Dissecting a Disk-instability Outburst in a Symbiotic Star: NuSTAR and Swift Observations of T Coronae Borealis during the Rise to the “Superactive” State

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Abstract

The current superactive state of the recurrent nova T Coronae Borealis (T CrB) has been observed with unprecedented detail. Previously published observations provide strong evidence that this state is due to an enhancement of the flow of material through the accretion disk, which increased the optical depth of its most internal region, the boundary layer. NuSTAR and Swift observed T CrB in 2015 September, roughly halfway through the rise to optical maximum. In our analysis of these data, we have found that: (i) the UV emission, as observed with Swift/UVOT in 2015, was already as bright as it became in 2017, after the optical peak; (ii) the soft X-ray emission ($E \lesssim 0.6$ keV) observed in 2017 after the optical peak, on the other hand, had not yet developed during the rising phase in 2015; (iii) the hard X-ray emitting plasma ($E \gtrsim 2$ keV) had the same temperature and about half the flux of that observed during quiescence in 2006. This phenomenology is akin to that observed during dwarf novae in outburst, but with the changes in the spectral energy distribution happening on a far longer timescale.

Key words: accretion, accretion disks – binaries: symbiotic – X-rays: binaries

1. Introduction

Depending on the rate at which material flows through the accretion disk, the optical depth of its most internal, non-Keplerian region can be large or small. This region, known as the boundary layer, would thus be optically thin or thick to its own radiation. A change in the accretion rate would change this condition. In dwarf novae (where a white dwarf (WD) accretes from a dwarf companion that orbits the WD with a period of hours), a thermal instability of the accretion disk changes the rate at which matter flows through the disk. On the rise to the outburst (optical high state), this typically happens in about 1 day, while during the decay, the transition usually takes several days. In dwarf novae, the transition from optically thin to thick regimes during outbursts manifests itself as an increase in the optical/soft-X-ray/extreme ultraviolet (EUV) flux and a decrease in the hard X-rays (Wheatley et al. 2003).

In WD symbiotic binaries, such as T Coronae Borealis (T CrB), a WD accretes from a red giant companion that orbits the WD with a period of hundreds of days to years, an ~astronomical unit-size accretion disk might form around the WD. Symbiotic stars often experience brightening episodes with changes of 2~3 mag in the optical light curves, known as symbiotic classical outburst (see e.g., Kenyon 1986). Interpretations for the origin of such outbursts include WD photospheric expansion at constant luminosity due to an accretion rate that is above the value for stable surface nuclear burning (Tutukov & Jungelson 1976); a shell flash (Kenyon & Truran 1983); a disk instability as in dwarf-nova outburst (Duschl 1986); or some combination of these phenomena (Sokoloski et al. 2006). Because many WDs in symbiotic binaries are intrinsically very luminous in the optical–EUV due to quasi-steady shell burning on their surfaces, changes in the accretion disk itself are often difficult to observe directly.

T CrB, however, is also a recurrent nova (Schaefer 2010), indicating that accreted material does not burn quasi-steadily on the surface of the WD. Nova eruptions (in which accreted hydrogen is suddenly ignited on the WD surface) took place in T CrB in 1866 and 1946; the presence of more than one nova outburst within a century likely indicates that T CrB hosts a massive WD accreting at a high rate from its red giant companion, although not high enough to produce quasi-stable nuclear burning on the WD surface. This lack of quasi-steady burning furnishes an important opportunity to diagnose the behavior of a WD accretion disk that is orders of magnitude larger than the WD disks in CVs.

In Luna et al. (2018a), we determined that a small optical brightening event ($\Delta V \sim 1$) that started in early 2014 (Munari et al. 2016) was due to an increase in the rate of accretion through the disk, which caused the boundary layer to become optically thick. The observed phenomenology, which consisted of a softening of the X-ray spectrum and the appearance of a blackbody component, a fading in the hard X-ray flux and an increase in the UV brightness confirmed, for the first time in a symbiotic binary, that this event was due to an increase in the accretion flow through the disk, similar to a disk-instability dwarf-nova outburst.

