Proceedings of the XIII Bulgarian-Serbian Astronomical Conference
(XIII BSAC) Velingrad, Bulgaria, October 3-7, 2022
Editors: Evgeni Semkov, Milan S. Dimitrijević, Momchil Dechev and Zoran Simić
Publ. Astron. Soc. "Rudjer Bošković" No 25, 2023, 17-25

ON THE ACCRETION EFFICIENCY, DISC'S DENSITY AND TEMPERATURE DISTRIBUTION OF TWO BINARY STARS

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Abstract. In this work, we present our study on the accretion disc' properties of two binary stars: the semi - regular (SR) symbiotic variable NQ Gem and the nova-like system V592 Cas. We apply observational data from both the National Astronomical Observatory (NAO) Rozhen and the American Association of Variable Star Observers (AAVSO). Using color indices from the observations, the color temperatures of the two objects are calculated.

A disc's surface temperature and density distribution in relation to the disc radius are presented. An accretion efficiency is estimated, based on the relation between luminosity and a rate of accretion. We trace changes in efficiency in three possible modes – disc accretion, spherical-like accretion and a two-stream feeding.

We discuss on the currently active mass transfer mechanisms between the binary components. This could be relevant to the type of accretion that is dominant for each of the objects, wind or disc accretion.

1. INTRODUCTION

Studying the properties and parameters of accretion discs could give more detailed view on the whole binary star structure.

The disc's density and surface temperature distributions give an information about the accretion disc's state. To evaluate them, we employ the Kurucz model and the model of D'Alessio and Merin (D'Alessio 1998, 1999). They work with the stars' and discs main parameters, as: mass of the central object M_1; radius of the primary star; disc radius; temperature. The calculations following the model read the assumptions that the heating is both from the stellar radiation and from viscous dissipation due to accretion. The involved into the model equations consider the disc emission. The detailed vertical disc's structure is also included.

An estimation of accretion efficiency is important, because it has a close relation to the emitted energy and has a further role in binaries evolution. An advantage to know the accretion rate is the possibility to estimate the mode of accretion and the possible transition between them.

For the purpose of this paper, we chose to study two binary stars. The first object NQ Gem is classified as a symbiotic star (catalogue of Belczyński et al. (2000)) and belongs to the variables of the Z Andromedae type. They are close binaries that consist of a hot star and a star of a late type. Influenced by the hot star's radiation, an existence of extended envelope is very possible. The Spectral types of those objects are usually C6 or CH3. They are known as "carbon stars" with an excess of carbon in their atmosphere (Bondi 1952).

NQ Gem has a long orbital period and it is found to be 1308 days (Carquillat and Prieur 2008), and its eccentricity is e = 0.182. The mass of the white dwarf or the object's primary component is estimated as M1 ~ 0.6 M⊙ (Luna et al. 2013). This star shows periodicity in its light curves variabilities, but with appearance of irregularity in the brightness with amplitudes 1-2 mag. A long observational period is necessary to detect this peculiarity, usually from 20 to even more than 2000 days. The magnitude range of NQ Gem is in a range 7.4−8.18 in V. Pulsations in its light curves are found, with a pulsation period Ppul ~ 58(±1) days (Gromadzki et al. 2013). The star has also been attached to the group of X-Ray symbiotic binaries (Donahue et al. 1996).

The second object V592 Cas is a Nova like (NL) system and it consists the late-type main-sequence secondary and white dwarf primary. The components are interacting via a warped and tilted accretion disc (Taylor et al. 1998; more generally see also Wood et al. 2000; Murray et al. 2002). V592 Cas is a low-inclination (i =28 deg, Huber et al. 1998) type Cataclysmic variable (CV), with an orbital period of 0.115063(1) d (Taylor et al. 1998), (Witherick et al. 2003) at a distance of 360 pc. The accretion rate of V592 Cas varies in between 9×10^{-9} M⊙ yr^{-1} (Taylor et al. 1998) and 1.3×10^{-8} M⊙ yr^{-1}, estimated by (Ringwald & Naylor 1998). The object exhibits an episodic bipolar wind outflow. V592 Cas shows a behavior of an orbital modulation in the velocity extended UV lines profiles, typical for some cataclysmic variables.

Some systems' parameters of the two objects, necessary for the calculations in this paper, are given in Table 1. The references in brackets are applied below the table.

