Simplified method for the identification of low mass ratio contact binary systems that are potential red nova progenitors

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Abstract. This study presents a simplified method to identify potential bright red nova progenitors based on the amplitude of the light curve and infrared (J–H) colour of a contact binary system. We employ published criteria for contact binary orbital instability to show that the amplitude of the light curve for a given contact system with a low mass (<1.4 M⊙) primary must be less than a specified value for it to be potentially unstable. Using this, we search the photometric data of a large survey to identify about 50 potential bright red nova progenitors. We analyse each of the survey photometry to determine the mass ratio and from the estimated mass of the primary, other physical parameters of the systems. We show that each system has physical characteristics indicating potential orbital instability. Using the absolute parameters from our sample, we model the expected instability separation and period for low mass contact binary systems.

Keywords. Contact binary—low mass ratio—light curve solution.

1. Introduction

The number of known contact binary systems has, and still is, growing at a phenomenal rate given the new discoveries resulting from sky surveys. As an example, All Sky Automated Survey (ASAS) (Pojmanski 2002) and the All Sky Automated Survey–Super Nova (ASAS–SN) (Shappee et al. 2014; Jayasinghe et al. 2020) have added more than 100,000 new discoveries. Theoretical models, such as Robertson & Eggleton (1977); Soker & Tylenda (2003); Stepić (2011); Eggleton (2012) predict that contact binary systems with extremely low mass ratios are likely to merge into a single, rapidly rotating relatively cool, giant star. The merger event is thought to result in a transient nova-like event that evolves to remain bright in the red and infrared bands. The event is usually termed a red nova. Although Galactic merger events are predicted to occur commonly (once in every 2–3 years), brighter events that are likely to be available for study are more limited to once a decade (Kochanek et al. 2014). There has been only one confirmed observation linking typical red nova-like transient to a contact binary progenitor, that of V1309 Sco (Tylenda et al. 2011). Other examples, such as V4432 Sgr (Martini et al. 1999), V838 Mon (Brown et al. 2002) and OGLE2002-BLG-360 (Tylenda et al. 2013) are postulated to represent stellar mergers although their progenitors remain unidentified. In addition, there exist possible historical and extra galactic examples (Kochanek et al. 2014; Pastorello et al. 2019).

Since the recognition of V1309 Sco, there has been heightened interest in the theoretical basis of orbital instability and the identification of low mass ratio contact binary systems (Gazeas et al. 2021; Wadhwa et al. 2021; Christopoulou et al. 2022).

In two papers, Rucinski (1993, 2001) showed that the shape of contact binary light curves is dependant on three main geometrical factors, namely, mass ratio (q), fill-out (f) (degree of contact or the thickness of the contact neck region) and inclination (i). In addition, the other somewhat minor determinant is the temperature difference between the components. He deduced that
the maximum amplitude for any given system was seen, if the system was observed to have a complete eclipse. In addition, he showed that only the mass ratio, fill-out and to a lesser extent (in the presence of complete eclipses) inclination determined the amplitude of the light curve with other factors, such as temperature of the components having little impact.

We combine the three techniques noted above namely, theoretical instability parameters, survey photometric data and photometric amplitude distribution of contact binary systems to derive a simplified method of identifying potential contact binary systems that show signs of orbital instability (potential red nova progenitors). For the purpose of this study, we define a contact binary system with a mass ratio at or below the theoretical critical level as being potentially unstable. The paper is divided into five sections. In Section 2, we model theoretical light curves to derive a relationship between the mass of the primary and the maximum amplitude of a potentially unstable system. In Section 3, we employ the relationship to the ASAS–SN survey to identify potential bright red nova candidates among low mass ($0.6 \ M_\odot < M_1 < 1.4 \ M_\odot$) contact binary systems. In Section 4, we define an average potential red nova progenitor in addition to comparing and contrasting our sample of bright potential red nova progenitors with other comparable systems. In Section 5, we briefly discuss the historical development of mass ratio as a determinant of orbital instability, limitations of the present study and further ongoing search of red nova progenitors along with a summary and conclusion of the current work.

2. Amplitude distribution of potential red nova progenitors

Critical to understand the orbital evolution of contact binary system is predicated on knowledge of parameters, such as mass ratio, masses of the components and geometry of the orbit, such as inclination, degree of contact and temperature variation between the components. Many, if not all, of these parameters can be derived from light curve analysis, but only if the light curve demonstrates a complete eclipse (Terrell & Wilson 2005). As such, we limit our modelling of systems that demonstrate a complete eclipse and would be applicable to observed light curves. Current light curve analysis tools can incorporate many tens of different parameters, however, as noted above in the case of contact binary systems only four main parameters are critical. Therefore in modelling the amplitude distribution of unstable systems, we have neglected complications associated with star spots and other stellar activity. We used the 2009 version of the Wilson–Devinney code as incorporated into the Windows front end utility WDwin56d (Nelson 2021) to model all light curves. The gravity darkening coefficients $g_1 = g_2 = 0.32$, the bolometric albedos $A_1 = A_2 = 0.5$ were fixed (Lucy 1967) and simple reflection treatment applied (Rucinski 1969). As per Nelson & Robb (2015), logarithmic limb darkening coefficients interpolated from van Hamme (1993) were used.

To confirm the findings of Rucinski (1993, 2001) with respect to the effects of fill-out and inclination on the amplitude of the light curve, we modelled light curves of an idealised contact binary system with primary of one solar mass with mass ratio ($q$) 0.1 and equal temperature of the components ($T_1 = T_2 = 5770$ K) to record the effects of inclination ($i$) and degree of contact ($f = 0 \rightarrow 1$). As we are only interested in systems that display a total eclipse, we modelled the system with an inclinations of $90^\circ$, which would yield the maximum eclipse time and $72^\circ$, which would yield a small total eclipse between phase 0.49 and 0.51. The change in inclination results in a reduction in the duration of the secondary eclipse with the lower inclination reducing the total amplitude slightly. We also modelled fill-out $f = 0$ and $f = 1$ for each inclination to determine the variation in amplitude and again to confirm previous findings using the current accepted modelling code. The fill-out has a significant effect on the amplitude of the light curve with high fill-out yielding the highest amplitude. This is as expected, because higher the degree of contact, the thicker the neck of the contact region. The neck bears some luminosity and thicker the neck, the greater the luminosity that is eclipsed. We did not model stars of different mass (hence different $T_1$) because as noted by Rucinski (2001), the combination chosen is a reasonable representation of the light curve of low mass contact binaries and confirms the previous findings that the maximum amplitude of a contact binary system occurs at high inclination and high degree of contact. The results are illustrated in Figure 1 and summarised in Table 1.