In this paper, we present contemporaneous X-ray observations of T CrB obtained with the NuSTAR and the Neil Gehrels Swift observatories. Both observations occurred during the rising phase of the recent optical brightening (see Figure 1), after which most of the boundary layer became optically thick. We use these observations to characterize the properties of the outburst, the timescale for the transition as manifested at
Various wavebands, and the accretion rate at which these occurred. We also revisit the 2006 Suzaku spectrum (hereafter Suzaku2006) to assess any long-term changes in the accretion rate and absorbing structures of the system. Throughout the paper we assume a distance to T CrB of $800_{-30}^{+30}$ pc, from the parallax measurement published in Gaia DR2 (Bailer-Jones et al. 2018).

2. Observations and Data Reduction

2.1. NuSTAR

We observed T CrB with the NuSTAR satellite on 2015 September 23 for a total of 79.8 ks (hereafter NuSTAR2015), well into the rising phase of the latest optical brightening event. We used the NUPRODUCTS v0.3.0 software to extract both spectral and light-curve products, resulting in a spectrum and light curve for each FPMA and FPMB units. Source events were extracted from a 70″ circular region centered on $\alpha = 15^h 59^m 30.160$ and $\delta = +25^\circ 55' 12.59'$, while background events were extracted from an equally sized circular region off-source. The resulting spectra were binned to have a minimum of 25 counts per bin.

2.2. Swift

The Swift satellite observed T CrB twice during the NuSTAR2015 observation (ObsID 00081659001 and 00081659002, hereafter Swift$^1_{2015}$) and a week later (ObsID 00045776003 and 00045776004, hereafter Swift$^2_{2015}$). The total duration of the combined exposures of Swift$^1_{2015}$ was 9853 s and of Swift$^2_{2015}$ is 2953 s. Data products were created by first combining the event files from the two observations and then...
extracting source events from a circular region of radius 20 pixels centered on the SIMBAD coordinates of T CrB, and background events from an off-source circular region with a radius of 80 pixels. The ancillary response files were created using the xrtmkarf tool.

During these same observations, we also obtained UVOT images in the U (λ3465 Å, FWHM = 785 Å) and UVW2 (λ1938 Å, FWHM = 657 Å) filters. T CrB was bright enough to saturate the UVOT detector, resulting in severe coincidence losses that meant that source brightness could not be estimated using the standard photometry tools in HEASoft. Instead, we utilized the readout streak in the images to estimate the source brightness (Page et al. 2013).

3. Results

3.1. X-Ray Spectral Analysis

The NuSTAR2015 spectra are well suited to looking for evidence of reflection of X-rays from the WD surface. We explored possible models for T CrB by jointly fitting the two NuSTAR2015 modules and the Swift2015/XRT data (Figure 2). The short exposure time and low number of counts detected during the Swift2015 observation did not provide a significant improvement to the joint fit. We fit the NuSTAR2015 spectra in the range 3–78 keV, and the Swift2015/XRT spectrum in the range 0.3–10 keV. For models that include reflection we used the reflect model in XSpec, which calculates the reflection of X-rays from neutral material using the method of Magdziarz & Zdziarski (1995). The angle between the line of sight and the reflecting surface normal (θ) is a key parameter in the reflection model, but Magdziarz & Zdziarski (1995) showed that cos(θ) = 0.45 provided a reasonable approximation for a wide range of θ (18°–76°; see their Figure 5). For the specific case of the WD surface reflecting X-rays from an equatorial boundary layer, θ will be close to 90 if the binary is very close to exactly face on (binary inclination i ∼ 0), while for an edge-on system, what we need is the average over azimuth changing from θ = 90° to 0° back to 90°, with real systems being intermediate cases. Done & Osborne (1997) evaluated this average for SS Cyg (assumed i ∼ 37°) and estimated the average θ to be close to 60° (so cos(θ) ∼ 0.5); for T CrB, with a higher binary inclination, this will be somewhat lower. However, given the relatively slow dependence of reflection on cos(θ) in this regime, we have fixed it to the Xspec default value of 0.45 in our analysis. To use the reflection model, we must extend the energy response over which XSpec evaluates the model. For T CrB, we need to do this well beyond the NuSTAR2015 response. We chose 200 keV as the high energy cutoff, and model in 400 linear bins using the command energies extend,200.0,400.0,lin in XSpec.

