What do we know about the Recurrent Novae T CrB & RS Oph?

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ABSTRACT

T CrB and RS Oph, are two of only ten known galactic recurrent novae (RNe). They are both long period binaries with massive white dwarfs and red giant primaries and thus present as appropriate comparisons for models and parameters. Observations made of both of these stars during quiescence often provide mass accretion rates which fall below the theoretical expectations to meet thermonuclear runaway conditions. This is believed to be due to fluctuations in the rate of mass accretion. Here a re-analysis of the AAVSO data of the visual, V and B bands as well as a compilation, comparison and discussion of various methods that have been used in the study of RNe are included in this paper. A conclusion is drawn that both systems, T CrB and RS Oph are Roche-lobe filling systems whose outbursts are triggered by thermonuclear runaway (TNR) during high activity and accretion rates.

Keywords: Recurrent Novae, Accretion disk, Thermonuclear Runaway, AAVSO, DASCH –stars: indiviual (T CrB, RS Oph)

1. INTRODUCTION

Recurrent Nova (RNe) form a group of cataclysmic variables which have a recurrency of novae outbursts on the scale decades. They consist of a white dwarf primary which accretes material via a Roche-lobe filling companion, or from the wind of a nearby giant along the scale of $10^{-8} \sim 10^{-6} M_{\odot} yr^{-1}$(Shara et al. 2018; Livio et al. 1986).

Regular nova systems are ones in which a single outburst has been detected and are labelled as 'Classical Novae' (CNe). Although additional outbursts from these systems may have been missed, raising the possibility that current known CNe may in fact be RNe. (Schaefer 2010) RNe occur much more frequently than CNe has two mains reason: Firstly the rate of mass transfer of RNe must be greater than that of CNe. This allows a significant amount of material to accumulate at the surface of the white dwarf, resulting in an environment conducive to TNR (Hachisu & Kato 2018). Secondly, related to the necessity of high rates of mass accretion, RNe also possess massive white dwarfs, near the Chandrasekhar limit. This condition would allow the accreted mass achieve the critical temperature for TNR, as a result of a stronger gravitational field. (Hachisu & Kato 2001; Townsley 2008)

As such, given these conditions of high mass transfer and massive white dwarfs resulting in frequent outbursts presents these systems as ones ideal for the study of accretion physics.

Additionally, questions arise as to whether these systems might present themselves as progenitors to type Ia supernovae. That is to say, that as long as the mass ejected during each outburst is less than that of the mass being accreted it can say with confidence that these systems will arrive at the Chandrasekhar limit at some point and collapse(Hillebrandt & Niemeyer 2000). The importance of this study is due to the lack of a known type Ia supernova progenitor. This has been motivated by the fact that supernovae have become increasingly important in cosmology due to their role acting as standard candles (Howell 2011).

Addressing the questions of mass accretion rates and whether they exceed the eject mass, it has been found that the International Ultraviolet Explorer (IUE) observations present significant evidence that RS Oph is a carbon-oxygen (CO) white dwarf (Mikołajewska & Shara 2017). Due to the fact that CO white dwarfs are not born in excess of $1.1 M_{\odot}$ (García-Berro et al. 1997) and that the most recent measurements and estimations of its mass place is currently $1.35 \pm 0.01 M_{\odot}$ (Hachisu & Kato 2001) means that there is significant evidence that RS Oph has grown significantly since its birth. In addition while T CrB has not been confirmed as a CO WD it is hoped that in the next UV observation of its outburst its composition may become clearer.

The purposes of this paper is to discuss the primary mechanisms of which the systems RS Oph and T CrB accrete mass between one another and to provide distance measurements for these stars.