Having established the condition of high inclination and high fill-out for high amplitude, we next modelled the effects of the difference in temperature of the components. The presence of a common envelope usually results in good thermal contact between the components, so there is usually little difference in the temperature of the components. Recently, Latković
Figure 1. Effects of inclination, fillout and temperature of the secondary on the maximum amplitude of a contact binary system with the mass ratio of 0.1. Eq: equal component temperatures, CS: cooler secondary and HS: hotter secondary.

Table 1. Effects of inclination, fillout and temperature of the secondary on the maximum amplitude of a contact binary system with the mass ratio of 0.1.

| Inclination (°) | Fill-out | $T_2$ | Max. ampl. (mag.) |
|----------------|----------|-------|-------------------|
| 90             | 1        | Eq    | 0.36              |
| 72             | 1        | Eq    | 0.31              |
| 90             | 0        | Eq    | 0.27              |
| 90             | 1        | CS    | 0.36              |
| 90             | 1        | HS    | 0.36              |

Eq: equal component temperatures, CS: cold secondary, HS: hot secondary and $r_{1,2}$: mean fractional radii of primary and secondary.

We can deduce from the above that for any given mass ratio, the maximum amplitude will be achieved with high inclination, high fill-out and the secondary slightly warmer.

Having established the modelling criteria for the maximum amplitude at a given mass ratio, we employ this to determine the maximum amplitude of a potential red nova progenitor. Recently, Wadhwa et al. (2021) linked the instability mass ratio of contact binary systems with the mass of the primary component. They demonstrated that the mass ratio at which instability ($q_{\text{inst}}$) is likely can be determined by a simple quadratic relationship for high and low level of contacts:

$$q_{\text{inst}} = 0.1269M_1^2 - 0.4496M_1 + 0.4403 \quad (f = 1),$$

$$q_{\text{inst}} = 0.0772M_1^2 - 0.3003M_1 + 0.3237 \quad (f = 0).$$

Using this relationship, say for a system with primary of one solar mass, the instability mass ratio at high fill-out would be ~0.12. If we now model a light curve with the following parameters: $T_1 = 5770$ K, $T_2 = 5970$ K, $i = 90°$, $f = 1$ and $q = 0.12$, this will give us the maximum amplitude at which such a system is possibly unstable. As amplitude increases with increasing mass ratio (see below and Rucinski 1993, 2001), any system with higher amplitude will likely have a higher mass ratio and therefore, would be stable. As inclination of a system drops eventually, a complete eclipse is lost and light from both components is observed.
Table 2. Summary of the maximum amplitude at the instability mass ratio \((q_{\text{inst}})\) for systems with low mass primary component.

| Mass \((M_1)(M_\odot)\) | \(q_{\text{inst}}(f = 1)\) | Max. ampl. |
|-------------------------|----------------|-----------|
| 0.6                     | 0.22           | 0.63      |
| 0.7                     | 0.19           | 0.60      |
| 0.8                     | 0.16           | 0.52      |
| 0.9                     | 0.14           | 0.45      |
| 1.0                     | 0.12           | 0.43      |
| 1.2                     | 0.08           | 0.32      |
| 1.4                     | 0.06           | 0.22      |

throughout the orbital cycle and the overall variation (amplitude) of the light curve drops (Rucinski 2001). Therefore, a system with amplitude significantly below the maximum amplitude is unlikely to have a complete eclipse and therefore, not suitable for photometric light curve analysis. We extended our modelling of the maximum amplitude for systems with primary star masses between 0.6 and 1.4 \(M_\odot\) and the calculated instability mass ratio at high fill-out. We adopted values of \(T_1\) based on the main sequence calibration from Pecaut & Mamajek (2013) + 200 K. The results are summarised in Table 2 and the line of best fit is as shown in Equation (3) and graphically shown in Figure 2. It is clear that higher the mass ratio, the greater the amplitude therefore, any system with an amplitude higher than that predicated at the theoretical instability mass ratio will likely have a mass ratio above the instability value and therefore, be likely stable.

\[
\text{Max. ampl. (mag.)} = -0.5179M_1 + 0.945. \tag{3}
\]

### 3. Search for potential red nova progenitors

As noted above, we confined our search to bright systems with lower mass \((0.6 \ M_\odot < M_1 < 1.4 \ M_\odot)\) primaries. The ASAS–SN variable database provides a friendly user interface to select variable stars of different types. We used this to select all contact binaries brighter than 13.5 magnitude. We limited our search to brighter examples as random review of the ASAS–SN light curves indicated that fainter examples had too much scatter and in most cases, it was impossible to visually confirm the presence of complete eclipses and/or the amplitude of the light curve. A secondary benefit for favouring brighter examples is the potential ease in obtaining long term follow-up monitoring.

The selected systems are within the reach of modest instruments and could potentially be observed regularly by campus-based telescopes or even by advanced amateurs. The systems were then ordered by amplitude and all systems with amplitude >0.65 were excluded as the maximum amplitude for a 0.6 \(M_\odot\) primary with a mass ratio at the instability level \((q_{\text{inst}} = 0.22)\) is 0.63 magnitude.

