Bulgarian Academy of Sciences. Space Research and Technology Institute.
Aerospace Research in Bulgaria. 37, 2025, Sofia

A HYPOTHESIS ON THE BINARY-DISK EVOLUTION OF AN 80-YEAR PERIOD BETWEEN TWO NOVA-OUTBURSTS OF T CRB

Krasimira Yankova[1], Daniela Boneva[1], Radoslav Zamanov[2]

[1]Space Research and Technology Institute – Bulgarian Academy of Sciences
e–mail: f7@space.bas.bg, danvasan@space.bas.bg
[2]Institute of Astronomy and NAO – Bulgarian Academy of Sciences
e–mail: rkz@astro.bas.bg

Keywords: *Stars: binaries, white dwarfs; Stars: Symbiotic; Stars: Individual: T CrB*

Abstract

SUMMARY: In this paper, we study the physical processes between two nova outbursts of the symbiotic binary star T CrB. We present our theoretical hypothesis on the binary evolution during 80-year period between similar states of the whole cycle. Our hypothesis consists of five consequent stages. We found that during the third stage of the suggested scenario, the accretion disk is reduced, which means a higher accretion intensity. The reduced disk's radius and the donor star's orbital contraction are calculated. To support our theoretical hypothesis, we compare the current results of T CrB with our previous results of the recurrent nova RS Oph, which shows a similar model's behaviour.

Introduction

Symbiotic systems are binary stars that consist of a red giant and a white dwarf companion [1]. The matter between the components could be transferred both by Roche - lobe overflow [2] or by a stellar wind through the giant's component [3]. Later, a part of this matter is accreting onto the white dwarf primary [4]. Many symbiotic binaries manifest outburst activity. Part of them, classified as recurrent novae objects, have characteristics of the classical novae stars with an amplitude more than four magnitudes, and these outbursts repeat over time, which makes them close to the dwarf novae objects [4]. As a member of the symbiotic binary stars group, T Coronae Borealis (T CrB) is also classified as recurrent novae, based on the registered outbursts of the system's historical observations [5]. The outburst event of this binary was registered every 80 years. The mass of the white dwarf is between $1.2\pm0.2M_\odot$ [6] and $1.37\pm0.13M_\odot$ [7]. The estimations of the red giant mass give the values $0.8 \pm 0.2M_\odot$ [6] and $1.12 \pm 0.13M_\odot$ [7]. The calculated average orbital period of the binary is 227.568±0.009

days [8]. The distance to the object is determined as 890 pc (Gaia DR3 data and [9]). At this distance, the estimated rate of accretion varies for different periods. The average accretion rate for the years between 1978 and 1990 is found to be 9.6 $\times 10^{-9} M_{\odot} yr^{-1}$ [7]. While in a high state of the object (from 1980 to 1988), the accretion rate is $1.1 \times 10^{-8} M_{\odot} yr^{-1}$, and in a low state (from 1978 to 1980 and 1988 to 1990), it is $1.5 \times 10^{-9} M_{\odot} yr^{-1}$ [7]. And the accretion rate with the same power of 10^{-9} but $\approx 0.7 \times 10^{-9} M_{\odot} yr^{-1}$ is measured between the nova eruptions [10]. Photometric observations of T CrB have shown various flickering amplitudes in different bands. The largest flickering amplitudes, 0.1 - 0.5, are observed in the U band [11], while in the B and V bands, the amplitudes are smaller. If the suggested recurrent outburst period of T CrB is ≈ 80 years, we could expect the next event to occur in the years of mid 2025 and late 2026 [5]. The outburst activity in these objects is often related to the accretion disk processes, as mass-transfer stream rate variations and disk instabilities (usually the thermal viscous instability and the tidal instability) [12] and the disk's evolution as a whole. Different scenarios for the physical mechanisms that provoke various T CrB states have been suggested. The novae eruption event could be reached during the high states, when the white dwarf accumulates the ignition mass. Zamanov et al. [13] discussed the decrease in brightness before the outbursts as "a pre-outburst dip" that could be related to the formation of an envelope around the white dwarf. Schaefer [5] proposes that the pre-eruption dip is caused by the formation of circumstellar dust, which causes a dimming around the star, fainting its brightness by several magnitudes. In this paper, we study the physical processes between two outbursts of T CrB. We present our theoretical hypothesis on the binary evolution of one 80-year period between similar states (Section 2). In Section 3, the disk's radius and contraction of the orbit are calculated. We compare the results with the model of RS Oph in Section 4.

