First Light Curve Analysis of NSVS 8294044, V1023 Her, and V1397 Her Contact Binary Systems (Postprint)

Authors: Atila Poro, Sabrina Baudart, Mahshid Nourmohammad, Zahra Sabaghpour Arani, Fatemeh Farhadi, Selda Ranjbar Salehian, Ahmad Sarostad, Saeideh Ranjbaryan Iri Olya, Maryam Hadizadeh and AmirHossein Khodaei

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Abstract

The first photometric light curve investigation of the NSVS 8294044, V1023 Her, and V1397 Her binary systems is presented. We used ground-based observations for the NSVS 8294044 system and Transiting Exoplanet Survey Satellite data for V1023 Her and V1397 Her. The primary and secondary times of minima were extracted from all the data, and, by collecting the literature, a new ephemeris was computed for each system. Linear fits for the O − C diagrams were conducted using the Markov Chain Monte Carlo (MCMC) method. Light curve solutions were performed using the PHysics Of Eclipsing BinariEs Python code and the MCMC approach. The systems were found to be contact binary stars based on the fillout factor and mass ratio. V1023 Her showed the O' Connell effect, and a cold starspot on the secondary component was required for the light curve solution. The absolute parameters of the system were estimated based on an empirical relationship between orbital period and mass. We presented a new T-M equation based on a sample of 428 contact binary systems and found that our three target systems were in good agreement with the fit. The positions of the systems were also depicted on the M-L, M-R, q-Lratio, and Mtot-J0 diagrams in the logarithmic scales.

Full Text

Preamble

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Atila Poro[1], Sabrina Baudart[2], Mahshid Nourmohammad[3], Zahra Sabaghpour Arani[4], Selda Ranjbar Salehian[6], Ahmad Sarostad[7], Saeideh Ranjbaryan Iri

Olya[8], Maryam Hadizadeh[9], Fatemeh Farhadi[5], and AmirHossein Khodaei[5]

[1]Department of Physics, Faculty of Science, Zanjan University, Zanjan, Iran
[6]Astronomy Students' Scientific Association, University of Tabriz, East Azerbaijan Province, Tabriz, Iran
[9]Khayyam Astronomy Association, Fars, Fasa, Iran

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Abstract

We present the first photometric light curve investigation of the NSVS 8294044, V1023 Her, and V1397 Her binary systems. Ground-based observations were used for NSVS 8294044, while Transiting Exoplanet Survey Satellite (TESS) data were employed for V1023 Her and V1397 Her. Primary and secondary eclipse times were extracted from all available data, and new ephemerides were computed for each system by incorporating literature values. Linear fits to the O−C diagrams were performed using the Markov Chain Monte Carlo (MCMC) method. Light curve solutions were obtained using the PHysics Of Eclipsing BinariEs (PHOEBE) Python code combined with an MCMC approach. Based on the fillout factor and mass ratio, all three systems were identified as contact binary stars. V1023 Her exhibited the O' Connell effect, requiring a cool starspot on the secondary component for an adequate light curve solution. Absolute parameters were estimated using an empirical relationship between orbital period and mass. We derived a new temperature-mass (T-M) relation based on a sample of 428 contact binary systems and found that our three target systems agree well with this fit. The positions of the systems were also plotted on mass-luminosity (M-L), mass-radius (M-R), mass ratio-luminosity ratio (q-Lratio), and total mass-orbital angular momentum (Mtot-J0) diagrams in logarithmic scales.

Key words: (stars:) binaries: eclipsing -techniques: photometric -stars: individual (NSVS 8294044)

1. Introduction

Eclipsing binaries are classified into different categories based on the degree of separation between their components, which can be identified through light curve morphology. These categories include detached, semi-detached, contact, and overcontact systems. Contact binary stars, commonly referred to as W UMa-type systems, exhibit several interesting physical properties (Drake et al. 2014). In W UMa systems, both components have filled their Roche lobes (Paczyński 1971) and share a common convective envelope between the inner and outer contact surfaces (Lucy 1968). The stars in these systems exchange mass and energy, resulting in similar surface temperatures and light curves with nearly equal eclipse depths. Furthermore, W UMa stars typically consist of main-sequence stars of late spectral types (Terrell et al. 2012).