It is well established that the primary component of a contact binary systems follows in general, a main sequence profile (Yildiz & Doğan 2013). The ASAS–SN database also provided J and H magnitudes for each system. We calculated the J–H magnitude for each system and using the calibration for low mass (F3-K9) main sequence stars of Pecaut & Mamajek (2013), we interpolated the mass and effective temperature of the primaries. All systems with masses outside our inclusion criteria were excluded. The remaining systems were examined visually to determine the presence of a total eclipse. Only those systems where a clear total eclipse were included. We note that such a crude selection system is likely to include or exclude some systems in the final sample. A more robust system of checking the variability within a defined time interval of the eclipses proved unworkable due to the cadence and scatter in many systems. The final sample totaled 189 contact binary systems. Having established the mass of the primaries for our selected 189 samples, we next determined the instability mass ratio for each using Equation (1) and the maximum amplitude using Equation (3). We next compared the amplitude of the survey light curve against the maximum amplitude for potential instability. If the observed amplitude was significantly (>5%) higher than the maximum instability amplitude, then such a system would be expected to have a mass ratio higher than the instability mass ratio and not to
be considered a potential merger candidate. All systems identified as such were excluded. The 5% leeway is arbitrary to account for the scatter normally present in survey data. This step left a sample of 65 systems of potential red nova progenitors.

Even though the ASAS–SN light curves were of reasonable quality, we searched the VSX database as well as the TESS and Kepler variable databases for all available light curves for the 65 systems. All light curves found from other databases were compared with the available ASAS–SN light curves and if they offered better phase coverage and clearer eclipses, they were chosen for the formal light curve analysis instead of the ASAS–SN curves. Although where TESS data was chosen for the formal light curve analysis instead of better phase coverage and clearer eclipses, they were available ASAS–SN light curves and if they offered found from other databases were compared with the able light curves for the 65 systems. All light curves in survey data. This step left a sample of 65 systems of is arbitrary to account for the scatter normally present systems identified as such were excluded. The 5% leeway be considered a potential merger candidate. All sys-
tems were analysed using the Wilson–Devenney code as noted above. We used the standard mass ratio search grid method to find the probable mass ratio for each system. Temperature of the primary was fixed according to the main sequence calibration of Pecaut & Mamajek (2013). Logarithmic limb darkening coefficients were interpolated from van Hamme (1993). The TESS and Kepler photometric data is provided as a flux and this was converted to magnitudes using the calibrations from Handberg et al. (2021) and Aigrain et al. (2015), respectively. We used the MIT quick look pipeline for the optimal aperture for the TESS data (Huang et al. 2020) and K-2 data when using Kepler mission data. The TESS photometry was acquired over a broad red to infra-red window centered on the standard Ic band (786.5 nm) (Ricker et al. 2015). We used limb darkening coefficients for the Ic band when analysing the TESS data. The Kepler and SWASP photometries were acquired with wide-band filters from blue to red (Pollacco et al. 2006; Van Cleve et al. 2010) and we used limb darkening coefficients for the central V band.

All the selected light curves from the final sample were analysed using the Wilson–Devenney code as noted above. We used the standard mass ratio search grid method to find the probable mass ratio for each system. Temperature of the primary was fixed according to the main sequence calibration of Pecaut & Mamajek (2013). Logarithmic limb darkening coefficients were interpolated from van Hamme (1993). The TESS and Kepler photometric data is provided as a flux and this was converted to magnitudes using the calibrations from Handberg et al. (2021) and Aigrain et al. (2015), respectively. We used the MIT quick look pipeline for the optimal aperture for the TESS data (Huang et al. 2020) and K-2 data when using Kepler mission data. The TESS photometry was acquired over a broad red to infra-red window centered on the standard Ic band (786.5 nm) (Ricker et al. 2015). We used limb darkening coefficients for the Ic band when analysing the TESS data. The Kepler and SWASP photometries were acquired with wide-band filters from blue to red (Pollacco et al. 2006; Van Cleve et al. 2010) and we used limb darkening coefficients for the central V band.

Given the scatter and potential incomplete phase coverage some of the systems upon analysis had a mass ratio above the instability mass ratio suggesting that the amplitude is probably higher than that measured by survey photometry. As noted by Christopoulou et al. (2022), a small uncertainty in the mass of the primary can result in a modest uncertainty in the instability mass ratio. Accordingly, for the purpose of this study, we consider any system with a mass ratio below or up to 10% above the theoretical maximum instability mass ratio to be potentially a red nova candidate. From our initial sample of 65, there were 45 that met the instability criteria and the basic parameters of these are summarised in Table 3. Abbreviation and cross matching of individual systems are presented in Table 5. Of course, in the future, the list will be refined as the mass of the primary of these systems, which is more accurately determined. It must be stressed that this study only covers the ASAS–SN variable database. Given the sheer number of bright contact binaries (magnitude ≤13.5) listed on the VSX (≈20000) at this time, we have not systematically reviewed other survey data (some with poor search interfaces) for more examples. We hope to do this over time and add to the list progressively. For completeness, we do add some examples to the list from the existing literature as described below.

4. Absolute parameters and the average potential red nova progenitor

4.1 Absolute parameters

We determined the absolute parameters for each system from the light curve solution and period of the system. As noted above, mass of the primary was estimated from the J–H colour of each system. The mass ratio provides the mass of the secondary. The relative radii of the components are dependant on the mass ratio and Roche geometry, as by definition both components overflow their inner Roche lobes in a contact binary system. The light curve solution provides fractional radii of the components (a1,2, b1,2, c1,2) in three orientations. The geometric mean of these was used to estimate r1,2 = √a1,2b1,2c1,2. The separation (A) between the components was determined using Kepler’s third law and the absolute radii of the components were determined as per Awadalla & Hanna (2005) R1,2 = A × r1,2.