A theoretical hypothesis

Our hypothesis is constructed based on physical conditions at the possible stages through which the configuration accretion disk around the primary passes. These several stages correspond to the observational period between two outbursts. We use the historical light curve of Schaefer [5] as the basis of our theoretical scenario for the cyclic evolution of the re-nova T CrB. The cycle shows a regular alternation of five successive states (scheme - Fig.1). The stages are numbered with I - V in order of the consequences they are expected to happen. A short explanation of the process is attached to each schematic figure (See Fig.1 (I - IV)).

Here are our explanations of the whole cycle: ***Stage I***. Each cycle starts after the (nova) outburst ends, at the beginning of the relatively quiescent period. As we can see from the figures of Schaefer [5] (Figures 2, 3), the brightness of the nova decreases. We formulate this point as a starting point for Stage I of the cycle, too. Its duration is $\sim$ 10 years, in the periods of 1866-1875 and 1946-1955. During this stage, the secondary maximum after the outburst is also observed (Figure 1 of [14], [15]). Munari [15], by using radiative modeling, shows that irradiation of the red giant (RG) by a cooling white dwarf (WD) well reproduces the major contribution to the secondary maximum. Besides this, an additional continuation of this maximum is observed that the modeling does not account for it. We suppose this extension in the secondary maximum could be explained by the recovery /formation of an accretion disk in the system, see [14].

Stage II. The second stage spans the years 1875-1935 and 1955-2015. We suppose that the primordial disk develops during these observational periods after the detected outburst. The observational data show brightness variabilities with a very small amplitude [5]. This tendency remains almost steady for more than 50 years. In our assumption, these parts of the curve point to a long-lasting, stable, and stationary accretion in the primary disk. Therefore, at this stage, the standard disk model is a good enough description. That is why the disk is relatively stable in most types of instabilities (Fig.1 - II).

Transitional (II-III). Theoretically, the binary system usually emits gravitational waves, and the mass transfer between the components runs. The activity of gravitational waves can lead to a century-long evolutionary change in the orbital period's variation. Then, as a result of the gravitational emission, the components lose rotational energy, and the distance between them changes permanently. The mass transfer amplifies this effect noticeably. This external impaction creates conditions of intra-structural instabilities that destabilize the disk. The instability could force it to further reconstruction and bring the system to the next transition.

Transitional to active state. Because of the total action and interaction of the various types of instabilities in the system (magneto-rotational (MRI), elliptic (EI), etc.), some of the geometrical parameters are smoothly reduced, especially the orbit of the donor (a - semi-major axis, C - orbit's length) and the disk's radius. Both processes, the disk's reconstruction and the contracting donor's orbit, have an evolutionary effect on the II-III transitional period by shortening it to 1-2 years.

Stage III. Based on the Stage II and transition II-III, we suppose that in the new state, the disk has a smaller radius and an order of magnitude higher accretion rate, which, according to [5], reaches even 20 times the rate in state II. Then the new-sized disk is denser, optically denser, with a higher opacity and increased temperature (Fig.1 - III). Therefore, the disk is already permanently unstable. This stage prolongs $\sim 8 - 10$ years, in the time periods 1935-1945, 2015–X.