Contact binary systems have short orbital periods, mostly ranging between 0.2 and 0.6 days (Qian 2003; Kouzuma 2018; Latković et al. 2021). Studying these systems provides an opportunity to investigate orbital period variations driven by system-wide physical processes, leading to a deeper understanding of stellar evolution (Li et al. 2021). Therefore, new observations are continually valuable for investigating these variations.

This study presents the first light curve analysis of three binary systems: NSVS 8294044 (R.A. 19h14m41.0475, decl. +37°11 51.0482 (J2000)), V1023 Her (R.A. 15h58m25.2669, decl. +16°45 55.0 (J2000)), and V1397 Her (R.A. 17h07m16.8455, decl. +37°04 22.3909 (J2000)). All three target systems have been classified as contact binaries in the ASAS and VSX catalogs. According to the VSX database, the orbital periods of NSVS 8294044, V1023 Her, and V1397 Her are 0.3779846, 0.3222336, and 0.387745 days, respectively. The apparent magnitude of NSVS 8294044 is V = 13.24 based on the VSX database, that of V1023 Her is V = 11.8, and that of V1397 Her is V = 11.3.

The structure of this paper is as follows: Section 2 describes ground- and space-based observations and data reduction; Section 3 presents the determination of new ephemerides for each system; Section 4 explains the light curve analysis; Section 5 describes the estimation of absolute parameters; and finally, Section 6 provides discussion and conclusions.

2. Observation and Data Reduction

We observed NSVS 8294044 in August-September 2023. The observations were conducted at a private observatory in Toulon, France, located at longitude 05°54 35 E, latitude 43°08 59 N, and an altitude of 68 m above mean sea level. The equipment used included a TS Optics Apochromatic Refractor with a 102 mm aperture, a ZWO ASI 1600MM CCD camera, and a V filter. Images were taken with 1$×$1 binning, an exposure time of 80 s, and an average CCD temperature of −15°C. Basic data reduction was performed using Siril 1.2.0-rc2 with bias, dark, and flat-field images. GSC 02665-00244 (R.A. 19h17m21.4390, decl. +37°11 51.0482 (J2000)) was used as the comparison star, while GSC 02665-01066 (R.A. 19h17m11.7567, decl. +37°13 32.9641 (J2000)) and Gaia DR2 2051151521582207232 (R.A. 19h17m06.8187, decl. +37°04 22.3909 (J2000)) served as check stars. Based on our observations, the maximum apparent magnitude of the light curve was determined to be Vmax = 13.24 mag.

TESS data were used for the binary systems V1023 Her (TIC 310170498) and V1397 Her (TIC 143100813). TESS observed V1023 Her in sectors 23, 24, 50, and 51, and V1397 Her in sectors 12 and 13. TESS employed a 120 s exposure time for these sectors. The data are available from the Mikulski Archive for Space Telescopes (MAST).

3. New Ephemeris

We extracted primary and secondary eclipse times from both ground-based and TESS light curves, determining mid-eclipse times using a Gaussian distribution. Uncertainties were computed using the Markov Chain Monte Carlo (MCMC) method. All minima are presented in Barycentric Julian Date in Barycentric Dynamical Time (BJDTDB). The minima for the three target systems, collected from the literature and extracted in this study, are listed in Table 1 . The extracted TESS mid-eclipse times for V1023 Her and V1397 Her are provided in the Appendix (Tables 4-6).

Each epoch and O−C value was computed using the appropriate reference ephemeris. For NSVS 8294044, we adopted t_0 = 2458423.7230 and P_{ref} = 0.3779833 from the ASAS-SN catalog as the reference ephemeris. For V1023 Her, t_0 = 2459636.8875 was taken from Nelson & Alton (2022) and P_{ref} = 0.3222341(87) from the WISE catalog of periodic variable stars. For V1397 Her, the reference ephemeris t_0 = 2453833.6397 and P_{ref} = 0.387745 were taken from Diethelm (2009).