By way of comparison with other contact binary systems, we looked at our list of possible red nova progenitors with low mass (0.6 M⊙ < M1 < 1.4 M⊙) primary contact binary systems listed by Latković et al. (2021). We accepted as true, the masses determined by the publishing authors regardless of the methodology employed. Allowing for a 10% margin, the final list of 300 systems includes nine systems that would be classified as potential red novas progenitors based on the instability criteria outlined above. Of these nine, three were already included in our list, while the others were either fainter than our cut-off limit, had poor phase coverage and in two cases were too bright for the ASAS–SN survey equipment. We have added these to our final list of potential red nova progenitors relying on the published absolute parameters. As the catalogue of
Table 3. Summary of the pertinent light curve solution and absolute parameters of potential red nova progenitors. Entries marked with ‘LIT’ have been taken from the literature. They were not identified from the examination of ASAS–SN light curves as described. $q_{\text{inst}}$ range is the instability mass ratio from $f = 0–1$.

| Name     | Period      | $q$  | $q_{\text{inst}}$ range | $T_1$       | $T_2$       | $M_1$ ($M_\odot$) | $R_1$ ($R_\odot$) | $R_1$/ZAMS | Survey          | References |
|----------|-------------|------|--------------------------|-------------|-------------|-------------------|-------------------|-------------|-----------------|------------|
| A0006    | 0.38318     | 0.115| 0.108–0.128              | 5700        | 5699        | 0.95              | 1.34              | 1.39        | TESS            |            |
| LM Psc   | 0.34013     | 0.096| 0.082–0.094              | 6075        | 6241        | 1.13              | 1.33              | 1.19        | ASAS-SN         |            |
| A0346    | 0.30717     | 0.148| 0.139–0.171              | 5120        | 5043        | 0.77              | 1.05              | 1.29        | TESS            |            |
| A0458    | 0.33348     | 0.086| 0.082–0.093              | 6100        | 5625        | 1.14              | 1.3               | 1.16        | TESS            |            |
| A0514    | 0.34572     | 0.127| 0.116–0.138              | 5600        | 5626        | 0.9               | 1.22              | 1.32        | TESS            |            |
| NSVS 470 | 0.35576     | 0.078| 0.095–0.110              | 5900        | 6231        | 1.04              | 1.37              | 1.32        | TESS            |            |
| V644 Pup | 0.33056     | 0.14 | 0.132–0.161              | 5300        | 5824        | 0.8               | 1.12              | 1.33        | TESS            |            |
| A0842    | 0.33353     | 0.1  | 0.086–0.098               | 6040        | 6315        | 1.1               | 1.3               | 1.23        | TESS            |            |
| A1037    | 0.34370     | 0.09 | 0.070–0.085               | 6200        | 6081        | 1.21              | 1.34              | 1.14        | CATALINA        |            |
| A1214    | 0.39850     | 0.085| 0.099–0.116              | 5850        | 5786        | 1.01              | 1.43              | 1.41        | KEPLER          |            |
| A1249    | 0.37191     | 0.095| 0.091–0.104              | 5950        | 5948        | 1.07              | 1.39              | 1.3         | TESS            |            |
| A1251    | 1.05207     | 0.085| 0.073–0.082               | 6200        | 5599        | 1.21              | 2.89              | 2.45        | TESS            |            |
| SSS1315  | 0.38281     | 0.075| 0.108–0.128              | 5700        | 5330        | 0.95              | 1.39              | 1.44        | CATALINA        |            |
| A1407    | 0.36358     | 0.088| 0.086–0.098              | 6040        | 6105        | 1.1               | 1.39              | 1.27        | TESS            |            |
| A1446    | 0.35170     | 0.09 | 0.116–0.138              | 5600        | 5369        | 0.9               | 1.28              | 1.39        | TESS            |            |
| A1517    | 0.32518     | 0.1  | 0.132–0.161              | 5300        | 5368        | 0.8               | 1.13              | 1.34        | ASAS–SN         |            |
| A1531    | 0.83309     | 0.085| 0.082–0.093              | 6100        | 5812        | 1.14              | 2.43              | 2.17        | KEPLER          |            |
| V396 Lup | 0.36324     | 0.132| 0.120–0.145              | 5500        | 5794        | 0.88              | 1.27              | 1.39        | TESS            |            |
| A1629    | 0.31077     | 0.059| 0.104–0.122              | 5800        | 6115        | 0.98              | 1.22              | 1.23        | ASAS            |            |
| A1651    | 0.35321     | 0.152| 0.129–0.157              | 5300        | 5158        | 0.82              | 1.19              | 1.38        | TESS            |            |
| V565 Dra | 0.39032     | 0.092| 0.091–0.104              | 5970        | 6055        | 1.07              | 1.42              | 1.34        | TESS            |            |
| A1751    | 0.93521     | 0.105| 0.095–0.110              | 5900        | 5551        | 1.04              | 2.46              | 1.49        | ASAS            |            |
| A1846    | 0.30284     | 0.162| 0.130–0.160              | 5250        | 5148        | 0.8               | 1.06              | 1.25        | KEPLER          |            |
| A1847    | 0.68961     | 0.077| 0.077–0.087              | 6150        | 5917        | 1.18              | 2.18              | 1.89        | ASAS–SN         |            |
| A1907    | 0.76308     | 0.06 | 0.093–0.106              | 5970        | 5619        | 1.07              | 2.32              | 2.18        | ASAS–SN         |            |
| A1928    | 0.32002     | 0.08 | 0.082–0.093              | 6100        | 6120        | 1.14              | 1.26              | 1.13        | SWASP           |            |
| A1946    | 0.38378     | 0.1  | 0.120–0.144              | 5520        | 5524        | 0.88              | 1.3               | 1.43        | ASAS–SN         |            |
| A2001    | 0.35088     | 0.12 | 0.123–0.140              | 5450        | 5614        | 0.86              | 1.18              | 1.33        | ASAS–SN         |            |
| A2003    | 0.45720     | 0.127| 0.107–0.128              | 5720        | 5613        | 0.95              | 1.52              | 1.58        | ASAS            |            |
| A2044    | 0.34289     | 0.103| 0.099–0.116              | 5800        | 5751        | 1                | 1.29              | 1.28        | TESS            |            |
Table 3. Continued.

