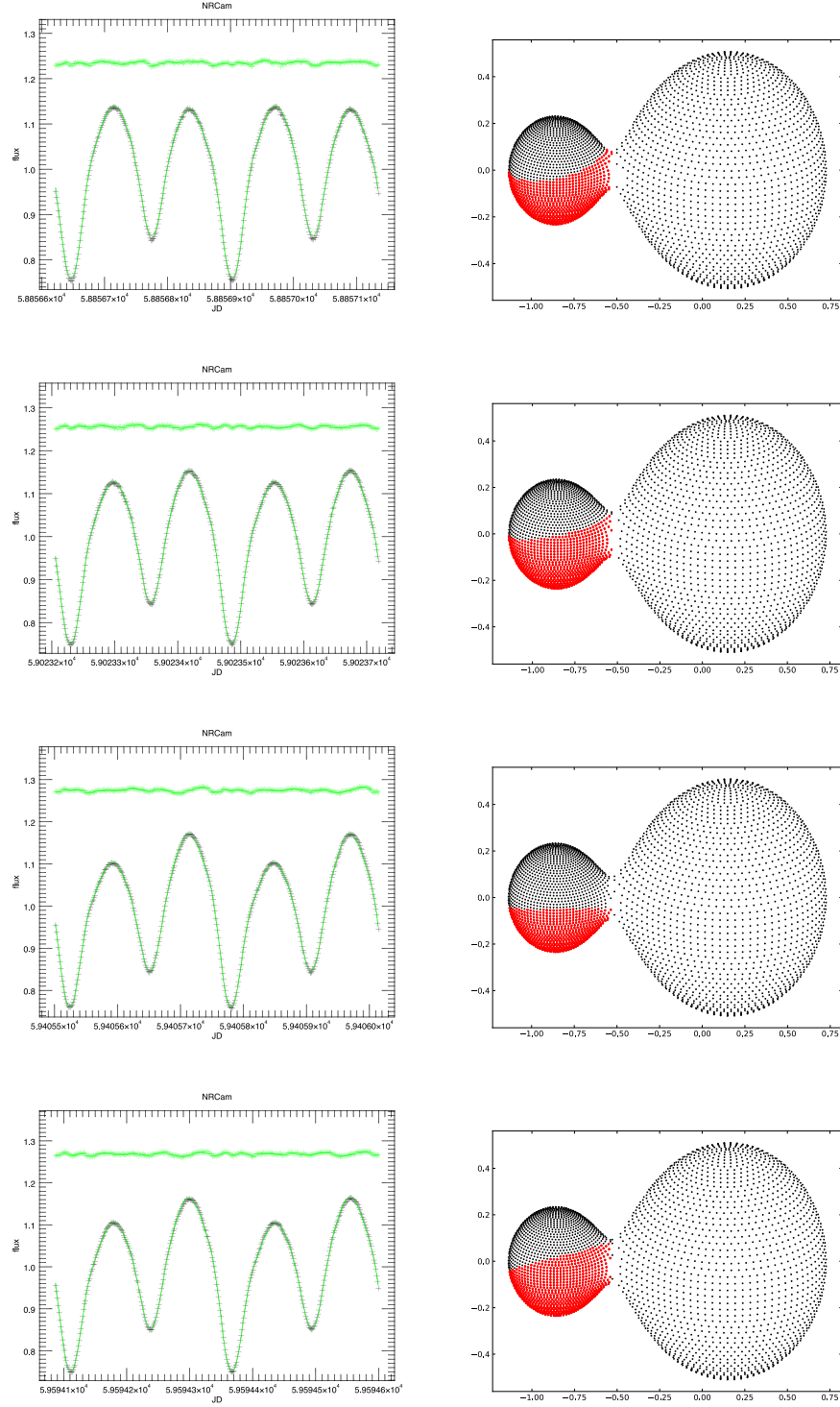


Figure 11. (Continued.)

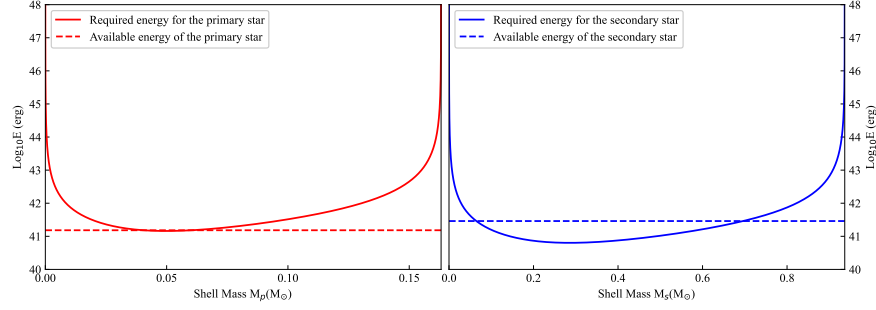


Figure 12. Energy required to produce the cyclic oscillation via Applegate’s mechanism (solid lines) and total radiated energy over one magnetic activity cycle (dashed lines) for the primary (left) and secondary (right) stars.

