KIC 9272276: AN EXTREME LOW MASS RATIO RED NOVA PROGENITOR

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SUMMARY: Photometric analysis of KIC 9272276 (K9272), a low-mass contact binary system, is presented. We find it to be an example of extreme low mass ratio system that satisfies the current theoretical criteria for a potential red-nova progenitor. V-band photometry of the system was modelled using the Wilson-Devenney code and we find the system to be in marginal contact with a mass ratio of 0.081. The estimated mass of the primary component is one solar mass and the theoretical instability mass ratio range, accounting for both metallicity and age, is well above the modelled mass ratio at 0.09 - 0.101. We find no evidence of a potential third light contamination and discuss other findings confirming our analysis.

Key words. Techniques: photometric – Stars: binaries: eclipsing – Stars: low-mass

1. INTRODUCTION

W Ursa Majoris binary systems usually consist of a low mass (spectral class F to K) main-sequence primary (Yildiz and Doğan 2013) with an even lower mass secondary. Due to their proximity, both components are tidally distorted such that the larger primary expands beyond its Roche lobe while still on the main sequence and there is significant transfer of mass from the primary to the secondary. The smaller secondary is not able to accrete the mass inflow, and it also expands beyond its Roche lobe, leading to bidirectional mass exchange, and the system becomes enclosed in a co-rotating common envelope. The rate of mass transfer depends on the initial masses of the components and how quickly the primary expands beyond its Roche lobe. Based on the model presented by Gazeas and Stępień (2008) and an initial pre-contact mass ratio of 0.5, a solar mass primary would lose nearly half its mass over an 8-9Gyr period to the secondary prior to the start of the contact phase. There is considerable transfer of energy from the primary to the secondary by processes not fully elucidated such that the temperature of the common envelope is close to that of the primary component and the secondary component is considerably more luminous than its main sequence counterpart of the same mass.

The current consensus is that angular momentum loss (AML) through magnetic breaking plays a significant role in contact binary evolution (Mochnacki 1981, Vilhu 1981, Li et al. 2004). Contact binary orbit can remain synchronised even with progressive

AML up until some critical separation where tidal instability (also known as Darwin instability) sets in (Darwin 1879). At this juncture, the orbital and rotational (spin) momentum approaches a 1:3 ratio, and the system can no longer maintain a synchronous orbit (Hut 1980). With continued AML, the orbit will begin to shrink rapidly, leading to the likely ejection of the common envelope and merger of the components. The Component merger is postulated to lead to a bright transient known as a red nova. However, to date, there is only one confirmed red nova event secondary to contact binary merger that of V1309 Sco (Tylenda et al. 2011).

Modelling has always suggested that merger would take place when the component mass ratio (M_2/M_1) (q) is extremely low (Rasio 1995, Arbutina 2009). Earlier considerations adopted a potential "universal" minimum mass ratio below which contact binaries would merge (Rasio and Shapiro 1995, Arbutina 2007, 2009). Recent theoretical updates have shown that it is unlikely to be a single minimum mass ratio at which orbital instability would begin. It is now suggested that each system has its unique mass ratio at which it is likely to become unstable (Wadhwa et al. 2021, Arbutina and Wadhwa 2024). In the case of low mass contact binaries, with primaries between $0.6M_\odot$ and $1.4M_\odot$, the instability mass ratio can range from 0.04 to 0.22. In addition, there is evidence that the internal composition (metallicity) and the age of the contact binary, both of which have a sufficient influence on the internal gas dynamics of the star to influence its gyration radius, also have a significant influence on orbital stability (Wadhwa et al. 2024). The net effect of the recent updates suggests that most contact binaries in the Solar vicinity are likely to be stable. Wadhwa et al. (2024) were unable to confirm any unstable system from hundreds of published light curve solutions.

As part of our ongoing search for potential merger candidates, we have used the rapid identification procedure from Wadhwa et al. (2022) to identify K9272 (= ASAS-SN-V J191059.37+454316.6, T-Lyr-07958) as a potential red nova progenitor from the All Sky Automated Survey - SuperNova (ASAS-SN) (Jayasinghe et al. 2020). The identification procedure links the estimated mass of the primary component (derived through colour and survey spectra) and the amplitude of the observed light curve with the theoretical instability mass ratio. If the amplitude is significantly higher than the expected amplitude for the instability mass ratio, then the system can be considered stable without further analysis. K9272 was recognised as variable by the Automated Survey of the Kepler mission fields in 2008 (Pigulski et al. 2008). It has been observed as part of both the Kepler and TESS missions as well as ASAS-SN. Photometry from all these surveys demonstrate total eclipses, indicating the system to be suitable for photometric analysis, and low amplitude, suggesting possible mass ratio in the instability range. We report the

modelling of V-band photometry and orbital stability analysis confirming that the system is potentially unstable based on the updated instability criteria.