2. DETERMINING THE MECHANISMS OF MASS ACCRETION

There are principally two schools of thought when it comes to the mass transfer of RNe and their outbursts. Firstly there is the thermonuclear runaway model, events by which a critical temperature and mass are achieved at the surface of the white dwarf, resulting in TNR. The calculations for these events are characterised in Livio et al. (1986). Given the similarity between the WDs of T CrB and RS Oph, the critical mass approximately required for the conditions is along the order of $6 \times 10^{-5} M_{\odot}$. This is inline with other estimations of where x-ray modelling of the 2006 RS Oph eruption produced a mass ejecta of $1.1 \times 10^{-6} M_{\odot}$. Hachisu & Kato (2001) have also proposed required masses of $3 \times 10^{-6} M_{\odot}$ and $2 \times 10^{-6} M_{\odot}$ for T CrB and RS Oph respectively. Given that T CrB, has only been viewed in outburst twice (1886-1946) it is speculated that it has a recurrency of approximately 80 years. RS Oph on the other hand has been viewed in outburst 7 times, which a speculated eruption in 1945 which was missed (Schaefer 2010). This produces a recurrency of approximately 15 years for RS Oph. Such determinations leads us to believe that the requirements for mass accretion in order to satisfy TNR conditions leaves us with a minimum rate of $9.75 \times 10^{-7} M_{\odot} yr^{-1}$ and $3.9 \times 10^{-6} M_{\odot} yr^{-1}$ for T CrB and RS Oph. These minimum rates of mass transfer exceed many of the calculations made of mass-loss rate from red giant wind. See Livio et al. (1986),Vaytet et al. (2007), Schröder & Cuntz (2007), all of which who's models fall short of these requirements along the magnitudes of $10^{-8} M_{\odot} yr^{-1} \sim 10^{-7} M_{\odot} yr^{-1}$. This is proposed at motivations for in the case of TNR powered outbursts of RNe that the systems T CrB and RS Oph must be filling their Roche-lobe size due to inadequacies in the Red giant wind mass loss rates. Secondly, the mode of outburst is due to that of the accretion disk model. These are proposed to occur as a result of disk instability or during an event where mass is transferred onto the disk(Luna et al. 2019). This instability of the disk is proposed from the idea that when the disk becomes unstable mass that has been accrued over a period of time will release its gravitational potential energy. These methods however have produced critical mass envelopes resulting in total energy release on a time scale not dissimilar to the diffusion time of the disk (Livio et al. 1986). This means to in order to satisfy the sharp rise in outburst for these systems the rate of mass accretion would also need to greatly increase (Hameury 2020). As these conditions would be much more chaotic and have not been observed, the most likely solution for these systems is the TNR model, whereby a steadily rising amount of mass reaches a critical temperature. As such I conducted an exercise to calculate the distance to T CrB and RS Oph assuming the systems of mass transfer under a Roche-lobe filled environment.

3. OBSERVATIONAL DATA

Part of this work involved in the analysis of the AAVSO visual,V and B magnitude records of T CrB and RS Oph by members of the association. The analysis of these files was carried out during points of quiescence such that the contributions of optical light would be dominated by the companion stars (Williams et al. 2016). A proportion of work in this project involved images from panSTARRS1. As both sources (T CrB and RS Oph) are particularly bright the images produced presented high levels of saturated pixels. The process involving PSF photometry to reclaim the peaks of these stars was conducted by modelling the point spread function of other unsaturated stars in the same field. This process is explored in more detail in the appendix in case of future use, ultimately this analysis did not lead to significant changes in the results.

4. DATA ANALYSIS

4.1. *Periodicity*

Having queried the Visual, V, and B band magnitudes from the AAVSO for T CrB and RS Oph the light curves of the stars were constructed. As can be seen in fig.1a and fig.1b the light curve during points of quiescence are dominated by the red giant primary. Fekel et al. (2000) and Leibowitz et al. (1997) have published their analysis of the periods for T CrB and RS Oph. I reanalysed the data using an independent method called Date-Compressed discrete Fourier transform (DCDFT) to calculate the periodicity of quasi periodic patterns in the light curves. The methodology for this method is implemented in Peranso 3 software and is outlined by Ferraz-Mello (1981). The method however returned significantly larger errors with the results for T CrB and RS Oph as 292.88±days and 292.88±days respectively. There was difficulty in determining points of low activity for RS Oph due to the short period between outbursts and ensuring the curve was not being affected by rises in activity. As such any attempts to measure the periodicity of the system were being tampered with by changes in the Mass accretion dynamics of RS Oph. Analysis was conducted for the Visual, V and B bands for low activity periods however a frequency could not be determined with confidence (see appendix B). Ideally the light curve could have been recalculated during different points repeatedly until better results were achieved however due to the significant calculation wait times between each compilation and the large errors I decided to use the accepted and independently produced results of Leibowitz et al. (1997) and Brandi et al. (2009) for T CrB and RS Oph respectively.