Table 7
TESS Photometric Solutions for NR Cam

Parameter	s20	s26	s40	s47	s53	s60	s73	s74
Mode	3	3	3	3	3	3	3	3
i [°]	73.09(70)	73.34(14)	72.35(7)	72.41(11)	71.90(8)	72.68(13)	72.85(9)	72.46(7)
q [m_2/m_1]	5.75	5.75	5.75	5.75	5.75	5.75	5.75	5.75
T_1 [K]	5570	5570	5570	5570	5570	5570	5570	5570
T_2/T_1	0.8570(220)	0.8564(34)	0.8575(6)	0.8578(22)	0.8659(28)	0.8709(17)	0.8711(29)	0.8614(25)
$\Omega_1 = \Omega_2$	9.942(34)	9.876(5)	9.905(3)	9.886(5)	9.932(4)	9.910(5)	9.897(5)	9.919(4)
$L_1/(L_1 + L_2)$	0.2850(230)	0.2889(38)	0.2863(4)	0.2869(24)	0.2760(29)	0.2720(17)	0.2725(30)	0.2814(27)
$L_2/(L_1 + L_2)$	0.7150(230)	0.7111(38)	0.7137(4)	0.7131(24)	0.7240(29)	0.7280(17)	0.7275(30)	0.7186(27)
r_1 (pole)	0.2305(17)	0.2340(3)	0.2323(2)	0.2333(3)	0.2309(2)	0.2321(3)	0.2327(2)	0.2315(2)
r_1 (side)	0.2407(20)	0.2448(3)	0.2428(2)	0.2440(3)	0.2412(2)	0.2426(3)	0.2432(3)	0.2418(2)
r_1 (back)	0.2797(40)	0.2881(7)	0.2840(4)	0.2864(7)	0.2807(5)	0.2835(6)	0.2848(6)	0.2819(4)
r_2 (pole)	0.5034(15)	0.5062(2)	0.5050(1)	0.5058(2)	0.5038(2)	0.5047(2)	0.5053(2)	0.5043(2)
r_2 (side)	0.5523(22)	0.5565(4)	0.5546(2)	0.5559(4)	0.5529(3)	0.5543(3)	0.5552(3)	0.5537(2)
r_2 (back)	0.5757(27)	0.5808(4)	0.5786(3)	0.5801(4)	0.5764(3)	0.5782(4)	0.5792(4)	0.5775(3)
The degree of contact (f)	0.219(54)	0.321(8)	0.277(5)	0.306(8)	0.234(6)	0.269(8)	0.289(7)	0.255(6)
θ_s (radian)	2.98296	2.94029	2.89821	2.74539	2.94753	2.80756	2.93479	2.99278
ψ_s (radian)	0.26664	5.56486	4.73596	5.24862	4.97644	5.38855	5.27463	4.96141
r_s (radian)	1.71647	1.66185	1.39568	1.58228	1.69943	1.45019	1.60682	1.73549
T_s/T	0.86298	0.85534	0.68078	0.85549	0.85922	0.82635	0.82405	0.82540

Table 8
Absolute Parameters of NR Cam

Parameter	Star1	Star2
Mass ($M_\odot$)	0.163(1)	0.937(2)
Radius ($R_\odot$)	0.450(5)	0.960(3)
Luminosity ($L_\odot$)	0.162(3)	0.307(37)

thus serves as a valuable case for studying magnetic activity and binary evolution. However, further photometric and spectroscopic observations are necessary to understand the variability characteristics of this binary system.

Acknowledgments

This research was supported by the College Students’ Innovation and Entrepreneurship Training Program (grant

Nos. 202410649025 and S202410649206), the Sichuan Science and Technology Program (grant No. 2025ZNSFSC0315), and the Key Laboratory of Detection and Application of Space Effect in Southwest Sichuan at Leshan Normal University, Education Department of Sichuan Province (grant No. ZDXM202401002). We acknowledge the support of the staff of the Xinglong 2.16 m, 85 cm and 60 cm telescopes. This work was partially supported by National Astronomical Observatories, Chinese Academy of Sciences. This paper makes use of data collected by the Transiting Exoplanet Survey Satellite (TESS) mission, obtained from the MAST data archive at the Space Telescope Science Institute (STScI). Funding for the TESS mission is provided by NASA’s Explorer Program. This research has also made use of the SIMBAD database, operated at CDS, Strasbourg, France.

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