2. OBSERVATIONS AND MASS OF THE PRIMARY COMPONENT

K9272 was observed over 8 nights between July 2024 and April 2025 with the 0.4m telescopes from the Las Cumbres Observatory (LCO) network (SBIG STL-6303 CCD camera) and 0.6m telescope (FLI ProLine PL23042 CCD camera) at the Astronomical Station Vidojevica in Serbia. Full phase light curve was obtained in the V-band (Bessell) and to document the colours of the primary we also acquired high cadence images during eclipses in the B, V and R-bands (Johnson-Cousins). All images were calibrated with appropriate dark, bias and flat field frames. We used the AstroImageJ (Collins et al. 2017) package to perform differential photometry with UCAC4 679-066810 (B: 14.29, V: 12.97 and R: 12.71 magnitudes from Henden et al. (2015)) as the comparison star and UCAC4 679-066805 as the check star. The software package calculates the difference in apparent magnitude between the comparison star and the target star and based on the reported apparent magnitude of the comparison star provides the apparent magnitude of the target star.

We used our data and the available data from ASAS-SN, Kepler, TESS and our observations to refine the ephemeris as follows:

$$BJD_{\min} = 2460781.0830844\,(\pm221) + 0.28061529\,(\pm200)E.$$

Our light curve demonstrates a V-band amplitude of 0.204 mag which is similar to the ASAS-SN amplitude of 0.21 mag, Kepler amplitude of 0.193 magnitude. The TESS amplitude is slightly higher at 0.226 mag. The TESS flux, obtained through from The Mikulski Archive for Space Telescopes (MAST) data portal, was converted to magnitude using the relationship $-2.5\log 10\,(\text{flux}) + 20.44$ from the TESS instrument handbook. Our observations indicate the following colours for the primary component $B - V = 0.97$ and $V - R = 0.13$. The light curve shows both maxima of equal brightness and similarly, both minima are of equal depth. The apparent V-band magnitude range is 13.154 - 13.358. The infinite-length extinction is estimated as 0.0591 (Schlafly and Finkbeiner 2011) and corrected for distance Wadhwa et al. (2023c) as 0.044, yielding an extinction magnitude of 0.138 mag. As the secondary eclipse is complete, the observed light during this time represents the light from the primary component, and we estimate its extinction corrected apparent magnitude as 13.22, which when combined with $GAIA$ DR 3 (Gaia Collaboration et al. 2016, 2023) estimated distance of 640.09 pc yields an absolute magnitude (M_{V1}) of 4.46 for the primary component and 4.26 (M_{VT}) for

the system at maximum brightness indicating an absolute magnitude of 6.19 (M_{V2}) for the secondary component. Adopting the calibrations (April 2022 update) for main sequence stars from Pecaut and Mamajek (2013) we estimate the mass of the primary as $1.04M_\odot$. This value is in good agreement with the *GAIA* estimate of $0.98M_\odot$ and $1.0M_\odot$ from the TESS input catalogue (Paegert et al. 2021). Given the agreement between various sources, we adopt the mass $1.01M_\odot \pm 0.03$ for the primary component. We adopted the combined error of the photometry and distance as the potential error for the mass of the primary component and for the ongoing propagation of errors.

3. LIGHT CURVE SOLUTION AND ORBITAL STABILITY

3.1. Light Curve Solution

The *V*-band light curve was modelled using a recent version (2015) of the Wilson-Devenney (WD) code (Wilson and Devinney 1971, Wilson 1990). The WD code requires the observed curve to be represented as a flux normalised to the brightest magnitude. The modelled curve is also normalised with maximum brightness at phases 0.25 and 0.75. The standard grid search procedure, suitable in the presence of complete eclipses, was used to find the best fitting solution over a range of mass ratios (0.06 - 15.00). Modelling was performed using mode 3 (overcontact) with the temperature of the secondary (T_2), inclination (i), potential (fillout) (f) and the scaling factor luminosity of the primary (L_1) being the adjustable parameters. The limb darkening coefficients were derived from van Hamme (1993) while the gravity coefficients ($g_1 = g_2$) were fixed at 0.32 and the bolometric albedos ($A_1 = A_2$) fixed at 0.5 and simple reflection treatment as applied. The temperature of the primary component is usually fixed during modelling and was set 5600K based on the medium resolution spectrum from the Large Sky Area Multi-Object Fiber Spectroscopic Telescope (LAMOST) survey (Zhao et al. 2012). In the case of complete eclipses there is a very strong correlation in the $[q,i]$ domain such that the absolute value of T_1 has little influence on the geometric solution. Variations in T_1 of up to 1000K have been modelled yielding the same geometric solution (Wadhwa et al. 2023a). If the temperature of the primary is not used in further analysis, as in the present study, the adopted value will not influence orbital stability analysis. As no significant O'Connell effect (variation in maximum brightness) was observed we did not include star spots in our analysis.