4.2. *Distances*

As outlined under the necessary mass envelopes and theoretical predictions for mass accretion rates it can be concluded that both systems, T CrB and RS Oph fulfill their Roche-lobe. As such I could implement the periodicity of these systems and masses as outlined in Frank et al. (2002) and Schaefer (2010) where q is the mass ratio $\frac{M_2}{M_1}$ used to calculate the binary separation (a) and Roche lobe size (R_{Roche}). The equations used were as follows:

$$a = 4.16R_{\odot}(M_{wd} + M_{comp})^{\frac{1}{3}}P_{orb}^{\frac{2}{3}} \tag{1}$$

$$R_{roche} = 0.49aq^{\frac{2}{3}}/[0.6q^{\frac{2}{3}} + ln(1 + q^{\frac{1}{3}})] \tag{2}$$

With these equations where the assumed M_{wd} for T CrB and RS Oph are outlined as $1.37 \pm 0.01M_{\odot}$ and $1.35 \pm 0.01M_{\odot}$ and a M_{comp} of $1M_{\odot}$, motivated by the fitting of outburst decline (Hachisu & Kato 2001). With the now known binary separations and Roche-lobe size of the system, the apparent and absolute bolometric magnitudes using K-band magnitudes were calculated as outlined in (Schaefer 2010).

$$m_{bol} = m_k - 0.33 * E_{B-V} + (V - K) + BC \tag{3}$$

$$M_{bol} = 42.36 - 10\log(T_{eff}) - 5\log(R_{Roche}/R_{\odot}) \tag{4}$$

$$D = 10^{(m_{bol} - M_{bol} + 5)/5} \tag{5}$$

E_{B-V}, T_{eff}. and $(V - K) + BC$ were calculated for using the range of valid spectral types of this system (Pecaut & Mamajek 2013). The radius of the red giant was assumed to be filling the Roche-lobe size, fulfilling the necessity of mass transfer. The results for these steps can be seen in table.1. In addition to calculating the distance via bolometric and Roche-lobe modelling a second method was used to measure the distance to RS Oph and T CrB. This method is known as 'Maximum magnitude versus rate of decline' (MMRD). This is popular within the community and has been used frequently as only a light curve is needed to calculate the distance. By measuring the time taken for the outburst to reduce by a magnitude of 2 and 3 after day 0 of the outburst a absolute magnitude can be calculated (Hachisu et al. 2020). The equations, as outlined by Downes & Duerbeck (2000) were as follows:

$$M_v = -10.79 + 1.53\log(t_2) \tag{6}$$

$$M_v = -11.26 + 1.58\log(t_3) \tag{7}$$

$$D = 10^{(\mu - 3.1(E_{B-V}) + 5)/5} \tag{8}$$

A re-analysis of the visual magnitudes of T CrB and RS Oph using the AAVSO measurements were used to satisfy this method.

