Accretion disks in symbiotic stars

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Resumen / En general, el mecanismo de acreción en sistemas simbióticos, donde una gigante roja transfiere materia a su compañera enana blanca, es difícil de observar y existen más posibilidades de hacerlo en aquellos sistemas donde no hay quema nuclear cuasiestable de material en la superficie de la enana blanca. Utilizando datos en altas energías, que permiten observar las regiones más internas del proceso de acreción, hemos estudiado dos eventos sin precedentes en dos sistemas simbióticos, RT Cru y T CrB, con masas de objeto compacto similares, pero con diferentes períodos orbitales lo que implica diferentes mecanismos de acreción.
Durante los últimos 20 años, se observaron dos aumentos de brillo en el óptico en RT Cru, separados por aproximadamente 4000 días y con una amplitud de ΔV$\sim$1.5 mag. Aunque similar a erupciones tipo *dwarf-nova*, el comportamiento en rayos X duros no se condice con lo observado en prototipos de la clase *dwarf-novae*. Alternativamente, estos eventos podrían explicarse si la tasa de acreción aumenta a medida que la enana blanca orbita dentro del viento de la gigante roja, con un período orbital de $\sim$4000 días.
En T CrB hemos observado un incremento en la tasa de acreción, el cual ha cambiado dramáticamente la estructura de la parte más interna del disco. Datos en óptico, UV y rayos X sugieren que el aumento de brillo en óptico que se registró en 2014 junto con la abrupta disminución del brillo en rayos X duros y la aparición de una componente *soft* en rayos X, indican que este evento, debido a una inestabilidad en el disco de acreción, podría ser similar a otro evento observado 8 años antes de la explosión termonuclear de 1946.

Abstract / The nature of accretion in symbiotic binaries, in which the red giant transfers material to a white dwarf (WD) companion, has been difficult to uncover. The accretion flows in a symbiotic binary are most clearly observable, however, when there is no quasi-steady shell burning on the WD to hide them. Through observations in the high energy regime, which provide a view of the innermost accretion structures, we have studied two unprecedented events in two systems, RT Cru and T CrB, which host similar massive white dwarf but have very different orbital periods with correspondingly different accretion mechanism.
In the past 20 years, RT Cru has experienced two similar optical brightening events, separated by $\sim$4000 days and with amplitudes of ΔV$\sim$1.5 mag, reminiscent of dwarf-novae-type outbursts, but the hard X-ray behavior does not correspond to that observed in well-known dwarf nova. An alternative explanation for the brightening events could be that they are due to an enhancement of the accretion rate as the WD travels through the red giant wind in a wide orbit, with a period of about $\sim$4000 days.
We have witnessed a change in the accretion rate for the first time in the symbiotic recurrent nova T CrB. Optical, UV and high energy data indicate that during an optical brightening event that started in early 2014 (ΔV$\approx$1.5), the hard X-ray emission has almost vanished and the X-ray spectrum became much softer and a bright, new, blackbody-like component appeared. We suggest that the optical brightening event, that could be a similar event to that observed about 8 years before the most recent thermonuclear outburst in 1946 is due to a disk instability.

Keywords / binaries: symbiotic — accretion, accretion disks — stars: individual (RT Cru, T CrB)

1. Introducción

White dwarf symbiotic stars are binary systems composed of an accreting white dwarf, a mass-lossing red giant and a nebulae that surrounds the system. The accretion mechanism/s in symbiotic stars is believed to be mostly due to some form of wind accretion, with a few exceptions where there is evidence of Roche-lobe overflow. A few symbiotic stars have X-ray emission sometimes hard and bright enough to be detected with the Neil Gehrels *Swift Observatory* Burst Alert Telescope (BAT). The hard X-ray spectrum is most likely due to a hot, highly absorbed, optically thin thermal plasma from the accretion disk boundary layer. Given the large size of the accretion disk, it should be prone to instabilities (Duschl, 1986). In fact, variability is virtually a hallmark of symbiotic stars. Large amplitude novae-type outburst are detected in those few symbiotic stars that belong to the recurrent novae class, where the sudden brightening is due to a thermonuclear runaway on the WD surface (see e.g. O'Brien et al., 2006, and references therein). Somewhat smaller outburst, known as classical symbiotic outburst, are also common and their origin is still a matter of debate (see e.g. Sokoloski et al., 2006; Kato et al., 2012). Outbursts with even smaller amplitude are observed in most symbiotic stars, likely due to instabilities in the accretion disks.