The geometric solution is summarised in Table 1 and the modelled and fitted curves along with a 3D representation of the system are illustrated in Fig. 1. Briefly, modelling reveals an extreme low mass ratio system with $q = 0.081$ and marginal contact. Our so-
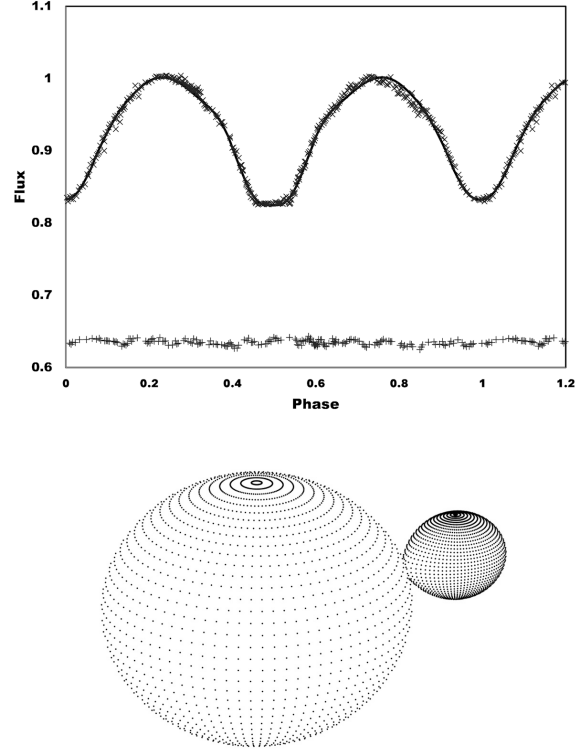

Fig. 1: Top: Modelled (Black) and Observed (X) light curves of K9272. Check star flux (+).
Bottom: 3D representation of K9272.

lution is similar to the automated solution of Kepler photometry obtained by (Li et al. 2020). As noted by Liu (2021), random errors contribute negligibly to the total error in the case of WD solutions with a low mass ratio completely eclipsing systems, and as such we adopt the standard deviation of the parameters (as reported by the WD code) as the parameter errors. Absolute parameters such as the mass of the secondary component, radii and separation follow from the combination of the geometric solution and Kepler's third law. The absolute parameters are also summarised in Table 1.

3.2. Orbital Stability

Orbital stability of contact binaries has received increasing attention since the confirmation of the red nova V1309 Sco as contact binary merger event. Our research group, over the last few years, has refined the theoretical instability criteria for contact binaries (Wadhwa et al. 2021, Arbutina and Wadhwa 2024, Wadhwa et al. 2024). Initially we showed that the instability mass ratio is not universal; each system has its own unique instability parameters largely dependent on the mass of the primary component and its gyration radius. Subsequently, we further refined the instability parameters by incorporating the effects of metallicity and age. We essentially concluded that

Table 1: Light Curve Solution and Absolute Parameters of K9272. SMA = separation.

T_1(K) - Fixed	5600
T_2(K)	5743±12
q	0.081±0.001
Incl(^{o})	68.5±0.4
Fillout (%)	4±2
$M_1/M_\odot$	1.01±0.03
$M_2/M_\odot$	0.081±0.004
$R_1/R_\odot$	1.13±0.02
$R_2/R_\odot$	0.34±0.02
SMA ($R_\odot$)	1.85±0.03

there are likely very few, if any, unstable systems in the solar vicinity. The stability of K9272 was assessed using the instability criteria described in the references cited above.

