KIC 9832227: Using Vulcan Data to Negate the 2022 Red Nova Merger Prediction

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Abstract

KIC 9832227 is a contact binary whose 11 hr orbital period is rapidly changing. Based on the apparent exponential decay of its period, the two stars were predicted to merge in early 2022 resulting in a rare red nova outburst. Fortunately KIC 9832227 was observed in 2003 as part of the NASA Ames pre-Kepler Vulcan Project to search for transiting exoplanets. We find that the Vulcan timing measurement does not agree with the previous exponential decay model. This led us to re-evaluate the other early epoch non-Kepler data sets, the Northern Sky Variability Survey (NSVS) and Wide Angle Search for Planets (WASP) survey. We find that the WASP times are in good agreement with the previous prediction, but the NSVS eclipse time differs by nearly an hour. The very large disagreement of the Vulcan and NSVS eclipse times with an exponentially decaying model forces us to reject the merger hypothesis. Although period variations are common in contact binaries, the physical cause of the period changes in KIC 9832227 remains unexplained; a third star scenario is unlikely. This study shows the data collected by the Vulcan photometer to be extremely valuable for extending the baseline for measurements of variable stars in the Kepler field.

Key words: binaries: close – binaries: general – stars: individual (KIC 9832227, KIC 9592855)

1. Introduction

Red novae are a recently discovered class of stellar transients whose change in luminosity is surpassed only by supernovae. Little is known about red novae, but they are thought to be the result of the merger of the cores in contact binaries. Due to large amounts of gas and dust dispersed by the outburst, luminosity peaks in the I-band (Kulkarni et al. 2007). The first confirmed observation was in M85 (Kulkarni et al. 2007), though the progenitor to this outburst was unresolved in archival Hubble Space Telescope (HST) data. V838 Monoceros was long thought to be an unusual, highly reddened nova eruption, but was later reclassified as a luminous red nova whose pre-outburst spectra suggest a binary star progenitor (Bond et al. 2003). The binary nature of red nova progenitors was finally confirmed in Nova Sco 2008 where archival data revealed the precursor was the contact binary system V1309 Scorpii. The progenitor had a $P \approx 1.4$ day and exhibited an exponentially decaying period (Tylenda et al. 2011). The merger resulted in a brightening in the I-band by 10 mag. Such stellar mergers are common in our galaxy, with a bright red nova outburst event occurring every 10–50 years, and many fainter events from low-mass progenitors happening that cannot be seen (Kochanek et al. 2014). However, a recent search with the OGLE-III survey was unable to identify any merger candidates in the galactic bulge field with rapidly decreasing periods (Pietrukowicz et al. 2017).

KIC 9832227 was originally classified as an RRc Lyrae type pulsator, but using Kepler data Kinemuchi (2013) show it to be an eclipsing (over) contact (W UMa) binary system. A subsequent study by Molnar et al. (2017) shows significant changes in its $\approx 11$ hr period using eclipse times spanning almost two decades fit with an exponentially decaying function of the same form as V1309 Scorpii ($P \propto \exp(\frac{t-t_0}{\tau})$). The parameter $t_0$ is the time of merging, predicted to be in the year 2022. Such a merger should result in a red nova, reaching an apparent visual magnitude of $\sim 2$ (Molnar et al. 2017). Thus, KIC 9832227 could provide us with a rare opportunity to study a red nova progenitor in detail before outburst. To test and better constrain the decaying period hypothesis, we used archival Vulcan data from 2003 (Caldwell et al. 2004) to add another point to the observed minus computed ($O-C$) diagram at an early epoch. We also provide our own observations from the summer of 2017.

2. The Vulcan Photometer

The Vulcan Photometer was a 10 cm aperture ground-based instrument at the Lick Observatory designed to detect Jovian-size planets around Sun-like stars (Borucki et al. 2001; Jenkins et al. 2002). It observed about 20,000 stars brighter than 13th magnitude in a 49 deg$^2$ field of view for about 90 days in the summer of 2003. The Vulcan project discovered numerous variable stars, many of which are eclipsing binaries or multi-star systems (Caldwell et al. 2004). The sky surveyed by Vulcan shares a substantial overlap with the Kepler field, making the survey particularly valuable.