Transitional state III-IV. Tidal forces between the components can cause pulsations in the orbits, which are indicated as a combination of oscillations with precession [16]. Due to the eccentricity and/or oscillations of the donor's orbit, the disk undergoes elliptical instabilities. The cycling behavior of the donor's orbital period is the main evidence of the EI development [5]. Now the disk is in an active state, and its parameters are at a supercritical level. Therefore, a larger part of the energy released remains in the disk. The presence of such free energy enhances the activity of instabilities (mentioned in II-III) and supports the formation of microstructures (as micro-vortices) in the flow - and this way, they can slow down the flow's rotation. In this sense, Webbink [14] shows that the disk can be divided into rings, each with different viscosity. Then the following collisions between them (friction – cat eyes) completely obstruct the rotation, and the average azimuthal disk's flow velocity (v_φ) tends to zero, and this may cause the disk destruction – fragmentation.

Stage IV. At this stage (Fig.1 - IV), the disk's fragments gradually form (layering) an opaque shell around the accretor. For a short period (in the order of several months), the shell becomes symmetric and stops losing energy from irregular movements. It is feeding from the surrounding matter and continues in the form of quasi-spherical accretion until a critical mass is reached.

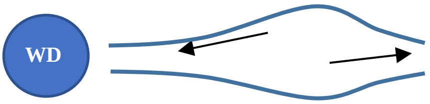
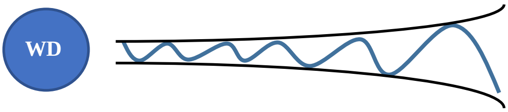
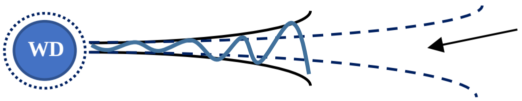
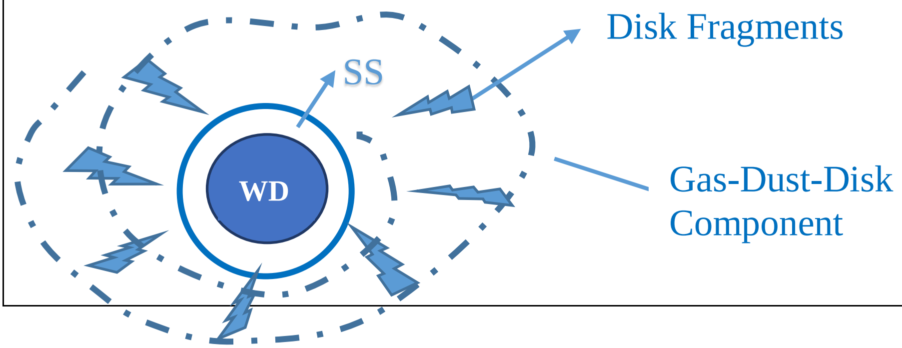
Based on ([17], [13]), they also suggest that the white dwarf accumulates an envelope, but they consider that during this phase, the disk survives, and it only recedes from the accretor.

We suppose that in this state, two mechanisms are working simultaneously: the dwarf obscuring and the absence of the high-energy source of radiation, which is a sign of the disappeared accretion disk. If the disk existed at this stage, the binary spectrum would not be so strongly reddened, despite the white dwarf being obscured by the envelope. The reddened colors (seen in Figure 2 of [17]) show that the intensity of all spectra weakens, and this happens most strongly in the B band. If the disk does not exist, the optical spectrum becomes red.

But, if the disk survived:

i. We know from the theory that the disk produces gamma and hard X-rays on the equatorial plane and re-radiates them as soft X-rays and UV rays from its surface. According to Figure 3 of [17], the existence of dust in the system is observed. However, the dust's quantity is insufficient to cause any dust obstruction and then to have an influence on the object's spectrum. On the other hand, we suppose that the disk fragments supply enough scattered matter. It will ensure that the emission of soft X-rays and UV rays from the disk's surface is scattered into the environment. Such scattering saturates the high harmonics in the optical region of the B band.

ii. ii. Detected in this state, flickering [18] could be caused by residual friction (viscosity) in the disk fragments or local collisions of material with magnetic field lines or other physical sources that do not require the existence of a complete disk structure with undisturbed rotation.