Here we present the observations of two symbiotic binary systems, RT Cru and T CrB, each one representing a case of the two accretion mechanisms. In both systems we have detected significant changes in their hard X-ray flux as observed with the *Swift*/BAT, which, together with changes in their X-rays/UV/optical fluxes, can be explained as due to a change in the accretion rate through the accretion disk. However, the overall behavior of both systems is fundamentally different. In T CrB we observed that in early 2014, an optical brightening with ΔV$\sim$1 mag started and was referred as a "super-active" state by Munari et al. (2016). The light curve from the AAVSO indicates that the maximum brightness was reached around 4–5 April 2016 (see Figure 1 in Luna et al., 2018a). Almost in tune with the optical brightness increase, the *Swift*/BAT 14–50 keV flux declined from $\sim$4 mCrab to $\sim$2 mCrab, and then exhibited a sudden drop to 0 (within 1 sigma) until now. The 0.3–10 keV X-ray flux has decreased significantly and the UV flux increased by at least a factor of 40 over the quiescent value. A deep *XMM–Newton* observation taken well into the super-active state revealed a complex spectrum (Fig. 1) that can be divided into three energy ranges. Above 3 keV, there is a highly absorbed thermal component, likely the same δ-type component seen in T CrB in its normal state (Kennea et al., 2009; Luna et al., 2013). Below $\sim$0.7 keV, the spectra are dominated by a soft, unabsorbed component. A blackbody provide an good description of this region. Photons are also detected in the intermediate energy range (0.7–3 keV). All components are absorbed by interstellar absorption and local, partial covering absorption that blocks 99.7 % of the emission. The softest X-ray spectrum consists of blackbody-like emission (with $T_{\rm bb}$=4$\times$10^5 K) from a region smaller than the surface of the WD, with a spherical surface area of 4.2$\times$10^7 km^2 (in the case of a WD with 1.2 M$_\odot$ and $R_{\rm WD}$=5$\times$10^8 cm, this represents approximately 13 % of the surface of the WD). The hard (0.6< E <10 keV) spectra were consistent with a multi-temperature, cooling flow, with maximum temperature $kT_{\rm max}$=12.9 keV.

In RT Cru we observed that the optical light curve shows two similar brightening events separated by $\sim$4,000 days. In contrast with T CrB, during the second event, *Swift* detected an increase in the BAT hard X-ray flux of at least a factor of two Luna et al. (see Figure 1 in 2018b). Interestingly, the hardness ratio within the BAT band remained fairly constant. During bright states, such as those seen during 2001 and 2012, lines from the Balmer series, He I λ5875, He II λ4686, [O III] λ5007 and other highly ionized species are strong, with a moderately bright continuum dominating at longer wavelengths. In turn, during faint optical states, Hα and other lines were very faint or absent in the spectra, with the red giant continuum prevailing toward longer wavelengths (see Figure 4 in Luna et al., 2018b). Our *NuSTAR* observations taken during a low-optical state allowed us to detect for the first time in a symbiotic system, a clear signature of reflection in the hard X-ray spectrum, with an amplitude of 0.77$\pm$0.21. This detection allows us to accurately determine the plasma shock temperature with a value of $kT_{\rm max}$=53$\pm$4 keV, which in the case of strong shock conditions and optically thin boundary layer, can be translated into a WD mass of 1.25$\pm$0.02 M$_\odot$.