Given the limited number of observations and minimum times for our three binary systems, a linear fit is most appropriate for the O−C diagrams. The O−C diagrams are presented in Figure 1 [Figure 1: see original paper] along with corner plots of the posterior distributions from MCMC sampling. To determine a new ephemeris for each system, we applied 20 walkers and 20,000 iterations per walker with a burn-in period of 2000 iterations in the MCMC process, using the PyMC3 package (Salvatier et al. 2016). The new ephemerides for each target system are presented in Equations (1) to (3):

NSVS 8294044:
Min.I BJD_{TDB} = 2458423.7230(1) + 0.3779833(2) × E

V1023 Her:
Min.I BJD_{TDB} = 2459636.8875(3) + 0.3222341(4) × E

V1397 Her:
Min.I BJD_{TDB} = 2453833.6397(5) + 0.387745(6) × E

4. Light Curve Analysis

We utilized the PHysics Of Eclipsing BinariEs (PHOEBE) Python code version 2.4.9 combined with an MCMC approach to model the light curves of the binary systems NSVS 8294044, V1023 Her, and V1397 Her (Prša & Zwitter 2005; Prša et al. 2016; Conroy et al. 2020). This represents the first analysis of these three target systems. Based on the appearance of the light curves and their short orbital periods, we selected contact mode for the solutions. The gravity-darkening coefficients and bolometric albedo were assumed to be $g_1 = g_2 = 0.32$ (Lucy 1967) and $A_1 = A_2 = 0.5$ (Ruciński 1969), respectively.

The limb-darkening coefficients were included in PHOEBE as free parameters, with stellar atmospheres modeled using the Castelli & Kurucz (2004) study. We applied the effective temperatures reported in Gaia Data Release 3 (DR3) to the hotter star; these temperature values were not fixed and remained free parameters during the MCMC process. The effective temperature ratio was used to estimate the temperature of the other component. Additionally, we checked and compared the initial temperatures of these systems from TESS through MAST. The TESS input catalog v8.2 reported temperatures of 5937(115) K, 5088(126) K, and 6440(113) K for NSVS 8294044, V1023 Her, and V1397 Her, respectively, which are close to the Gaia DR3 values.

The q-search method was employed to estimate the mass ratio of each binary system, given that only photometric data were available. We performed q-searches on each target system over a range of 0.1–9, identifying the mass ratio that minimized the sum of squared residuals. These results were used as initial values to fit synthetic light curves to the observational data. Figure 2 [Figure 2: see original paper] displays the q-search results for each system.

The light curve analysis of V1023 Her required a cool starspot on the secondary component to account for the difference between the light curve maxima. Contact systems are known for their magnetic activity, which is described by the O’ Connell effect (O’ Connell 1951). We used PHOEBE’ s optimization tool to refine the light curve solutions and obtain initial parameters for the MCMC process. The five main parameters (T_1, T_2, q, i, l_1) were then processed using the MCMC approach to determine their values and uncertainties. We employed 96 walkers with 1000 iterations per walker, initially positioned from a Gaussian distribution based on our parameter estimates, with widths adjusted according to the sensitivity of the light curves to various parameters.

The results of the light curve solutions for the three binary systems are listed in Table 2 . The observed and synthetic light curves, along with corner plots, are displayed in Figure 3 [Figure 3: see original paper]. The geometric structures of the systems are illustrated in Figure 4 [Figure 4: see original paper].

5. Absolute Parameters

We estimated absolute parameters using empirical relationships between mass and orbital period (Poro et al. 2024). The following equation was adopted from Latković et al. (2021), based on a large sample of contact binaries:

$\log(M/M\ ) = 0.63(7) \times \log(P) + 0.28(4)$ (4)

This approach accounts for the dependence on mass ratio q, as noted in the Latković et al. (2021) sample and discussed in Poro et al. (2024). We applied Equation (4) to the more massive star in each system and used the mass ratio from the light curve solution to determine the mass of the companion star. The semi-major axis a(R) was computed using Kepler’ s third law, and stellar radii were estimated from $R = a \times r(\text{mean})$. Luminosities were determined using $L = 4\pi R^2\sigma T^4$, with effective temperatures and radii from our solutions. Bolometric magnitudes $Mbol_{1,2}$ were calculated using Pogson' s relation (Pogson 1856), where Mbol = 4.73 mag (Torres 2010). We extracted bolometric corrections (BC) from Flower (1996) and computed absolute visual magnitudes using MV = Mbol − BC. Surface gravities were calculated with $g = GM/R^2$.

The estimated absolute parameters for the target systems are presented in Table 3 . Uncertainties were propagated from the errors in Equation (4) and the relevant parameters.