Given our knowledge of the current superactive state, which is most likely due to an enhancement of the accretion rate through the disk and an increase of the optical depth of the boundary layer (Luna et al. 2018a), we considered that both complex absorption and reflection could be at play. Our preferred spectral model that fits the NuSTAR2015 + Swift2015 spectrum includes both a partial covering absorber and reflection, i.e., TBabs × (partcov × TBabs) × (reflect × mkcfw + Gauss). In this model, X-rays from the accretion disk boundary layer are attenuated by two high column density absorbers, one of which partially covers the source. This complex absorbing system was required to explain the lack of X-rays below 2 keV, and to reproduce the high energy curvature observed in the XIS and HXD Suzaku2006 spectra. We find a statistically acceptable fit to the NuSTAR2015 + Swift2015 data with the Suzaku2006 model; the best-fit parameters are shown in the first column (“Complex absorption only”) of Table 1. This model yields a shock maximum temperature of kT_max = 40 ± 3 keV and a reflection fraction of 1.1 ± 0.2 (model “Both” in Table 1).

Using the more up-to-date absorption model TBabs (Wilms et al. 2000), we also fit the spectra using the model that Luna et al. (2008) fit to the Suzaku2006 spectrum, i.e., TBabs × (partcov × TBabs) × (mkcfw + Gauss). In this model, X-rays from the accretion disk boundary layer are attenuated by two high column density absorbers, one of which partially covers the source. This complex absorbing system was required to explain the lack of X-rays below 2 keV, and to reproduce the high energy curvature observed in the XIS and HXD Suzaku2006 spectra. We find a statistically acceptable fit to the NuSTAR2015 + Swift2015 data with the Suzaku2006 model; the best-fit parameters are shown in the first column (“Complex absorption only”) of Table 1. This model yields a very high column density for the partial covering absorber of 1.62 × 10^{24} cm^{-2}. The high column densities on the order of 10^{24} cm^{-2} and 10^{23} cm^{-2} of the partial and full covering absorbers, respectively, imply that, for the photons created behind the absorber, only those above 10 keV are being transmitted. This is the energy range precisely where reflected X-rays from the WD surface are expected to be observed. Furthermore, with a column density in excess of 10^{24} cm^{-2}, the partial covering medium is itself optically thick enough to be a reflecting surface for X-rays. The results of X-ray spectral fitting using models without an explicit reflection component thus suggest that significant reflection was indeed present in the spectrum.

We therefore also tested simpler models in which the high energy X-ray spectral shape was due only to reflection of X-rays near the WD surface, with no complex absorption. We modeled this in Xspec as TBabs × (reflect × mkcfw + Gauss). In this scenario, the cooling flow component is reflected by material near the WD surface, which modifies its shape above 10 keV. Finally, the Gaussian component models the 6.4 keV Fe Kα line, which is also due to reflection but is
not included in the reflect model. The resulting fit is also statistically acceptable, with $\chi^2$/dof = 1.06/1091. The best-fit maximum temperature of the cooling flow was $kT = 39 \pm 2$ keV, and the accretion rate through the optically thin X-ray plasma was lower than the value returned from the model “Complex Absorption Only,” $M_{\text{thin}} = 4.8 \pm 0.2 \times 10^{-10} M_\odot \text{yr}^{-1}$. The absorber had a column density of $3.2 \times 10^{25} \text{cm}^{-2}$, and the reflection fraction was $1.8 \pm 0.3$. We disfavor this model based on the results from the $r$-s test when compared with the model that includes both reflection and absorption (see Table 1).

The $Suzaku_{2006}$ data alone cannot probe the presence of reflection due to the systematic uncertainties in the HXD background spectrum, which are energy-dependent. We can, however, apply the knowledge about reflection onto our model. We derived from the NuSTAR2015 data to the $Suzaku_{2006}$ spectrum. Fixing the reflection fraction to 1.1 (as we found for the NuSTAR2015 data), we find a maximum temperature for the cooling flow in 2006 ($kT = 43 \pm 3$ keV) that is very similar to that in 2015. The normalization for this model was slightly higher than for the NuSTAR2015 observation, suggesting a higher accretion rate through the optically thin portion of the boundary layer of $M_{\text{thin}} = 7.7 \pm 0.5 \times 10^{-10} M_\odot \text{yr}^{-1}$.