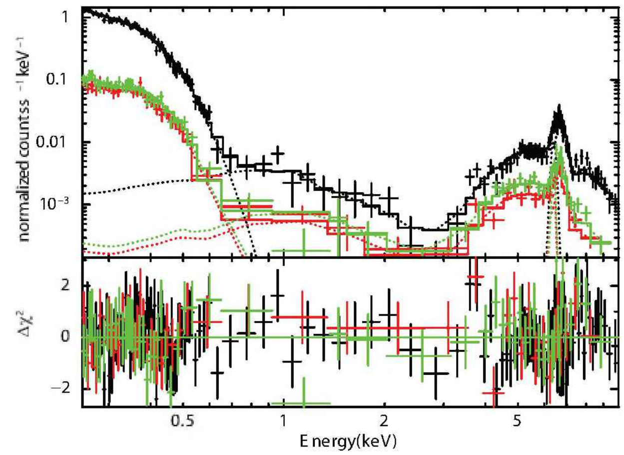

Figure 1: *XMM*-Newton *pn* (black), MOS1 (red), and MOS2 (green) X-ray spectra of T CrB data with the best spectral model (solid line) and the contribution of each model's component (dotted lines). The model consists of a blackbody plus an optically thin cooling-flow and a Gaussian profile centered at the Fe Kα energy of 6.4 keV. The fit residuals in units of χ^2_ν are shown in the bottom panel.

2. Consequences of changing $\dot{M}$

A major question for accreting WDs, particularly in those accreting at rates around 10^{-9} $M_\odot$ yr^{-1}, is the structure of the boundary layer. At lower $\dot{M}$, the boundary layer should remain optically thin to its own radiation and emit entirely in the hard X-rays regime, with temperatures of a few 10^8 K. At high $\dot{M}$, the boundary layer is expected to become optically thick, and begin radiating with temperatures of less than 10^6 K, in the extreme UV/soft X-rays. The threshold where the boundary layer becomes optically thin or thick has been modeled in some cases. Narayan & Popham (1993) concluded that when $\dot{M}$=3.16$\times$10^{-10} $M_\odot$ yr^{-1}, the boundary layer would be hot and a source of hard X-rays, with a transition to this regime starting at $\dot{M}$ $\sim$10^{-10} $M_\odot$ yr^{-1}. In their study of optically thick solutions for the boundary layer in cataclysmic variables, Popham & Narayan (1995) derived $\dot{M}$ values for the transition for different values of M$_{WD}$, Ω and the viscosity parameter α. By assuming that the transition would occur at τ_*=1, the authors found that in a non-rotating WD, the transition accretion rate at τ_*=1, $\dot{M}(\tau_* = 1)_{tr}$, would occur at rates greater than about 7.5$\times$10^{-7} $M_\odot$ yr^{-1}. A slightly smaller optical depth, τ_*=0.8 yielded $\dot{M}(\tau_* = 0.8)_{tr}$=4.6$\times$10^{-8} $M_\odot$ yr^{-1}. Suleimanov et al. (2014) found that these thresholds might be overestimated due an underestimation of the Rosseland opacity which can be off by two orders of magnitude.

We suggest that the optical brightening event observed in T CrB, which could be similar to that observed about 8 years before the most recent thermonuclear outburst in 1946, is due to a disk instability. The changes observed in optical, UV and X-rays demonstrate that after early 2014, the rate of mass transfer onto the WD, $\dot{M}$ increased and the boundary layer became predominantly optically thick. We modeled the X-ray spectrum with all components absorbed by interstellar absorption and local, partial covering absorption that blocks 99.7 % of the X-rays. The soft X-ray spectrum is modeled with a blackbody-like emission. The hard spectrum was modeled with a multi-temperature, cooling flow. In fact, at a distance of about 800 pc (as recently determined with *GAIA*), the blackbody-emitting region has a luminosity of 6.68×10^{35} ergs s^{-1}. Assuming an standard accretion disk where half of the accretion luminosity is radiated in the boundary layer, we found that the accretion rate feeding the optically thick portion of the boundary layer was about 6.6×10^{-8} $M_\odot$ yr^{-1}. The luminosity of the optically thin portion of the boundary layer, from the cooling flow spectral model in the 0.3-50 keV, was 4.7×10^{32} ergs s^{-1}. These accretion rates are consistent with the expected theoretical values where the boundary layer is optically thick/thin to its own radiation (Patterson & Raymond, 1985; Narayan & Popham, 1993; Popham & Narayan, 1995).