| Name          | Period | $q$  | $q_{\text{inst range}}$ | $T_1$ | $T_2$ | $M_1 (M_\odot)$ | $R_1 (R_\odot)$ | $R_1/ZAMS$ | Survey          | References                  |
|---------------|--------|------|--------------------------|-------|-------|-----------------|-----------------|-------------|----------------|--------------------------|
| A2044         | 0.37054| 0.07 | 0.082–0.093              | 6100  | 6076  | 1.14            | 1.45            | 1.29        | ASAS–SN        |                          |
| NSVS 114      | 0.35470| 0.096| 0.116–0.138              | 5580  | 5572  | 0.9             | 1.28            | 1.38        | ASAS–SN        |                          |
| A2048         | 0.80583| 0.115| 0.104–0.122              | 5800  | 5870  | 0.98            | 2.2             | 2.23        | SWASP          |                          |
| A2132         | 0.31634| 0.1  | 0.108–0.127              | 5700  | 5953  | 0.95            | 1.18            | 1.22        | TESS           |                          |
| A2145         | 0.35385| 0.075| 0.099–0.116              | 5850  | 5770  | 1.01            | 1.32            | 1.3         | TESS           |                          |
| SSS 2213      | 0.36990| 0.08 | 0.082–0.093              | 6100  | 6249  | 1.14            | 1.42            | 1.26        | TESS           |                          |
| A2222         | 0.40609| 0.133| 0.116–0.138              | 5580  | 5853  | 0.9             | 1.38            | 1.49        | TESS           |                          |
| A2243         | 0.33535| 0.085| 0.091–0.104              | 6000  | 6004  | 1.07            | 1.29            | 1.22        | TESS           |                          |
| A2250         | 0.31196| 0.132| 0.126–0.153              | 5400  | 5584  | 0.84            | 1.11            | 1.26        | SWASP          |                          |
| A2258-26      | 0.32764| 0.093| 0.084–0.095              | 6050  | 5955  | 1.12            | 1.29            | 1.17        | SWASP          |                          |
| A2258         | 0.30946| 0.162| 0.126–0.157              | 5300  | 5496  | 0.82            | 1.05            | 1.22        | ASAS–SN        |                          |
| NSVS 902      | 0.32510| 0.108| 0.104–0.122              | 5800  | 5718  | 0.98            | 1.19            | 1.21        | SWASP          |                          |
| A2348         | 0.34719| 0.108| 0.091–0.104              | 5970  | 5807  | 1.07            | 1.29            | 1.22        | SWASP          |                          |
| V1222 Tau     | 0.29536| 0.104| 0.116–0.138              | 5600  | 5439  | 0.9             | 1.06            | 1.15        | LIT            | Liu et al. (2015)        |
| NSVS 431      | 0.25596| 0.147| 0.151–0.188              | 6000  | 5875  | 0.7             | 0.87            | 1.14        | LIT            | Kjurkchieva et al. (2020)|
| A0822         | 0.28005| 0.11 | 0.087–0.099              | 5960  | 6080  | 1.1             | 1.1             | 1.01        | LIT            | Kandulapati et al. (2015)|
| GSC 0341      | 0.27716| 0.055| 0.092–0.106              | 5870  | 5828  | 1.06            | 1.17            | 1.1         | LIT            | Li et al. (2021)         |
| A0832         | 0.31312| 0.067| 0.072–0.081              | 6300  | 6602  | 1.22            | 1.34            | 1.13        | LIT            | Sriram et al. (2016)     |
| NSVS 780      | 0.28120| 0.098| 0.141–0.173              | 5490  | 5706  | 0.79            | 1.1             | 1.31        | LIT            | Popov et al. (2021)      |
| PZ UMA        | 0.26267| 0.178| 0.139–0.170              | 5430  | 4972  | 0.77            | 0.92            | 1.12        | LIT            | Zhou & Soonthornthum (2019)|
| NSVS 256      | 0.28780| 0.078| 0.078–0.088              | 6030  | 6100  | 1.17            | 1.19            | 1.04        | LIT            | Kjurkchieva et al. (2018)|
| SX Crv        | 0.31662| 0.079| 0.069–0.077              | 6340  | 6160  | 1.25            | 1.32            | 1.09        | LIT            | Zola et al. (2004)       |
| A1328         | 0.38470| 0.086| 0.071–0.079              | 6300  | 6319  | 1.23            | 1.49            | 1.25        | LIT            | Li et al. (2021)         |
| ZZ PsA        | 0.37389| 0.078| 0.086–0.098              | 6514  | 6703  | 1.213           | 1.42            | 1.24        | LIT            | Wadhwa et al. (2021)     |
Latković et al. (2021) covers literature to the early part of 2021, we performed a literature search from March 2021 to March 2022 for any new reported contact binary systems that may be regarded as red nova progenitors. This resulted in the addition of three more potential systems. In total, we catalogue 54 low mass ratio contact binary systems that may be regarded as potential red nova progenitors (Table 3).

The period distribution of low mass contact binary systems \(0.6 \, M_\odot < M_1 < 1.4 \, M_\odot\) as adopted from Latković et al. (2021) as a whole relative to potential red nova progenitors is illustrated in Figure 3. The median period for the entire sample is in the order of 0.330 days, only marginally <0.346 days for potential red nova progenitors. Most of the systems in both groups have periods between 0.25 and 0.5 days although the peak in the distribution around 0.35 days is more pronounced in the potential red nova progenitor sample. There is a hint of possibly some systems with higher periods being more common in the potential red nova progenitors group. The finding is in line with Kobulnicky et al. (2022) who found that extreme mass ratio systems tended to have a slightly increased frequency of longer periods.

