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IDENTIFICATION OF POTENTIAL RED NOVA PROGENITORS

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Abstract. Luminous red novae are rare transient events thought to be the result of the merger of contact binary system components into a single star. So far, there is only one confirmed observed event, that of V1309 Sco (Nova Sco 2008). Unfortunately, that system was recognized as a contact binary only after the merger event, so targeted observations to fully elucidate the properties of the components and events leading up to the merger itself could not be performed. With ever increasing number of identified contact binary systems from sky surveys there is heightened interest in the identification of red nova progenitors. We have developed and are refining methods and relationships linking geometric parameters obtained through light curve analysis and the mass of the primary component with orbital instability. We discuss some theoretical and practical application of the new relationships to a group of poorly studied contact binary systems. In addition, we briefly touch on the effects of stellar composition on contact binary orbital stability.

1. INTRODUCTION

Although there is only one confirmed event, the transients resulting from the merger of contact binary components are thought to be the small number of observed luminous red novae (LRN). Frequency of LRN is predicted to be as high as 1 every 3 years with observable events occurring once every decade, so far however, there is only one confirmed observed event, that of V1309 Sco (Tylenda et al. 2011). Unfortunately, the progenitor of V1309 Sco was recognized as a contact binary only after the merger event and pre-merger study of the components was limited to low cadence survey photometry. Based on the observed spectra of most contact binaries (F to K) it is estimated that the primary component of most systems has mass from 0.5 to 1.5 Solar mass and as such they are likely to be quite faint and not within reach small to intermediate instruments. The primary of V1309 Sco was fainter than 19th magnitude. The frequency of contact binaries in the Galactic disk is high (1 in 500) (Rucinski 2006) and sky survey projects such as All Sky Automated Survey (ASAS) (Pojmanski 1997) and All Sky Automated Survey-Super Novae (ASAS-SN) (Shappee et al. 2014), among many others, are continually adding to our lists of contact binary systems. Identification of bright candidates that are close to merging is critical to our understanding of these systems.

Theoretical modelling suggests that several factors such as the mass ratio, degree of contact and separation (and hence period) influence the rate at which any system moves towards merger. Among the most critical is the relationship between orbital and spin angular momentum (Arbutina 2007). Merger is likely to occur when the mass ratio (q) of the components ($= M_2/M_1$) is low, however, there is no clear mechanism to estimate the mass ratio at which any particular system is likely to merge. The first part of the current project was to to define the instability mass ratio (q_{inst}) more precisely at which merger is likely.

As noted above most contact binary systems are likely to be faint however many brighter examples have been identified by sky surveys. The second part of the current project was to develop techniques that allowed survey photometry data to be used to exclude likely stable systems and to determine if survey photometric data was of sufficient quality to identify potentially unstable systems.

Once established the orbital stability criteria and search criteria were combined to select several potential extreme low mass ratio systems from ASAS-SN for follow-up observations and analysis.

2. ORBITAL STABILITY AND THE INSTABILITY MASS RATIO

Contact binary systems are thought to merge into a single, rapidly spinning object when the total angular momentum of the system is at a critical value such that tidal instability ensues (Darwin 1879). Previous investigators (Rasio 1995, Arbutina 2007,2009, Jiang et al. 2010) have attempted to estimate the minimum mass ratio at which merge will occur. Prior to this study the estimated minimum mass ratio of for a contact binary was 0.07-0.075. These estimates however were based on using a fixed value for the gyration radius of the primary ($k_1 = 0.06$) and many investigators did not consider effects of the secondary component, rotation, tidal distortions, or the degree of contact. We have undertaken theoretical refinement and incorporated many of the previously thought minor effects such as tidal distortions, non equivalent gyration radii of the components and the degree of fillout. These combined with modelled values for the gyration radius of the primary which incorporates rotation and tidal distortions (Wadhwa et al. 2021) we have shown that there is no universal minimum mass ratio at which merger is likely and that each system has its own unique mass ratio at which it will merge dependent on the mass of the primary (M_1) and the degree of contact (f). The instability mass ratio range for systems with primaries from 0.5 to 1.6 Solar mass can be expressed as two simple quadratic relationships; at the onset of contact ($f = 0$) and full over-contact ($f = 1$) as follows:

$$q_{inst} = 0.0772M_1^2 - 0.3003M_1 + 0.3237(f = 0). \tag{1}$$

and

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

Modelling of gyration radii at this time is limited to solar metallicity and zero age main sequence. We plan to further refine the instability criteria with incorporation of metallicity and age into the modelling of gyration radii to determine any significant deviations.