5. RESULTS

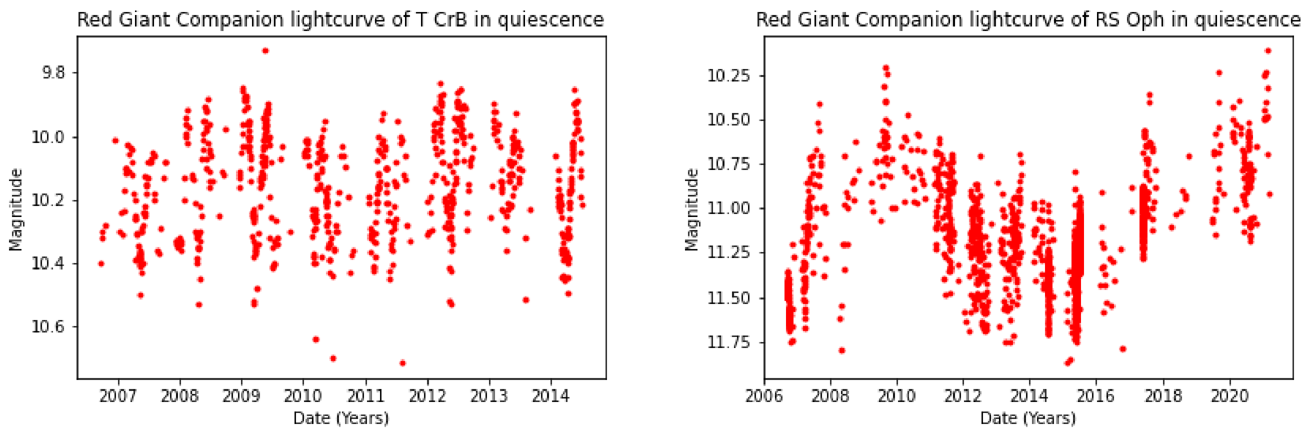
The results of the data analysis can be found in table 1. A compilation of known and currently accepted parameters are shown alongside the distances and orbital period found in this exercise. Additional rows have been added giving the results of the proposed methods of mass transfer between the systems.

6. DISCUSSION

The most interesting and significant part of the results in this exercise are that of the distance calculations for T CrB and RS Oph, the distances calculated by GAIA via parallax result in $806^{+34}_{-30}pc$ (Bailer-Jones et al. 2018) and $2.26 \pm .27kpc$ (Gaia Collaboration et al. 2018) . These results are reassuring in the assumption of a Roche-lobe filling environment as the distance calculated from method 1 fulfills these parallax measurements including errors. It is worth noting however that these parallax measurements may be unreliable due to the orbital wobble of these systems (Schaefer 2018) they are still useful indicators. For much shorter period binary systems, in the order of hours, it has been proposed that it is giant wind loss that drives these outburst events. In a paper by Knigge et al. (2000), the RNe T Pyx is proposed to be a wind-driven supersoft x-ray source. In the scenario proposed the radiation induced wind is excited from the red giant companion beyond normal mass loss rates and accelerates the evolution. Given that T Pyx is believed to by $3185^{+607}_{-283}pc$ (Schaefer 2018), observations using K-band magnitudes and using the bolometric magnitudes to calculate the distance under assumption of Roche-lobe overflow could help address the situation of rapid mass transfer and determine the exact mechanism at play.

7. CONCLUSION

In conclusion, examining the current models and thought process behind the deductions of mass transfer systems of T CrB and RS Oph I have produced evidence that these systems are filling their Roche-lobe size. This is backed up by the parallax measurements of these stars being in agreement with the calculated errors. This paper lacked the NIR and UV analysis needed to expand the conclusion and examine the instantaneous rates of mass transfer as well as disk stability. As such it would be highly recommended to continue missions into these systems across instruments such as CHARA and Swift



(a) (b)

Figure 1. Red giant companion light curves during low activity using AAVSO data. As you can see in (b) since the nova outburst in 2006 RS Oph has undergone fluctuations in its magnitude even during quiescence.

Table 1. Collection of T CrB and RS Oph parameters

Parameters	T CrB	RS Oph
$M_{wd}[M_\odot]$ [1]	1.37±0.01	1.35±0.01
P_{orb}[days] [2]	227.57 ± 0.01	455.72 ± 0.83
P_{orb}[days]	238 ± 62	317±242
Recent Outbursts [year]	1866,1946	1985,2006
Distance [pc] [3]	806^{+34}_{-30}	$2260 \pm 270pc$
Method 1 : Distance [pc]	900±153	3050±544
Method 2 : Distance [pc]	3200±992pc & 2100±651pc	
t_2	4	7
t_3	6	14
Next Eruption [year]	2026±3 [4]	2021±6 [5]

NOTE—This table displays the known and currently accepted parameters for T CrB & RS Oph. As well as the distances calculated in this paper, the uncertainties come from that of the spectral type of the companion. References: 1.(Hachisu & Kato 2001),2.(Schaefer 2010),3.(Gaia Collaboration et al. 2018),4.(Luna et al. 2020),5.(Schaefer 2019)

UVOT in order to spatially resolve the tidal distortions of the companions stars for these systems. This would provide the information needed shed light on the mechanism of mass transfer of some of the most promising type Ia supernovae progenitors in our galaxy.