4.2 Average potential red nova progenitor

Based on the work of Arbutina (2007) and Wadhwa et al. (2021), the separation at the onset of instability \(A_{\text{inst}}\) can be written as:

\[
A_{\text{inst}} = \frac{q \left( \frac{Q}{P} \right) P Q}{q \left( \frac{Q}{P} \right) P^2 + q/(1 + q) k_1^2}
\]

\[+ \left( q \left( \frac{Q}{P} \right) P Q \right)^2 + 3 \left( 1 + q \left( \frac{Q}{P} \right) Q^2 \right) \left( q \left( \frac{Q}{P} \right) P^2 + \frac{q}{(1 + q) k_2^2} \right)
\]

\[= q \left( \frac{Q}{P} \right) P^2 + \frac{q}{(1 + q) k_2^2},\]  

(4)

where \(k_{1,2}\) is the gyration radius for the primary and secondary components and

\[
P = \frac{0.49q^{2/3} - 3.26667q^{-2/3}(0.27q - 0.12q^{4/3})}{0.6q^{2/3} + \ln(1 + q^{1/3})},\]

(5)

\[
Q = \frac{(0.27q - 0.12q^{4/3})(0.6q^{-2/3} + \ln(1 + q^{-1/3}))}{0.15(0.6q^{2/3} + \ln(1 + q^{1/3}))}.\]

(6)

Assuming our sample of potential red nova progenitors as representative, we found the median radius (±SD) of the primary to be 1.285 (±0.3) times the corresponding ZAMS equivalent. As noted previously, the primary of contact binary systems can be considered as ZAMS, so we can estimate the typical radius and hence, the instability separation for a typical potential red nova progenitor. We perform this for low mass contact binary systems with low and high degree of contact as described in Wadhwa et al. (2021) and adopt the mean. Using equations outlined above and mean instability separation, we estimate the mean period at the onset of instability \(P_{\text{inst}}\) for low mass contact binary systems. The results are summarised in Table 4. From these, we derive simple quadratic relations (Figures 4 and 5) linking the mass of the primary with the instability separation and period as follows:

\[
A_{\text{inst}} = -0.6766M_1^2 + 2.6932M_1 + 0.1878,\]

(7)

\[
P_{\text{inst}}(d) = -0.1446M_1^2 + 0.4645M_1 + 0.0401.\]

(8)

From the above, we see that a typical one solar mass contact binary system that is near the onset of instability will have a mass ratio near 0.12, maximum light
Figure 4. Instability separation for low mass contact binary systems.

Figure 5. Instability period for low mass contact binary systems.

curve amplitude near 0.43 and period near 0.36d. As a means of selecting potential low mass ratio contact binary stars for photometric analysis, one could follow the relationships described to select candidates that are more likely to reflect features of orbital instability. Given the inherent scatter and varying cadence of survey photometry, we stress the above analysis is only an aid in the selection process and follow-up observations would be required to confirm instability criteria that may be evident on survey photometry. We are however, confident given the success of survey photometric analysis compared to dedicated ground-based observations, in determination of accurate light curve solutions (Devarapalli et al. 2020; Sun et al. 2020; Wadhwa et al. 2022) has greatly facilitated the potential for being able to identify low mass ratio contact binary systems. In this study, we enhance this capability by establishing simple light curve and colour parameters that can be used to exclude systems that are likely to have mass ratios above the theoretical instability value. By excluding likely stable systems, we greatly increase our chance of identifying potentially unstable systems from the remaining sample. We apply the techniques on bright contact binary systems from the ASAS–SN and identify ∼50 extreme low mass ratio system (most previously not reported) satisfying the mass ratio criteria for orbital instability.

5. Discussion and conclusions

Although contact binary merger events are predicted to be relatively frequent so far only a single event has been confirmed and that only in retrospect. The linking of orbital stability with the mass ratio of contact binary systems has long been recognised as potential avenue for identifying unstable systems (Rasio 1995; Arbutina 2007, 2009). The earlier work clearly showed that orbital instability is likely to occur at very low mass ratios and higher mass ratio configurations are likely to be stable. Our theoretical work (Wadhwa et al. 2021) linking the instability mass ratio to the mass of the primary has progressed this further by demonstrating that there exists no global minimum mass ratio at which a system will become unstable rather the instability mass ratio is dependant on the mass of the primary component. In addition, we showed that systems with less massive primaries can have mass ratios >0.2 and still be potentially unstable. When combined with work showing the suitability of survey photometry for light curve analysis (Devarapalli et al. 2020; Sun et al. 2020; Wadhwa et al. 2022) has greatly facilitated the potential for for being able to identify low mass ratio contact binary systems. In this study, we enhance this capability by establishing simple light curve and colour parameters that can be used to exclude systems that are likely to have mass ratios above the theoretical instability value. By excluding likely stable systems, we greatly increase our chance of identifying potentially unstable systems from the remaining sample. We apply the techniques on bright contact binary systems from the ASAS–SN and identify ∼50 extreme low mass ratio system (most previously not reported) satisfying the mass ratio criteria for orbital instability.

As with almost all low mass contact binary systems (Latković et al. 2021), our identified sample of potential merger candidates demonstrate radii that are significantly larger than their main sequence counterparts and secondaries that are considerably hotter than main sequence counterparts of similar mass. We found that relative to the general population of comparable contact binaries those exhibiting signs of orbital instability generally have similar periods although with a more pronounced peak near 0.35d. In addition, there is a significant number of systems, relative to the general population, that have longer (>0.5d) periods. Kobulnicky et al. (2022) suggested that it is possible for the period to lengthen to above 0.5d in some cases of extreme low mass ratios and the onset of orbital instability. In this respect, our sample of possible unstable systems with long periods represent a good subset study group for future observations.