6. Discussion and Conclusion

We present the first light curve analysis of the binary systems NSVS 8294044, V1023 Her, and V1397 Her, using ground-based observations for NSVS 8294044 and TESS data for V1023 Her and V1397 Her. Our discussion and conclusions are summarized as follows:

1. We extracted eclipse times from ground- and space-based photometric data and, by incorporating literature values, derived new ephemerides for each system. A linear fit was the most appropriate choice for the O−C diagrams of our target systems. The O−C diagram of V1023 Her shows a decreasing trend based on the linear fit, while NSVS 8294044 and V1397 Her display increasing trends (Figure 1 [Figure 1: see original paper]).
2. Light curve analysis was performed for each target binary system, with V1023 Her requiring a cool starspot. The results indicate effective temperatures ranging from approximately 4600 to 6400 K. Star1 is hotter than Star2 in NSVS 8294044 and V1023 Her, but cooler in V1397 Her. The temperature differences between components are 440 K for NSVS 8294044, 356 K for V1023 Her, and 87 K for V1397 Her. Based on these temperatures and the studies of Cox (2000) and Eker et al. (2018), the spectral types can be identified as: Star1 = G0 and Star2 = G7 for NSVS 8294044; Star1 = K1 and Star2 = K3 for V1023 Her; Star1 = F6 and Star2 = F5 for V1397 Her.
3. We used empirical parameter relationships and orbital periods to estimate stellar masses. Based on the absolute parameters, we plotted the stars' positions on Mass-Luminosity (M-L) and Mass-Radius (M-R) diagrams relative to the Zero-Age Main Sequence (ZAMS) and Terminal-Age Main Sequence (TAMS) (Figure 5 Figure 5: see original paper, (b)). The positions of the systems on the q-Lratio relation from Poro et al. (2024) are shown in Figure 5(c), demonstrating good agreement with the model.
4. We calculated the orbital angular momentum (J_0) of the systems using the equation from Eker et al. (2006). The results are listed in Table 3 . As shown in Figure 5(d), the Mtot-J_0 diagram indicates that all three systems are located in the region of contact binary systems. The parabolic fit marking the boundary between detached and contact binaries in Figure 5(d) is taken from Eker et al. (2006).

5. The relationship between parameters in binary systems is a topic of considerable interest. However, most investigations of the mass-temperature (M-T) relationship have focused on detached and semi-detached systems (e.g., Paczyński 1967; Harmanec 1988; Kovaleva 2002; Malkov 2007; Spada et al. 2013; Eker et al. 2018). The Yakut & Eggleton (2005) study presented a log M-log T diagram for contact binaries showing A- and W-type systems. Figure 6 [Figure 6: see original paper] demonstrates that our three target systems are in good agreement with this fit and other stars in the sample.

The M-T diagram for a limited number of contact systems in Kjurkchieva et al. (2019) shows a weak relationship due to large dispersion. The relationship between P-T_1-M_1 was presented using a machine learning model in another work by Poro et al. (2024), who employed 134 contact systems analyzed with spectroscopic data. Using an Artificial Neural Network (ANN) model, they estimated masses of 1.20(8), 0.99(9), and 1.27(6) M for NSVS 8294044, V1023 Her, and V1397 Her, respectively. These values are consistent with our results within the uncertainty range.

We provide a T_1-M diagram with a linear fit using 428 contact systems from the Latković et al. (2021) sample (Equation (6)):

$\log(T_1) = 3.78(2) + 0.12(1) \times \log(M\ )$ (6)

where M denotes the more massive star.

6. First light curve studies of binary stars are important for creating larger samples for deeper parameter investigations of these systems. This work presents new ephemerides and the first light curve analysis of our target binary systems. We conclude that NSVS 8294044, V1023 Her, and V1397 Her are contact binary systems based on their mass ratios, fillout factors, inclinations, absolute parameters, and positions on the Mtot-J_0 diagram.

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Data Availability: Ground-based data will be made available upon request.

Appendix

The appendix tables contain the extracted TESS primary and secondary eclipse times for the V1023 Her and V1397 Her binary systems.

Table 4 : Extracted Times of Minima for V1023 Her
Table 5 : Continued for V1023 Her
Table 6 : Available Times of Minima for V1397 Her

Note: All times of minima have been reduced to 2,400,000. The error value for minimum times extracted from TESS is 0.0001 day.

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