Table 1: Basic parameters of two binary stars V592 Cas and NQ Gem, used in the calculations: $\mathbf{M_1}$ and $\mathbf{R_1}$ are the mass and radius of the primary components in the Solar masses; **L** - the luminosity of V592 Cas, in the solar luminosity; the X-ray luminosity value of NQ Gem is **Lx**; **Teff** is the effective temperature of V592 Cas; $\acute{M}d$ is the disc accretion rate; $\acute{M}sph$ is the spherical accretion rate.

Parameters ------------ **Object**	$\mathbf{M_1}$ **[M⊙]**	$\acute{M}sph$ **[M⊙/y]**	$\acute{M}d$ **[M⊙/y]**	**Porb [days]**	$\mathbf{R_1}$ **[R⊙]**	**L [L⊙]**	**Teff [K]**
NQ Gem	0.6 [6]	---	1.02 x 10^{-8} [6]	1308 [3]	0.03 ≈ Rm [2]	0.2 = Lx [6]	7.2×10^4 ≈ Tm [2]
V 592 Cas	0.75 [4]	5×10^{-10} [5]	1.3×10^{-8} [7]	0.115 [7, 8]	0.01 [4]	0.012 [1]	45000 [4]

[1] Balman, Şölen et al. [2] Boneva and Yankova 2021; [3] Gromadzki et al. 2013; [4] Hoard et al. 2009; [5] Kafka et al. 2009; [6] Luna et al. 2013; [7] Ringwald & Naylor 1998; [8] Witherick et al. 2003.

We consider a shock inflow process, locally onto the accretion stream. In this reason, two additional parameters for NQ Gem are included in the table. **Rm** is the distance from the place with maximum accretion rate to the central object (or primary star). The effective temperature in this place is ***Tm***.

In the next Section 2, consisting of four subsections, we present the obtained results from calculations of density and temperature, color indices and accretion efficiency. We compare the results for V 592 Cas and NQ Gem.

2. RESULTS

2.1. The surface density distribution and temperature variations against the disc radius and time.

The model used for the calculations of the surface density and temperature (see the Introduction) has some limitation of the input parameters' values. One has limit of the primary star effective temperature: Teff = 4000K – 10000K. In this reason it is applicable for NQ Gem, only. The input value of Teff into the model is 4000 K, which is a maximum allowed for this object (Kipper et al. 1996).

In the result, the distribution of both the surface density and two types of the calculated temperatures (the surface Tsurf and the viscous Tvisc) has the form as in Figures 1a and 1b.

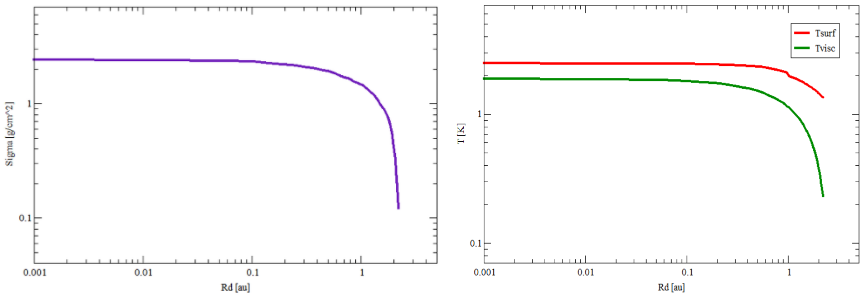

Figure 1: The surface density distribution against maximum disc radius (*left*). The two temperatures (the disc surface Tsurf and the viscous Tvisc) distribution against maximum disc radius (*right*). The input effective temperature for the model calculation is = 4000K. The plotted values in both figures are in a logarithmic scale. The result is applicable for NQ Gem.

As it is seen in the figure, both the surface density and the viscous temperature Tvisc start to decline at the radii larger that 1 AU, while the surface temperature Tsurf remains more stable throughout the disc's structure. This could mean that only a small part of the inner disc formation is active for the objects like NQ Gem.

2.2. Color index and color temperature.

To obtain the color index B-V, we use observational data performed with NAO Rozhen for V592 Cas and AAVSO (American Association of Variable Star Observers) for both objects. The observational times are different for two objects, according to their activity periods and available data. For V 592 Cas it is: JD 2459027 – 2459070 and for NQ Gem: JD 2452287-2453480.