From our sample of potential red nova progenitors, we construct theoretical models for low mass potentially
Table 5. Abbreviation, coordinates and ASAS–SN designation of low mass contact binary systems with mass ratios suggesting orbital instability.

| Abbreviation | RA/DEC | Name |
|--------------|--------|------|
| A0006        | 00 06 50 −35 37 29 | ASASSN-V J000649.98−353729.1 |
| LM Psc       | 00 34 13 20 52 25 | ASASSN-V J003412.63+205225.4 |
| A0346        | 03 46 33.6 41 08 15.8 | ASASSN-V J034633.63+410815.8 |
| A0458        | 04 58 14 06 43 09 | ASASSN-V J045813.80+064309.1 |
| A0514        | 05 14 59 −73 56 15 | ASASSN-V J051459.38−735615.4 |
| NSVS 470     | 07 19 25 41 57 04 | ASASSN-V J071924.64+415705.4 |
| V644 Pup     | 07 27 29 −50 56 30 | ASASSN-V J072728.92−505631.1 |
| A0842        | 08 42 20 −03 03 25 | ASASSN-V J084219.98−030325.3 |
| A1037        | 10 37 37 −37 09 30 | ASASSN-V J103736.72−370928.0 |
| A1214        | 12 14 30.5 −02 57 04 | ASASSN-V J121430.46−025704.6 |
| A1249        | 12 49 08 −29 44 38 | ASASSN-V J124907.83−294437.7 |
| A1251        | 12 51 19 −28 08 25 | ASASSN-V J125119.31−280824.8 |
| SSS 1315     | 13 15 59.6 −37 00 17.7 | ASASSN-V J131559.62−370018.8 |
| A1407        | 14 07 13 −30 24 44 | ASASSN-V J140712.93−302443.8 |
| A1446        | 14 46 21 −30 04 40 | ASASSN-V J144620.72−300440.9 |
| A1517        | 15 17 02 14 10 23 | ASASSN-V J151702.56+141023.3 |
| A1531        | 15 31 18 −17 42 36 | ASASSN-V J153118.10−174236.0 |
| V396 Lup     | 16 03 02 −37 49 21.2 | ASASSN-V J160302.12−374921.2 |
| A1629        | 16 29 19.9 35 40 03 | ASASSN-V J162919.96+354003.5 |
| A1651        | 16 51 39.4 22 55 44 | ASASSN-V J165139.40+225543.0 |
| V565 Dra     | 17 38 49.8 2+57 12 23.2 | ASASSN-V J173849.79+571222.6 |
| A1751        | 17 51 10 03 13 20 | ASASSN-V J175109.86+031319.5 |
| A1846        | 18 46 43.4 −27 36 29 | ASASSN-V J184643.38−273629.3 |
| A1847        | 18 47 37 21 56 06 | ASASSN-V J184737.28+215606.0 |
| A1907        | 19 07 28.30 −53 47 24.7 | ASASSN-V J190728.21−534724.9 |
| A1928        | 19 28 49 −40 45 54 | ASASSN-V J192848.87−404554.0 |
| A1946        | 19 46 45 −04 03 39 | ASASSN-V J194644.82−040339.6 |
| A2001        | 20 01 26 07 37 40 | ASASSN-V J200125.92+073739.9 |
| A2003        | 20 03 04 −02 56 02 | ASASSN-V J200303.64−025603.3 |
| A2044        | 20 44 00 57 52 17 | ASASSN-V J204400.26+575217.6 |
| A2044        | 20 44 52 06 22 31 | ASASSN-V J204452.22+062231.3 |
| NSVS 114     | 20 45 26 16 59 13 | ASASSN-V J204525.65+165912.7 |
| A2048        | 20 48 35 −46 09 42 | ASASSN-V J204835.36+460942.4 |
| A2132        | 21 32 19.4 −53 51 33 | ASASSN-V J213219.30−535133.7 |
| A2145        | 21 45 37 −58 35 00 | ASASSN-V J214537.35−583500.9 |
| SSS 2213     | 22 13 27.3 −44 54 00.5 | ASASSN-V J221327.33−445400.3 |
| A2222        | 22 22 17 37 37 41 | ASASSN-V J222217.40+373740.6 |
| A2243        | 22 43 19 −73 51 18 | ASASSN-V J224318.80−735118.0 |
| A2250        | 22 50 00 −23 16 24 | ASASSN-V J224959.89−231623.1 |
| A2258-26     | 22 58 26 −26 03 36 | ASASSN-V J225825.91−260337.8 |
| A2258        | 22 58 50 13 49 18 | ASASSN-V J225849.67+134917.7 |
| NSVS 902     | 23 19 49 36 03 51 | ASASSN-V J231948.59+360350.6 |
| A2348        | 23 48 23 −40 54 41 | ASASSN-V J234823.30−405440.6 |
| V1222 Tau    | 03 28 26 09 04 24 | V1222 Tau |
| NSVS 431     | 04 59 45 49 25 03 | NSVS 4316778 |
| A0822        | 08 22 43 19 26 58 | ASASSN-V J082243.00+192658.5 |
| GSC 03415−02229 | 08 27 01 46 28 50 | GSC 03415−02229 |
| A0832        | 08 32 41 23 32 26 | ASASSN-V J083240.96+233225.9 |
| NSVS 780     | 09 06 43 70 03 29 | NSVS 780649 |
| PZ UMA       | 09 29 07 49 51 23 | PZ UMA |
| NSVS 256     | 10 10 42.7 67 39 31 | NSVS 2569022 |
| SX Crv       | 12 40 15 −18 48 01 | SX Crv |
| A1328        | 13 28 29 55 52 45 | ASASSN-V J132829.15+555245.4 |
| ZZ PsA       | 21 50 35.2 −27 48 35.5 | ZZ PsA |
unstable contact binary systems which place further constraints on the light curve morphology and timings. We note that for low mass systems there is a narrow period domain from $\approx 0.27$ to $0.4$ d at which they may become unstable and this increases with the mass of the primary. Those results will further aid in the identification of potential red nova progenitors from large survey samples. We hope to employ all the techniques and modifications described to the VSX database to further identify bright potential red nova candidates.