8. SOFTWARE AND THIRD PARTY DATA REPOSITORY CITATIONS

V-star for determining the MMRD values. The python packages: Astropy, matplotlib, numpy, pandas, and Julian were all used for methods for data analysis, ranging from the DCDFT to the PSF photometry measurements of panSTARRS1.

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APPENDIX

A. PSF PHOTOMETRY OF SATURATED SOURCES

Although this exercise did not affect the outcome of this paper it was a useful exercise exploring alternatives method of photometry. PSF photometry that was carried out to recover saturated imagery represented a significant amount of time spent on this project. By following the steps outlined in Heasley (1999)'s 'PSF Cookbook' the stars in the panSTARRS1 field for T CrB and RS Oph were identified. Then, using Astropy all saturated pixels were removed and replaced with crude interpolations, as seen in fig.2. After then determining the original PSF estimate using stars with the more accurate aperture photometry a preliminary PSF was created to fit all the stars. This was looped for all stars and compared until it was certain all stars were identified and had a preliminary PSF fit. The final product can be seen in figures 3 and 4(a)&(b) where the saturated and simulated images are compared as well as a 3d plot of their peaks.

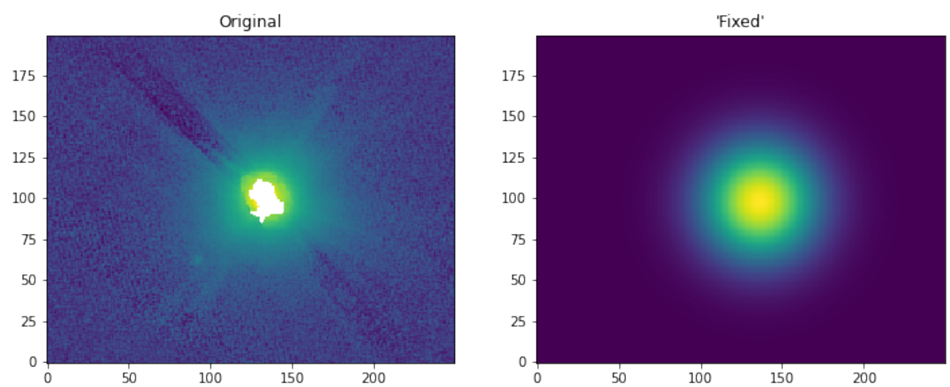
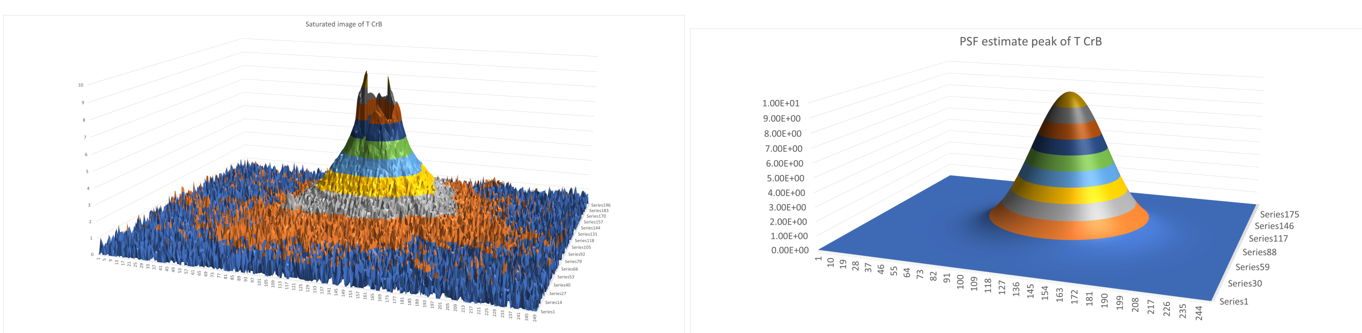