To summarize our spectral results: (i) the distribution of fit residuals, as measured by the $r$-s test statistic, indicates that the model that includes reflection and complex absorption is preferable over other models; (ii) both the NuSTAR2015 and $Suzaku_{2006}$ spectra can be described by highly absorbed cooling flow models. There is clear evidence of reflection in the NuSTAR2015 spectrum, and including this source of emission in the $Suzaku_{2006}$ data resulted in acceptable model fits. The maximum temperature of the cooling flow was similar in 2006 and 2015, but the $Suzaku_{2006}$ data implies a slightly higher accretion rate through the optically thin part of the boundary layer in 2006.

### 3.2. UVOT Data Analysis

First, we used the readout streak method on the Swift UVOT data to estimate count rates through the U and UVW2 filters (corrected for coincidence losses) of 0.220 and 0.070 c s$^{-1}$, or Vega system magnitudes of 10.1 and 10.33, respectively. We used the UVW2 values to estimate the broadband UV flux of T CrB at the time of the NuSTAR2015 observation, which we take as a proxy of its disk luminosity.

Previously, Selvelli et al. (1992) analyzed the International Ultraviolet Explorer (IUE) observations of T CrB from 1979 January 5 through 1990 February 9. They estimated the 1250–3200 Å flux (hereafter $F_{UV}$) for each pair of SWP and LWP/LWR spectra, assuming a reddening of $E(B - V) = 0.15$, and showed that T CrB was highly variable in the UV during the IUE era: $F_{UV}$ ranged from $6.9 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ (on 1989 August 1) to $1.33 \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$ (on 1983 May 1; see their Table 1). They measured an increase in $F_{UV}$ from $1.57 \times 10^{-10}$ to $3.02 \times 10^{-9}$ erg cm$^{-2}$ s$^{-1}$ between 1989 March 2 and April 8, so T CrB is demonstrably capable of a factor of almost two change in approximately one month.

These IUE observations provided low-resolution, wide-band spectroscopy covering the 1250–3200 Å range, and the Swift UVOT data provide filter photometry in a small part of the IUE band. We downloaded archival IUE data from MAST, already reduced and fluxed, and combined short and long-wavelength spectra that were taken on the same day or on nearby dates. We folded them through the UVOT filter effective area curve to predict the magnitude that would have resulted, had Swift UVOT observations taken place during the IUE era. We also made our own estimates of $F_{UV}$ during the 1980s, by dereddening the IUE spectra using $E(B - V) = 0.15$ and integrating over the 1250–3200 Å range. Our values are similar to those found by Selvelli et al. (1992), although often ∼10% lower. This may be due to different reduction and/or