The techniques described in no way ensure all potential red nova progenitors are identified. Limiting our selection to those exhibiting complete eclipses clearly excludes a significant portion of contact binary systems, however, identification of potential systems among these would require both time-consuming dedicated observations on modest sized telescopes and high resolution spectroscopic observations. Such requirements are unlikely to be readily available. The light curves of non totally eclipsing systems cannot be reliably analysed due to the high degree of correlation between the three geometric parameters, specifically, inclination, mass ratio and degree of contact. The presence of a total eclipse places significant constraints, particularly in the $q/i$, domain allowing for manual search to be performed to find the correct light curve solution. Also, as already noted, survey photometric data although useful in light curve analysis does have limitations given the scatter, particularly with respect to the determining the fill-out fraction (Devarapalli et al. 2020; Wadhwa et al. 2022). Looking at Equations (1) and (2) above, we see that the fill-out can have a significant influence on the instability mass ratio particularly, for systems with the primary below one solar mass. The methodology employed places sorting restrictions assuming a high fill-out, so it is possible that some of the identified samples may still be in the stable range. The small sample identified offers a good opportunity for dedicated observations with modest optical instruments to further refine the list of potential merger candidates. To this end, we have started a programme of dedicated multi-band observations of some of the identified systems with instruments in the 0.5 m range with results to be presented progressively.

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References

Aigrain S., Hodgkin S. T., Irwin M. J., Lewis J. R., Roberts S. J. 2015, MNRAS, 447, 2880
Arbutina B. 2007, MNRAS, 377, 1635
Arbutina B. 2009, MNRAS, 394, 501
Awadalla N. S., Hanna M. A. 2005, Journal of Korean Astronomical Society, 38, 43
Brown N. J., Waagen E. O., Scovil C., et al. 2002, iaucirc, 7785, 1
Christopoulou P.-E., Lalounta E., Papageorgiou A., et al. 2022, MNRAS, 2202.12835
Devarapalli S. P., Jagirdar R., Prasad R. M., et al. 2020, MNRAS, 493, 1565
Drake A. J., Djorgovski S. G., Catelan M., et al. 2017, MNRAS, 469, 3688
Eggleton P. P. 2012, JASS, 29, 145
Gazeas K. D., Loukaidou G. A., Niarchos P. G., et al. 2021, MNRAS, 502, 2879
Handberg R., Lund M. N., White T. R., et al. 2021, AJ, 162, 170
Huang C. X., Vanderburg A., Pál A., et al. 2020, RNAAS, 4, 204
Jayasinghe T., Stanek K. Z., Kochanek C. S., et al. 2020, MNRAS, 491, 13
Kandulapati S., Devarapalli S. P., Pasagada V. R. 2015, MNRAS, 446, 510
Kjurkchieva D. P., Popov V. A., Petrov N. I. 2018, Research in Astronomy and Astrophysics, 18, 129
Kjurkchieva D. P., Popov V. A., Petrov N. I. 2020, New Astronomy, 77, 101352
Kobulnicky H. A., Molnar L. A., Cook E. M., Henderson L. E. 2022, arXiv e-prints 2202.01187
Kochanek C. S., Adams S. M., Belczynski K. 2014, MNRAS, 443, 1319
Latković O., Čeki A., Lazarević S. 2021, ApJS, 254, 10
Li K., Xia Q.-Q., Kim C.-H., et al. 2021, ApJ, 922, 122
Liu L., Qian S.-B., Soonthornthum B., et al. 2015, PASJ, 67, 74
Lucy L. B. 1967, ZAp, 65, 89
Martini P., Wagner R. M., Tomaney A., et al. 1999, AJ, 118, 1034
Nelson R. H. 2021, New Astronomy, 86, 101565
Nelson R. H., Robb R. M. 2015, Information Bulletin on Variable Stars, 6134, 1
Pastorello A., Mason E., Taubenberger S., et al. 2019, AAP, 630, A75
Pecaut M. J., Mamajek E. E. 2013, ApJS, 208, 9
Pojmanski G. 2002, Acta Astronomica, 52, 397
Pollacco D. L., Skillen I., Collier Cameron A., et al. 2006, PASP, 118, 1407
Popov V., Acerbi F., Barani C. 2021, Research in Astronomy and Astrophysics, 21, 225
Rasio F. A. 1995, ApJl, 444, L41
Ricker G. R., Winn J. N., Vanderspek R., et al. 2015, Journal of Astronomical Telescopes, Instruments, and Systems, 1, 014003
Robertson J. A., Eggleton P. P. 1977, MNRAS, 179, 359
Rucinski S. 1969, Postepy Astronomii Krakow, 17, 163
Rucinski S. M. 1993, PASP, 105, 1433
Rucinski S. M. 2001, AJ, 122, 1007
Shappee B. J., Prieto J. L., Grupe D., et al. 2014, ApJ, 788, 48

Soker N., Tylenda R. 2003, ApJl, 582, L105
Sriram K., Malu S., Choi C. S., Vivekananda Rao P. 2016, AJ, 151, 69
Stępień K. 2011, AAP, 531, A18
Sun W., Chen X., Deng L., de Grijs R. 2020, ApJS, 247, 50
Terrell D., Wilson R. E. 2005, Ap&SS, 296, 221
Tylenda R., Hajduk M., Kamiński T., et al. 2011, A&A, 528, A114
Tylenda R., Kamiński T., Udalski A., et al. 2013, AAP, 555, A16
Van Cleve J. E., Caldwell D. A., Jenkins J. M., et al. 2010, in American Astronomical Society Meeting Abstracts, Vol. 215, American Astronomical Society Meeting Abstracts #215, 420.02
van Hamme W. 1993, AJ, 106, 2096
Wadhwa S. S., De Horta A., Filipović M. D., et al. 2021, MNRAS, 501, 229
Wadhwa S. S., De Horta A. Y., Filipovic M. D., Tothill N. F. H. 2022, arXiv e-prints, 2202.09120
Yildiz M., Doğan T. 2013, MNRAS, 430, 2029
Zhou X., Soonthornthum B. 2019, PASJ, 71, 39
Zola S., Rucinski S. M., Baran A., et al. 2004, AcA, 54, 299