The obtained B-V index for NQ Gem is in the range: 1.88 - 2.07(±0.002) and the values are in agreement with the results of Kipper et al. 1996 (2.06) and Zamanov et al. 2022 (2.01).

For V592 Cas, we combined data from both observational sources. In the result, we obtain: (B-V) = 0.15 (± 0.043) - 0.207 (± 0.053). These values differ from the index by Tailor et al. (1998), where the star is estimated as bluer for other observational period. Further, using the B-V index we estimate the color temperature (Tcol) for two objects, by using the formula of Ballesteros (2012):

$$(1)\; T = 4600K \times \frac{1}{(0.92(B-V)+1.7)} + \frac{1}{(0.92(B-V)+0.62)}$$

Then, all the values of obtained color indices and color temperature are given in Table 2.

Table 2: Color index (B-V) and color temperature Tcol of NQ Gem and V 592 Cas, based on observational data.

Parameter / Object	**B-V (min) [mag]**	**B-V (max) [mag]**	**Tcol (B-V) [K]**	**Time [JD]**
NQ Gem	2.070 ± 0.005	1.885 ± 0.002	(3098 ± 160) -- (3299 ± 176)	2453310 -- 2453480
V 592 Cas	0.381 ± 0.05	0.151 ± 0.043	(8109 ± 200) -- (8571 ± 200)	2459027 -- 2459070

From the estimated color indices (B-V), we see that the color of both objects are rather red during the studied observational time. With a tendency for higher values of the color temperature, V 592 Cas shows it is a hotter star.

2.3. An accretion efficiency estimation.

The effciency ***η*** expresses the amount of energy gained from the matter with mass ***m***, in units of its mass energy (Kolb 2010). It measures how e□ciently the mass energy, c^2 per unit mass, of the accreted material is converted into radiation. The accretion e□ciency η_{acc} is defined by the expression:

(2) $\eta_{acc} = \frac{GM_1}{R_1 c^2}$,

$$\eta_{acc} = \frac{GM_1}{R_1 c^2} \eta_{acc} = \frac{GM_1}{R_1 c^2}$$

obtained by the expressions of accretion luminosity:

(3) $L_{acc} = \frac{GM_1 \acute{M}}{R_1}$ and $L_{acc} = \eta_{acc} \acute{M} c^2$

Where M_1 and R_1 are the mass and radius of the primary star; G is the gravitational constant; c is the speed of light; $\acute{M}$ is the accretion rate. We also use the relation between the luminosity *L* and the effective temperature *Teff*, by the Stefan-Boltzmann's law:

(4) $L = 4\pi R_{R1}^2 \sigma T_{eff}$

The changes in efficiency could be traced in three possible modes: disc accretion - ***η***, spherical-like accretion - *ξ* and a two-stream feeding - *ξ*+***η***. Since, equation (2) gives the efficiency of the disc' accretion, we should obtain expressions for the other two modes. First, we apply equations of the related accretion rates: disc and spherical. If we denote the accretion rate in general case with $\acute{M}$, then $\acute{M}_d$ expresses the disc accretion, by the equation (5), based on (Frank et al 2002):

$$(5)\ \acute{M}_d = 2\pi R_{R1}\Sigma(-V_r),$$

where Vr is the radial velocity of the stream, Σ is the surface density; R_{R1} represents the distance to the central object (in some cases, it coincides with the radius of the primary or the disc inner radius). Further, the spherical accretion rate could be expressed as (Bondi 1952, Edgar 2004):

$$(6)\ \acute{M}_{sph} = \pi R_{R1}^2\rho(-V_r),$$

$\boldsymbol{\rho}$ is a volume density in this case. The ratio of the spherical accretion efficiency ξ to the efficiency of the disc accretion - $\boldsymbol{\eta}$ can be expressed as a relation between the two types of accretion rate:

$$(7)\ \frac{\xi}{\eta} = \frac{\acute{M}_d}{\acute{M}_{sph}}$$

Then for the efficiency of the spherical accretion we can write:

$$(8)\ \xi \approx \left(\frac{4H_d}{R_d}\right)\eta$$

Where $\boldsymbol{H_d}$ is the full half disc thickness and the whole disc radius is $\boldsymbol{R_d}$. We obtain the minimum and maximum values of the ratio, as: $4H_d/R_d = [0.04; 0.2]$. Our estimation for NQ Gem gives the value ≈ 0.16 and for V 592 Cas it is ≈ 0.14.