Evolutionary scheme T Coronae Borealis (T CrB)	
Stage	Period [y], possible reason
I – disk restoration (renovation) 	**≈ 10 years** 1866 -1875; 1946 -1955
II – primordial disk development 	Standard disk, stable accretion ≈ **60 years** 1875 - 1935; 1955 – 2015
II→III transition	1-2 **years**
III – reduced disk, 0.88% 	Active state: Intensive accretion **≈ 8 - 10 years** 1935 - 1945, 2015--;
III→IV transition 	

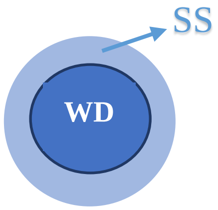
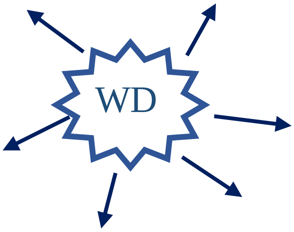
<table>
<tr><td colspan="2"></td></tr>
<tr><td>IV

</td><td>IV – pre-outburst dip: missing disk
WD+ super-shell (SS) atmosphere,
1 - 2 yrs.</td></tr>
<tr><td>V – A Recurrent novae stage

</td><td>1 - 2 months
(0.08 - 0.17 yrs.)</td></tr>
<tr><td></td><td></td></tr>
<tr><td>I – a new cycle starts</td><td>A New 80 yrs. cycle</td></tr>
</table>

Fig. 1. Schematic view of the evolutionary stages. The images show the equatorial profile of the accretor, with and without accretion disk: Stage I – disk's renovation; Stage II - standard disk; Stage III - the full-sized disk is represented with the dashed line and the reduced disk (RD) with the solid line; III-IV – transitional stage; Stage IV - presents a white dwarf with a super-shell (SS); Stage V - a recurrent nova.

Degrees of the disk radius reduction and the orbital contraction

An interaction of a set of mechanisms affects the binary components' separation as they become closer to each other and the radius/length of the donor's orbit decreases. We call this "an orbital contraction" (see Section 2). During the transitional II-III stage, we assume a reduction in some of the parameters of the system. Here, we can estimate the degree of these reductions.

We use the fluctuations in the orbital period from observations [5] and from the 3rd Kepler's law:

(1) $$\frac{(\Delta P)^2}{P^2} \sim \frac{(\Delta a)^3}{a^3}$$

We can roughly estimate the degree of orbital contraction to be around ≈ (0.88±0.01) % for a full cycle; where the denotations are standard: a is the distance between the components (or orbital separation); and P is the orbital period; we denote the variations in **a** and **P** with Δa and ΔP.

We accept that the processes of the disk's reconstruction are the main reason for the disk's transition to a new state. In addition, the narrowed orbit of the donor affects the disk, as it compresses its outer sides and thus the disk's decrease in size is stimulated. The disk reconstruction, by the instabilities activity, contributes to a more intensive accretion.

We can estimate the degree of the disk's reduction using the expressions of the disk's accretion efficiency [19]:

(2) $$L_{acc} = \eta_{acc}\dot{M}c^2$$

Where η is the accretion efficiency; L_{acc} is the accretion luminosity; c is the speed of light; and $\dot{M}$ is the accretion rate. The luminosity, by the Stefan-Boltzmann law, is:

(3) $$L = 4\pi R^2 \sigma T^4$$

In the case of the accretion disk, however, the luminosity increases inward towards the accretor and therefore has an inverse dependence on the radius:

(4) $$L_{acc} \sim \frac{T^4}{R_d^2}$$

Where σ is the Stefan-Boltzmann constant, R_d is the disk radius, and T is the effective temperature.