Our earliest refinements did not incorporate the effects of metallicity or system age with respect to orbital stability (Wadhwa et al. 2021). Based on these the instability mass ratio range for a contact binary with one solar mass primary would be 0.10 - 0.118. Incorporating the effects of age and metallicity Wadhwa et al. (2024), the instability mass ratio range decreases to 0.09 - 0.101. We adopted the metallicity based on the LAMSOT spectra and GAIA photometry both of which indicate a near solar metallicity for the system. As noted by Wadhwa et al. (2024) it is not possible to determine the true age of contact binaries and, as adopted by them, we assumed the primary to be a main sequence star halfway through its main sequence lifespan.

The modelled mass ratio of the system at 0.081 is well below the instability mass ratio range taking full consideration of metallicity and age. Similarly, the separation ($1.82R_\odot$) and period ($P = 0.28061529d$) are below the theoretical instability onset values.

4. DISCUSSION AND CONCLUSION

Potential red nova progenitors are rare. Most reported examples suffer from lingering doubts with respect to the validity of the light curve solution (see Wadhwa et al. 2024, for some recent examples). There is a direct correlation between the amplitude of the light curve and the mass ratio of a contact binary system when total eclipses are present (Wilson and Devinney 1971, Wadhwa et al. 2022). Unfortunately, the light curve amplitude can be significantly reduced in the presence of a third light leading to a falsely reduced mass ratio being modelled. The effect was dramatically illustrated in the case of CRTS J192848.7-404555 where the presence of a third light reduced the modelled mass ratio to 0.08 based on survey photometry from the true mass ratio of 0.425 based on higher resolution observations (Wadhwa et al. 2023b).

In the case of K9272 the observed luminosity is in keeping with the estimated spectral mass of the primary component. Many previous examples of extreme low mass ratio contact binaries have luminosity far in excess of that predicted by their estimated mass of the primary component, see Wadhwa et al. (2024) for some examples. The GAIA DR3 catalogue does show a companion ≈ 2.3 arc seconds from K9272. We could not separate the two in our images however the GAIA estimate of the companion brightness is almost 3 magnitude fainter than the main source and as such its influence on the amplitude of the contact binary light curve is not considered significant.

In addition to a simple line of sight third light, many contact binaries have been shown to be part of multiple star systems. We did not find any improvement in the light curve solution with the addition of a third light however, the potential for a tertiary companion to K9272 has been explored by Borkovits et al. (2016). They found that there is indeed a likely third companion to K9272. Their analysis suggests that the tertiary companion has a long period ($> 1400d$) and that it is unlikely to influence the amplitude of the main contact binary in any meaningful way.

Another issue that has not been addressed in the case of many extreme low mass ratio contact binaries is the mass of the secondary component. In many cases, see Wadhwa et al. (2024) for representative examples, the estimated mass of the secondary component falls well below the minimum hydrogen fusion mass of $0.08M_\odot$. Based on our results and previous modelling by (Li et al. 2020) the mass of the secondary component is estimated to be above the hydrogen fusion mass and the calculated mass ratio in both solutions is in the instability range.

Current theoretical considerations of orbital stability of low mass contact binaries indicate that most contact binaries, at least in solar vicinity, are likely stable and unlikely to merge and lead to a red nova type transient (Wadhwa et al. 2024). The analysis of K9272 presented here is among the most definitive for a contact binary system in an unstable configuration. Given the relative brightness of the system long term high cadence follow up observations are within the reach of modest instruments and encouraged.

5. DATA AVAILABILITY

Photometry data from ASV observations are available in the machine-readable form at: http://saj.matf.bg.ac.rs/211/KIC9272276.dat (phased/normalised). All other data are available upon reasonable request to the corresponding author.

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KIC 9272276: ПРОГЕНИТОР ЦРВЕНЕ НОВЕ
СА ЕКСТРЕМНО МАЛИМ ОДНОСОМ МАСА

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У раду је представљена фотометријска анализа контактног двојног система са малим односом маса KIC 9272276 (К9272). Налазимо да је овај систем један пример система са екстремно малим односом маса који задовољавају тренутни теоријски услов за потенцијалног прогенитора црвене нове. Фотометријске криве сјаја система у V филтру моделоване су помоћу Вилсон-Девинијевог кода и модели показују да се ради о систему у маргиналном контакту са односом маса 0.081. Процењена маса примарне компоненте је једна Сунчева маса, а теоријски критеријум за нестабилност, који укључује и металичност и старост, даје критични однос маса 0.09 - 0.101, значајно изнад вредности добијене из модела. Нисмо пронашли доказе контаминације тзв. трећим светлом, а дискутовали смо и друге налазе који потврђују нашу анализу.