Next, the parameters' values of V 592 Cas and NQ Gem (see Table 1) are applied into the Equations (2-8). An important note for the calculations of NQ Gem is that we are using the effective temperature ***Tm***, measured in the place with maximum accretion rate at ***Rm*** (see the explanations in the Introduction).

The obtained values of the accretion efficiency in the three suggested accretion modes are given in Table 3:

Table 3: The mean values of accretion efficiency calculated for both objects in the three suggested accretion modes: ξ for spherical accretion, **η** - for disc accretion, and a sum of both **η** + ξ expresses the two-stream feed accretion.

Object/Mode	**1**	**2**	**3**
X 10 $^{-4}$	ξ	η	ξ+η
NQ Gem	0.20 ± 0.02	1.28 ± 0.12	1.50 ± 0.14
V 592 Cas	0.16 ± 0.02	1.17 ± 0.11	1.28 ± 0.13

We see that the values for NQ Gem and V 592 Cas are similar. The distribution of accretion efficiency throughout the development of accretion modes is represented in Figure (2).

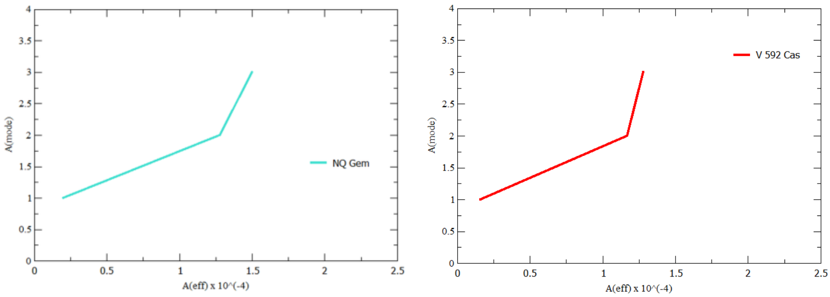

Figure 2: A growth of accretion efficiency A(eff) against the development of accretion modes A(mode), 1(ξ), 2(η) and 3(η + ξ), for two objects. For NQ Gem (*left*) and for V 592 Cas (*right*).

These two empirically created figures depict a slow and smoothly increase of the spherical accretion efficiency, while the growth of the efficiency in the disc accretion mode is sharper.

2.4. Mass-transfer between the components.

The matter transfers between the binary stars' components usually in two currently known ways. When one of the stars increases in the radius and fills its Roche lobe, the matter overflows through the Lagrange point L1 (Frank et al. 2002). The further product of this interaction could be the formation of accretion flow or an accretion disc. In some binary stars, one of the components throws out much of its material in a form of a stellar wind, which could be later attracted by the gravitational field of the primary star. By a relation to the accretion efficiency parameters' values, we could give a point to a currently active mass-transfer mechanism in the two binary stars studied here.

In the Novae like object V 592 Cas, a precessing accretion disc around the primary component is observed (Long 2003). This might be not a main, but a possible reason for the relatively low values of the disc's accretion efficiency. We give a suggestion that in this binary, the stream from the secondary is transferring through the Lagrange point L1. A pseudo-spherical inflow is also possible to contact the outer parts of the accretion disc.

A reason of the relatively higher efficiency of NQ Gem could be that the parameters' calculations are performed for the zone with a maximum accretion rate. The activity of NQ Gem in X-ray luminosity could be contributed by the mass transfer via the stellar wind (see also Boneva & Yankova 2021).

3. CONCLUSIONS

In this paper, we presented some accretion disc properties for two binary stars: V 592 Cas and NQ Gem. Based on the irradiated disc model, the density and temperature distribution is estimated for NQ Gem.

Using observational data, we compared the color indices and color temperatures of V 592 Cas and NQ Gem.

We estimated the accretion efficiency variations of the two studied objects, on the three considered accretion modes: spherical accretion, disc accretion and a two-stream feed accretion. The results showed that the growth of disc efficiency of V592 Cas is sharper than that of NQ Gem, but both objects have a smoothly development of accretion efficiency throughout the modes.

Acknowledgements

This work is partially supported by the grant “Binary stars with compact object”, КП-06-Н28/2 08.12.2018 (Bulgarian National Science Fund).

The authors thank the AAVSO (American Association of Variable Star Observers) for providing the data of Light Curve Generator, contributed by observers worldwide and used in this research.

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