We de-archived and recalibrated the Vulcan observations of KIC 9832227. Eclipse times are crucial to this study, so to confirm the accuracy of the Vulcan times, we measured the eclipse times of KIC 9592855, a binary system that has an ephemeris measured to a high precision and shows no evidence for a variable period (Guo et al. 2017). We find the Vulcan timing to be within 20 s of the Kepler eclipse times projected back to the 2003 Vulcan epoch. This is within $1\sigma$ of the propagated uncertainty in the ephemeris. To further confirm the stable period of KIC 9592855, we measured eclipse times from the Wide Angle Search for Planets (WASP; Butters et al. 2010) survey data from 2007 and 2008 to be within $1\sigma$ (45 s) of the expected time. (All times were converted from UTC to BJD using the Ohio State University UTC2BJD Time Utility4; Eastman et al. 2010.)

4 http://astroutils.astronomy.ohio-state.edu/time/
3. Observations

Kepler data from Quarters $^5$ Q0 through Q17 (Prša et al. 2011; Kirk et al. 2016) were downloaded from MAST and obvious bad data were eliminated. To remove any remaining systematic calibration errors, continuous segments of the light curve were detrended by dividing by a low order polynomial fit. Each of these segments was then concatenated into one normalized light curve. To measure the Kepler primary eclipse times, an iterative method was employed. Each iteration began with a set of estimated eclipse times which were used to produce a stacked light curve two-cycles long in phase (i.e., phases 0.0–2.0, with primary eclipse at phase 0.0, 1.0, and 2.0). A piecewise cubic Hermite spline (PCHS) was then fit to the stacked data to construct a template. The PCHS used 35 nodes, with the nodes at the primary eclipse minima (middle and end points) forced to have zero derivative to minimize any skew in the fit. The template was then shifted across a small neighborhood of time surrounding each of the 2857 primary eclipses, and the chi-square was used to give refined estimates of the eclipse times with uncertainties. The process was then iterated until convergence. The final set of times was then used to derive a linear ephemeris, resulting in $T_0 = 2454953.949183 \pm 9 \times 10^{-6}$ BJD and $P_{\text{Kepl}} = 0.457948557 \pm 5 \times 10^{-9}$ days. Figure 1 shows the $O–C$ times for these eclipses. The Kepler $O–C$ shows a curious feature that oscillates for the first half of the data set with a period of about 100 days, likely due to starspots creating a beat period with the binary orbit. This corresponds to a starspot period of $P_{\text{starspot}} = 0.46$ days. Variations like these have been previously shown to be caused by starspots, supported by the anticorrelated nature of primary and secondary eclipse timings for this system (Tran et al. 2013). These variations of up to 10 minutes are present, setting the limit on the accuracy (not precision) of any individual eclipse timing measurement.

The Northern Sky Variability Survey (NSVS; Woźniak et al. 2004) was queried and KIC 9832227 appears twice, as object 5597755 and 5620022 in two different camera fields. The two were then combined into one light curve. $^6$ The NSVS times were converted from MJD (MJD $= JD - 2450000.5$) to JD, then to BJD (Eastman et al. 2010). Two data sets from the WASP survey were obtained, from 2007 and 2008, with both seasons consisting of about 90 days of observation. Two other seasons were determined to be too incomplete to measure reliable eclipse times. Times were converted from HJD to BJD using the HJD2BJD utility (Eastman et al. 2010). Observations were also made with the Mount Laguna Observatory (MLO) 40 inch telescope in 2017 on the nights of June 2, 3, 30, July 1, and September 25. Exposures ranged from 15 to 20 s and were made in the Johnson–Cousins R filter. The data were reduced using AstroImageJ (AIJ; Collins et al. 2017), removing the usual charge-coupled device (CCD) bias, performing flat-field division, and differential photometry using comparison stars in the 14.5 square arcmin image field. AIJ utilizes the Ohio State UTC2BJD calculator to convert JD to BJD times. Figure 2 shows the Vulcan, Kepler, and MLO phase-folded data. Notice the clear offset in the eclipse minima. The eclipse times were measured by phase folding the light curve from each data set on the Kepler ephemeris ($P_{\text{Kepl}} = 0.457948557$ days), then shifting the Kepler template to best match the observations. The BJD$_0$ time listed by the Kepler Eclipsing Binary Catalog (Kirk et al. 2016) was used to identify the primary eclipse; this is consistent with the radial velocity determination of the primary star (Molnar et al. 2017). Table 1 lists the measured primary eclipse times.