Then, from Eqs. 2 and 4, we obtain the next relations:

(5) $$\frac{L_r}{L_p} = \frac{\dot{M}_r}{\dot{M}_p} = \frac{R_p^2}{R_r^2}\frac{T_r^4}{T_p^4}$$

where an index "p" corresponds to the disk in the II-nd stage and "r" for the III-rd stage (see the cycle presented in Section 2).

Using the values for these two discs states from [5]:
$\dot{M}_p = 3.2 \times 10^{-9} M_\odot yr^{-1} = 2.2 \times 10^{17} gs^{-1}$; $\dot{M}_r = 6.4 \times 10^{-8} M_\odot yr^{-1} =$
$= 4.5 \times 10^{18} gs^{-1}$; $T_p = 1.3 \times 10^3 K$; $T_r = 2.4 \times 10^3 K$.
We calculate the radius reduction as: $R_r \approx (0.77 \pm 0.01) R_p$

Comparison with the behavior of the recurrent novae model of RS Oph. Discussion

To support the model behaviour, we could compare the disk's reduction degree and other evolutionary stages of T CrB with those of similar objects. We observe a similar evolutionary behaviour of another symbiotic binary, RS Oph [20, 21], a member of the same subclass of the recurrent novae group. The recurrent nova outbursts of RS Oph happen in approximately every 15-20 years, with a brightness variability of ≈ 11 to 6 magnitudes in the V band. The novae outbursts could result from thermonuclear processes on the white dwarf's surface or by accretion disk instabilities as in the dwarf-nova-like objects [22].

Here, for comparison, we use the solutions for the global and local structures of the RS Oph's disk in two evolutionary moments, similar to stages 2 [21] and 3 [20]. The obtained value of R_r for RS Oph is different: $R_r \approx (0.1 \pm 0.01) R_p$, by applying $R_{out} = 100 R_{wd}$ [20] and $R_{out} = 10^3 R_{wd}$ [21], but the basic concept of the cycle is the same as the one proposed for T CrB in the current paper. The higher value of the reduction rate in the RS Oph disk could be enhanced by additional physical factors.

The model for this object also shows a disk reduction, but the observational proof is still unavailable. Due to the similarity of both objects, considering the archival picture for RS Oph would give an answer to whether the cycle really exists, whether it is regular, and whether all the presented stages have been developed in it.

In a plan, it will be necessary to track as many spectral bands as possible in photometry and spectroscopy, which are running during the progress of the T CrB cycle. Thus, a more detailed picture of the accretion disk throughout the various evolutionary phases would be obtained. Suitable disk models to explain the evolution in the third stage, such as an advection disk or models with different activity controlling mechanisms, can also be proposed.

The disk's fragmentation, which we proposed in stage IV, can also be observed in other objects with various physical conditions, such as self-gravitating systems [23].

In all cases considered in this paper, the mechanism that controls the instabilities' activity is not in a dominating regime, and it allows the microstructures to fragment the disk.

Conclusions

Based on the review of the historical observations of Schaefer [5], we build a theoretical hypothesis on the possible evolution of the recurrent nova T CrB for one period of a full 80-year cycle between two identical states. This hypothesis consists of five evolutionary stages. We estimated the degrees of the accretion disk's radius reduction in the second stage, where the accretion rate is higher. We obtained the disk's radius reduction to be $\approx (0.77 \pm 0.01)$ of the primordial disk's radius and the orbital contraction value to be $\approx (0.88 \pm 0.01)$ %. We compared the results with the recurrent nova RS Oph, which in our research [20, 21] showed an analogous model's behavior for the second and third evolutionary stages. Our estimates are relative and presented in percentages. The real values of the chosen parameters vary in each new cycle. Since the behavior of the binary star is regular during each of the cycles, the relative estimations stay unchanged.