Figure 2. A comparison of the original panSTARRS1 saturated image and a PSF model of T CrB



(a)

(b)

Figure 3. 3d plots of the original panSTARRS1 saturated image and a PSF model of T CrB

B. DATE-COMPRESSED DISCRETE FOURIER TRANSFORM

As mentioned earlier the DCDFT is an application used in the Peranso 3 software and whose methodology is outlined by Ferraz-Mello (1981). This was chosen was the chosen for determining the periodicity of the light curves. T CrB has had a long period of quiescence between its outburst in 1946 and its recent rise to a 'Super active state' (Munari et al. 2016). This meant that a determination of its period was much more reliable. However issues arose when attempting to calculate the orbital period of RS Oph. Due to its frequent nature of outbursts it was difficult to determine a period that spanned a long amount of time without appearing to be affected by the activity of the system in some way. This can be seen in the original fig.1(a) however can also been in the figures I've attached below for each period of quiescence. The additional variance in these magnitudes is clear and has skewed the period calculations of the DCDFT for RS Oph.

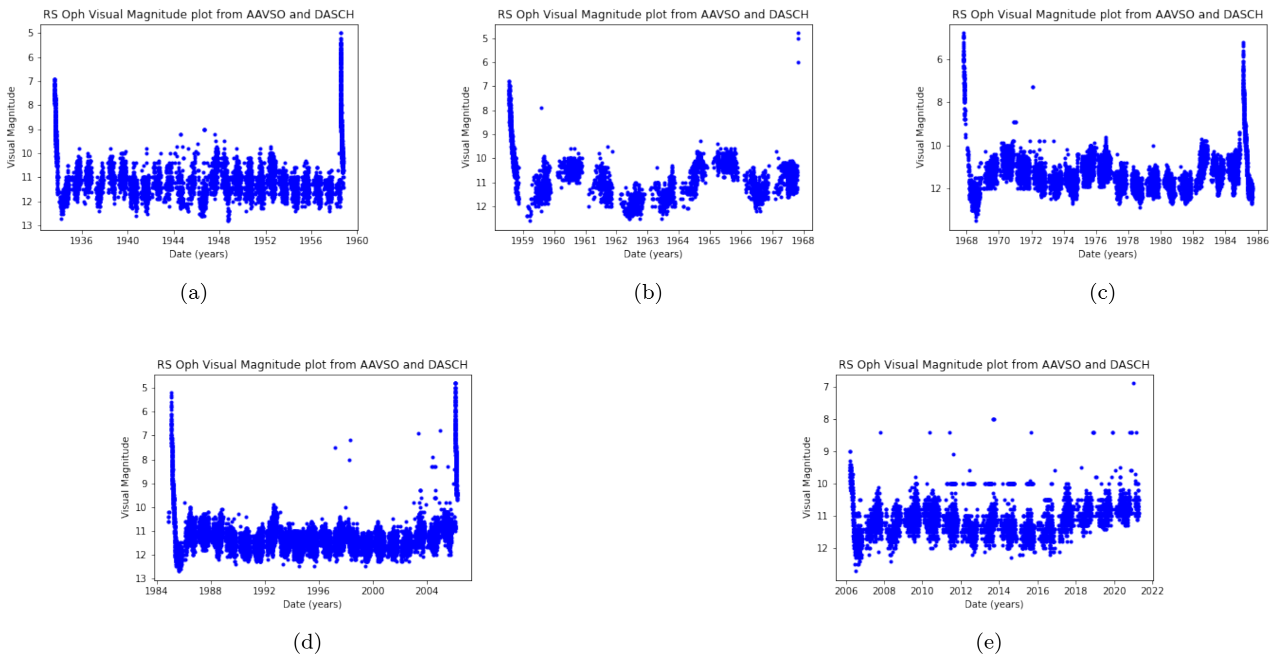


Figure 4. RS Oph's periods in between bursts as plotted from the AAVSO and DASCH archives for visual magnitudes.