$^5$ Note that the Molnar et al. study omitted Quarters 4, 12, and 13. These Quarters are also missing from the Kepler Eclipsing Binary Catalog V3.

$^6$ No corrective offset was applied to either object. Following Molnar et al. (2017), we offset observation set 5620022 by $-0.062$ mag before combining the two into one light curve. Measurements with and without the magnitude offset are within 1σ. Due to an inconsistent sampling for each field, finding an optimal offset is nontrivial and beyond the scope of this Letter.
4. Analysis and Discussion

To our surprise, the measurements of the eclipse times in the Vulcan data do not match the exponentially decaying prediction of Molnar et al. (2017). Furthermore, our NSVS measurement differs by +1.01 hr from the Molnar et al. reported eclipse time (Molnar et al. 2017). Based on the evidence from the Vulcan data, we speculate that the very large discrepancy with the NSVS timing measurement may be caused by a cycle count error and an MJD to BJD conversion error. Since the period of the binary is 10.99 hr, if the 0.5 day offset from the MJD to JD conversion were omitted, and the eclipses were one cycle off, there would be a difference in the eclipse time of 0.99 hr. The red X in Figure 3 is the hypothetical data point with these two factors included. The X matches the exponential decay curve remarkably well, lending credibility to our hypothesis. Furthermore, Wozniak et al. (2004) defines in their Table 6 MJD = JD − 2,400,000; this unfortunately is different from the preprint version of the paper which includes the standard half-day offset. In addition, L. A. Molnar (2018, private communication) pointed out that from Los Alamos, KIC 9832227 would not be above the horizon at the time reported in Wozniak et al. (2004), thereby clinching the MJD timing error hypothesis. We henceforth ignore the fictitious datum given by the red X. Using all valid data points, we determined a new linear ephemeris for the binary to be $T_0 = 2454953.48885$ BJD $\pm 9 \times 10^{-5}$ days, and $P = 0.45794896$ days $\pm 5 \times 10^{-8}$ days. This ephemeris is used as the “C” in the $O-C$ of Figure 4.

The $O-C$ does show real changes in period. In particular, the MLO eclipses occur 40 minutes early with respect to the calculated Kepler ephemeris. Such a change is not unusual for contact binaries: mass transfer, magnetic braking, or magnetic cycles are plausible explanations (Applegate 1992; Kalimeris et al. 1994), though magnetic braking would only cause a decrease in period and would not explain the increases. A majority of contact binary stars are found to have changes in their periods with $P$ evenly distributed around zero and up to $\pm 2.3 \times 10^{-7}$ day year$^{-1}$, indicating that decreasing periods are not favored (Kubiak et al. 2006). Systems like AB Andromedae (Hasanadeh et al. 2008), AH Virgo, and V566 Ophiuchus vary in their eclipse times by up to 2 hr. V502 Ophiuchus (Kalimeris et al. 1994) is a contact binary with a period of 0.453925 days that shows a 40 minute change in its $O-C$ times, quite similar to KIC 9832227. We therefore conclude that since KIC 9832227 does not exhibit the same type of period decay as V1309 Scorpii, it is very unlikely it will merge in 2022.