3. SUITABILITY OF SURVEY PHOTOMETRY

Although many thousands of bright contact binaries have been identified by sky surveys the published photometry in all cases is of low cadence with high degree of scatter. We and others (Devarapalli et al. 2020, Wadhwa et al 2022a) have been conducting ground-based observations on systems selected from survey identified systems and comparing the light curve analysis results. There is good agreement between the determined geometric elements such as the mass ratio from both survey and dedicated high cadence observations. As with photometric light curve analysis in the absence of radial velocity measurements the comments above only apply to systems that display total eclipses.

Having established the suitability of survey photometry to accurately determine the mass ratio of totally eclipsing contact binaries we next developed techniques to rapidly exclude most (not all) stable systems. As is well known the major determinants of the shape of contact binary light curves, especially those displaying total eclipses, are the mass ratio, degree of contact, the temperature of the components and the orbital inclination (i). We modelled theoretical contact binary light curves for a range of the four main determinants and show that the maximum amplitude is directly correlated to the mass ratio at $f = 1$ and $i = 90°$ (Wadhwa et al. 2022b). We then used equation 2 above to estimate the maximum amplitude at the instability mass ratio for systems with the primary in the range 0.5 to 1.4 Solar mass and show that there is strong linear correlation between the maximum amplitude at the instability mass ratio and the mass the primary as follows:

$$MaxAmpl\ (mag) = -0.5179M_1 + 0.945 \tag{3}$$

Equation 3 now allows rapid identification of at least some (not all) stable systems. As an example, consider a system with an estimated 1 Solar mass primary with an observed survey amplitude of 0.47mag. Based on equation 3 the maximum amplitude for such a system to be unstable is ≈0.43mag. As the observed amplitude is higher than the maximum for an unstable system it is likely that the system has a mass ratio greater than the instability mass ratio at $f = 1$ and would be considered stable and can be excluded from follow up observations assuming the original aim was to identify potentially unstable systems. As discussed in the cited reference the approach allows exclusion of most but not all stable systems as some systems with lower level of contact and shallower inclination may well have amplitudes smaller than the maximum but still have mass ratio greater than the instability mass ratio.

4. BRIGHT POTENTIAL RED NOVAE PROGENITORS AND SUMMARY

Over the past 3 years we have employed the above relationships by examining the survey photometry of bright contact binaries from ASAS-SN with follow up ground-based observations to identify 19 examples of bright potentially unstable systems (Wadhwa et al. 2021, 2022, 2023a, 2023b). Basic parameters of the nineteen systems identified by us are summarised in Table 1. Full details of data and image acquisition can be found in the cited references. The instability parameters are being continually refined and we will be soon reporting the effects of metallicity and age on instability of contact binary systems.

The rapid explosion of newly identified contact binaries (through sky surveys) and the confirmation that transients such as LNR are the result of contact binary star has resulted in heightened interest in the identification of pre-merger candidates. Over the past few years, we have refined the theoretical framework to dispel the notion of a universal minimum mass ratio for all contact binary systems and shown that each system is unique and has its own instability mass ratio dependent on the mass of the primary component and the degree of contact. We have developed techniques to rapidly identify potentially unstable systems from survey photometry and have used these relationships to identify 19 bright potentially unstable systems all of which are within reach of modest instruments for long term follow-up and review.

Table 1: Basic parameters of 19 potential red novae progenitors identified using the newly developed techniques described. In cases where the instability mass ratio is less than the modelled mass ratio the original articles indicate that the systems are within the error estimates and as such regarded as unstable

Name	$M_1(M_\odot)$	q	q_{inst}
ZZ PsA	1.21	0.078	0.073 - 0.082
ASAS J082151-0612.6	1.01	0.097	0.099 - 0.116
TYC 7281-269-1	1.08	0.082	0.089 - 0.103
TYC 7275-1968-1	1.11	0.075	0.085 - 0.098
ASAS J045814+0643.1	1.17	0.088	0.078 - 0.088
ASAS J051459-7356.3	0.98	0.120	0.103 - 0.122
ASAS J100101-7958.6	0.83	0.138	0.128 - 0.155
V396 Lup	0.95	0.133	0.108 - 0.128
ASAS J170715-5118.7	1.22	0.072	0.072 - 0.081
ASAS J184644-2736.4	0.90	0.150	0.116 - 0.138
ASAS J202231-4452.5	1.11	0.100	0.085 - 0.098
ASAS J204452+0622.6	1.13	0.088	0.083 - 0.094
ASAS J213219-5351.6	1.04	0.113	0.095 - 0.110
SSS-J221327.1-445401	1.15	0.088	0.080 - 0.091
ASAS J225826-2603.6	1.12	0.087	0.084 - 0.096
ASAS J234823-4054.7	1.11	0.117	0.085 - 0.098
ASAS J084220-0303.4	1.12	0.100	0.084 - 0.096
ASAS J103737-3709.5	1.18	0.090	0.074 - 0.086
V565 Dra	1.15	0.108	0.080 - 0.091

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