References

1. Kenyon, S. J. 1990, Astronomical Society of the Pacific Conference Series, Vol. 9, Cool Stars, Stellar Systems, and the Sun, ed. G. Wallerstein, 206 10.48550/arXiv.2308.04104), 5
2. Frank, J., King, A., and Raine, D. J. 2002, Accretion Power in Astrophysics: Third Edition
3. Munari, U. 2019, Cambridge Astrophysical Series: The Impact of Binary Stars on Stellar Evolution, 54, 77
4. Warner, B. 2003, Cataclysmic Variable Stars, Cambridge University Press
5. Schaefer, B. E. 2023, MNRAS, 524, 3146
6. Belczynski, K. and Mikolajewska, J. 1998, MNRAS, 296, 77
7. Stanishev, V., Zamanov, R., Tomov, N., and Marziani, P. 2004, A&A, 415, 609
8. Fekel, F. C., Joyce, R. R., Hinkle, K. H., and Skrutskie, M. F. 2000, AJ, 119, 1375
9. Bailer-Jones, C. A. L., Rybizki, J., Fouesneau, M., Demleitner, M., and Andrae, R. 2021, AJ, 161, 147
10. Luna, G. J. M., Nelson, T., Mukai, K., and Sokoloski, J. L. 2019, ApJ, 880, 94
11. Sokoloski, J. L., Bildsten, L., and Ho, W. C. G. 2001, MNRAS, 326, 553
12. Lasota, J. P. 2001, NewAR, 45, 449
13. Zamanov, R. K., Marchev, V., Marti, J., and Latev, G. Y. 2023, arXiv e-prints, (DOI:
14. Webbink, R. F. 1976, JAAVSO, 5, 26
15. Munari, U. 2023, arXiv e-prints, https://arxiv.org/pdf/2311.15909, https://doi.org/10.48550/arXiv.2311.15909
16. Guo, Z., Shporer, A., Hambleton, K., and Isaacson, H. 2020, ApJ, 888, 95
17. Schaefer, B. E., Kloppenborg, B., Waagen, E. O., and Observers, T. A., 2023, The Astronomer's Telegram, 16107, 1
18. Zhekov, S. A. and Tomov, T. V. 2019, MNRAS, 489, 2930
19. Kolb, U. 2010, Extreme Environment Astrophysics
20. Yankova, K. 2019, in Eleventh Workshop on Solar Influences on the Magnetosphere, Ionosphere and Atmosphere, ed. K. Georgieva, B. Kirov, and D. Danov, 60-64

21. Yankova, K. 2023, Publ. Astron. Soc. “Rudjer Bošković”, 25, 179
22. Alexander, R. D., Wynn, G. A., King, A. R., and Pringle, J. E. 2011, MNRAS, 418, 2576
23. Portegies Zwart, S. F. 2016, MNRAS, 457, 313

ХИПОТЕЗА ЗА ЕВОЛЮЦИЯТА НА ДВОЙНАТА И ДИСКА ЗА ПЕРИОДА МЕЖДУ ДВЕ ИЗБУХВАНИЯ В T CrB

К. Янкова , Д. Бонева и Р. Заманов

Резюме

В тази статия ние изучаваме физическите процеси между две нова-избухвания на симбиотичната двойна звезда T CrB. Представяме нашата теоретична хипотеза за еволюцията на двойната през 80-годишен период между подобни състояния на целия цикъл. Нашата хипотеза се състои от пет последователни етапа. Установихме, че по време на третия етап от предложения сценарий акреционният диск е редуциран, което означава по-висока интензивност на акрецията. Изчисляват се редуцираният радиус на диска и орбиталното свиване на звездата-донор. За да подкрепим нашата теоретична хипотеза, сравняваме настоящите резултати от T CrB с нашите предишни резултати за повтарящата се нова RS Oph, която показва подобно моделно поведение.