Contact binaries commonly have tertiary components ($\sim 60$% occurrence rate), as a third star is likely necessary to remove angular momentum, allowing the binary to tighten into a contact system (D’Angelo et al. 2006; Pribulla & Rucinski 2006; Rucinski et al. 2007; Rappaport et al. 2013; Tokovinin 2014; Pietrukowicz et al. 2017). The occurrence rate of triple systems in the Kepler close binary sample is estimated by Conroy et al. (2014) to be about 10% and by Rappaport et al. (2013) to be 20%. For longer period binaries ($P > 1$ day), the occurrence of triple star systems is 15%–20% (Orosz 2015). It is therefore quite possible that the $O-C$ variation is induced by a third star. We fit the eclipse timing variations using the Python package lmfit (Newville et al. 2016), a Levenberg–Marquardt nonlinear least-squares fitting algorithm, to find orbital parameters for a possible third star. The mass of the

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Table 1

| Data Origin (Year) | Eclipse Time (BJD) | Uncertainty (days) |
|-------------------|-------------------|--------------------|
| NSVS (1999)       | 2451299.9802      | ±0.0021            |
| Vulcan (2003)     | 2452838.2290      | ±0.0014            |
| WASP (2007)       | 2454270.6834      | ±0.0002            |
| WASP (2008)       | 2454632.4654      | ±0.0002            |
| Kepler (2009–2013)| 2454953.9492      | ±0.0002            |
| MLO (2017)        | 2457906.7735      | ±0.0003            |

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9 arXiv:astro-ph/0401217
third body was constrained by the combined masses of the primary and secondary stars, from measurements made by Molnar et al. (2017), which is 1.714 $M_\odot$. Also, the hypothetical third star does not appear in the spectra (Molnar et al. 2017), which puts an upper limit to its mass. Molnar et al. (2017) rule out a hypothetical star of mass $\geq 0.8 M_\odot$. Three different mass solutions are shown in Figure 4, none of which provide a good match to the data. We used emcee, a Markov chain Monte Carlo ensemble sampler (Foreman-Mackey et al. 2013), to set a lower limit on the period of a third star of 7200 days, or about 20 years. This period is, of course, suspicious as it is roughly the duration of our observations. The lower limit of the third mass using a fixed 7200 day period is about 0.7 $M_\odot$, which is uncomfortably high considering it is not detected in the spectra.

Our original intent was to strengthen the very exciting red nova prediction and to better characterize the decay of the suspected progenitor binary. Our results cast doubt on the prediction that the stars will merge in 2022, as the data do not follow the exponential decay at early epochs. The $O-C$ does show real changes in period, but our most favored explanation is that these are merely period wanderings common in many contact binaries. This investigation, however, does demonstrate

![Figure 3](image-url)  
*Figure 3. O–C diagram of KIC 9832227 with a reference period of $P_{\text{ref}} = 0.4579515$ days. The blue curve is a recreation of the exponentially decaying fit from Molnar et al. (2017) with the same reference period. The red “X” on the left of the figure is the NSVS datum with a 1 cycle count and MJD +0.5 day error, creating a plausible, but misleading datum. Our measured value, the green triangle, is at +42 minutes, which is about 1.01 hr later. To prevent the 2857 eclipses in the Kepler data from completely dominating our fit, the $O-C$ values were cast into 7 bins of approximately 200 days in length.*

![Figure 4](image-url)  
*Figure 4. Revised O–C diagram using all of our eclipse times. The horizontal line on each datum represents the duration of each data set. Three tertiary star fits to the O–C data are shown, none of which agree well with NSVS or Vulcan eclipse times.*
the substantial value of the Vulcan project data for extending the baseline of Kepler eclipse timing measurements.

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Facilities: SuperWASP, Kepler, MLO.

Software: AstroImageJ (Collins et al. 2017), emcee (Foreman-Mackey et al. 2013), lmfit (Newville et al. 2016).

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\(^8\) https://exoplanetarchive.ipac.caltech.edu/
\(^9\) http://keplerebs.villanova.edu/