The multiwavelength behavior in RT Cru is different from disk instability, dwarf-novae type outbursts, which have a rapid rise to maximum, the time-lapse of which is determined by the distance between the region in the accretion disk where the instability has started and the boundary layer. In RT Cru, it took approximately 2000 days from optical minimum to maximum, but a similar delay was not observed between optical and hard X-rays. The prototypical dwarf nova SS Cyg (Wheatley et al., 2003) exhibits a hardening of the X-ray spectrum during optically faint phases, which can be explained if the accretion rate is low and the optical depth of the boundary layer is small. During outburst, the X-ray spectrum softens due to the increase of the accretion rate, similarly to what we have observed in T CrB. Such softening of the X-ray emission is not observed during the optical brightening in RT Cru. The constancy of the hardness ratio observed with BAT indicates that the temperature of the hard X-ray emitting plasma has not changed during the optical brightening. The optical brightening around JD 2451870 and the re-brightening approximately 4 000 days later could, nevertheless, have been due to disk instabilities such as those behind dwarf novae-type outbursts, if the accretion rate did not change enough to greatly increase the optical depth of the boundary layer. Our simultaneous *Swift* XRT and UVOT observations suggest that the boundary layer has remained optically thin throughout the optical brightening and thus the derived accretion rate of $\approx4.1\times10^{-9}$ $M_\odot$ yr^{-1} is still below the optically thick/thin threshold.

In Fig. 2 we show the phase-folded AAVSO+ASAS light curve with a period of 3 992 d (best period found through phase-dispersion minimization) and we include an auxiliary color scale for the observation to clearly highlight the time of phase coincidence. The fact that not only the maximum but also the fading rate after it seem to repeat, suggest that there could be a periodicity.

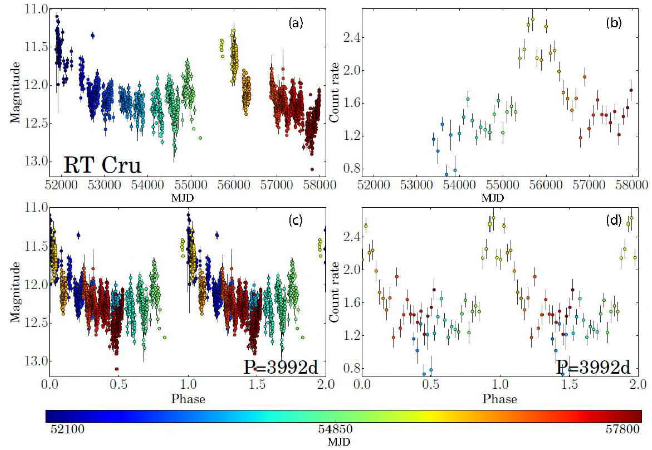

Figure 2: *(a)*: AAVSO+ASAS *V* magnitude light curve. *(b)*: *Swift*/BAT light curve in 10^{-4} count s^{-1}, with 100 d bin size. *(c)* AAVSO+ASAS *V*-magnitude light curve folded at a period of 3 992 d. *(d) Swift*/BAT light curve at a period of 3 992 d. We include an auxiliary color scale to clearly highlight the time of phase coincidence. The observations cover a single cycle, which is not enough to obtain a secure determination of its likelihood. However, the fact that the maximum and the fading rate seem to repeat, suggests that the periodicity could be real.

Until more data are available, this is only speculative. If this is indeed a periodic behavior, it could be a long orbital period and in such a case, the optical and high-energy brightening could be explained if the accretion rate onto the WD increases when it "travels" through the densest part of the red giant's wind.

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References

Duschl W.J., 1986, A&A, 163, 56
Kato M., Mikołajewska J., Hachisu I., 2012, ApJ, 750, 5
Kennea J.A., et al., 2009, ApJ, 701, 1992
Luna G.J.M., et al., 2013, A&A, 559, A6
Luna G.J.M., et al., 2018a, A&A, 619, A61
Luna G.J.M., et al., 2018b, A&A, 616, A53
Munari U., Dallaporta S., Cherini G., 2016, NewA, 47, 7
Narayan R., Popham R., 1993, Nature, 362, 820
O'Brien T.J., et al., 2006, Nature, 442, 279
Patterson J., Raymond J.C., 1985, ApJ, 292, 535
Popham R., Narayan R., 1995, ApJ, 442, 337
Sokoloski J.L., et al., 2006, ApJ, 636, 1002
Suleimanov V., et al., 2014, A&A, 571, A55
Wheatley P.J., Mauche C.W., Mattei J.A., 2003, MNRAS, 345, 49