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**Table 1**

|        | Complex Absorption Only | Reflection Only | Both   | Complex Absorption Only | Reflection Only | Both   |
|--------|-------------------------|-----------------|-------|-------------------------|-----------------|-------|
| $N_{\text{HI}}$ (ISM) (10$^{22}$ cm$^{-2}$) | 0.05             | 0.05            | 0.05  | 0.05                    | 0.05            | 0.05  |
| $N_{\text{HI}}$ (int.) (10$^{22}$ cm$^{-2}$) | 32 ± 5           | 32 ± 1          | ...   | 27 ± 2                  | 22 ± 3          |       |
| $N_{\text{HI}}$ (P.C.) (10$^{22}$ cm$^{-2}$) | 162 ± 80         | ...             | 43 ± 3 | 49 ± 5                  | 32 ± 3          |       |
| Covering Fraction                      | 0.4 ± 0.1        | ...             | 0.93 ± 0.06 | 0.71 ± 0.05           | 0.8 ± 0.1       |       |
| $kT_{\text{max}}$ (keV)                 | 42 ± 5           | 39 ± 2          | 40 ± 3 | 49 ± 3                  | 43 ± 3          |       |
| $M_{\text{thin}}$ (10$^{-6}$ $M_\odot$ yr$^{-1}$) | 0.9 ± 0.1        | 0.48 ± 0.02     | 0.55 ± 0.02 | 0.93 ± 0.07           | 0.77 ± 0.05     |       |
| EW$_{\text{FeK}_{\alpha}}$ (eV)         | 191 ± 2          | ...             |       | 138 ± 2                 |                 |       |
| $Z/Z_{\odot}$                          | 1.00 ± 0.01      | 1.01 ± 0.01     | 1.04 ± 0.09 | 1.04 ± 0.08           | 1.03 ± 0.09     |       |
| Reflection Fraction                     | ...              | 1.8 ± 0.3       | 1.1 ± 0.2 | ...                   | 1.1            |       |
| $\chi^2$                                | 1.1              | 1.06            | 1.01   | 1.01                    | 1.06           |       |
| d.o.f                                  | 1090             | 1091            | 1090   | 1322                    | 1321           |       |
| Flux                                   | 0.95 ± 0.02      | 0.50 ± 0.01     | 0.58 ± 0.01 | 1.00 ± 0.05           | 1.11 ± 0.01     |       |
| Luminosity                             | 7.4              | 3.89            | 4.5    | 7.8                     | 8.7            |       |
| Runs Statistic*                        | −2.50            | −1.22           | −1.16  | ...                    |                |       |

Note. Unabsorbed X-ray flux and luminosity, in units of 10$^{-10}$ erg s$^{-1}$ cm$^{-2}$ and 10$^{33}$ erg s$^{-1}$, respectively, are calculated in the 0.3–50 keV energy band. Elemental abundances are quoted in units of abundances from Wilms et al. (2000). Luminosity and $M$ are determined assuming a distance of 800 pc. Statistical errors are calculated at the 90% confidence level. Systematic errors between Suzaku and NuSTAR are of about 5%–10% depending on the energy range (Madsen et al. 2017).

* The Runs test evaluates if the fit residuals are randomly distributed above and below zero. We tested if the hypothesis that the residuals are randomly distributed can be rejected at the 5% significance level, with higher values of abs(Runs) indicating the hypothesis can be rejected.

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8 https://archive.stsci.edu/iue/
involves extrapolation of the source spectrum, which we do not power law photometry to the results of Selvelli et al. e.g., the dereddening process. The only other caution regarding calibration. Going in the other direction, from above mentioned minor issues of exact reduction procedure and 43

fl to be 10.33 extrapating the bright in the UV during the current high state, we are be interpreted with caution because given that T

UVOT magnitudes from Swift comparison with ours. These values should though imperfect proxy for the luminosity of the Keplerian disk.

4. Discussion

From the light curves presented in Figure 1 we can identify a few different stages during the brightening phase (Figure 4). As mentioned in Luna et al. (2018b), in the optical, the brightening started early in 2014 and reached its maximum in 2016 April. We identify this as the rising phase from a mostly optically thick boundary layer, which thus took about two years. During the optical rising phase, UV observations were taken along with the NuSTAR2015 observation in 2015 September and a week later. These observations show that the UV flux had already risen to the value it attained during the 2016 optical high state by 2015 September, before the completion of the optical rise. We identify this as the first sign that a heating wave had reached the inner disk. The next change appeared in the BAT light and softness ratio curves (panels (b) and (c) in Figure 1), where a significant softening of the high energy emission started about 60 days after the NuSTAR2015 (2015) observation and about 650–700 days after the beginning of the optical outburst.

The UV luminosity of T CrB at the time of the NuSTAR2015 observation was at least 5–10 times higher than the hard X-ray luminosity, depending on the X-ray spectral model we use (see Table 1). This ratio could have been even higher if there was a substantial bolometric correction (i.e., if a substantial fraction of disk luminosity was emitted shortward of 1250 Å). The hard X-ray luminosity, on the other hand, represents that of the optically thin portion of the boundary layer. Thus, we find ourselves in the familiar position of trying to understand the missing boundary layer luminosity “problem” (van Teeseling et al. 1996).

Here we consider two broad categories of solutions for the missing boundary layer “problem” in T CrB. If the boundary layer was completely optically thin at the time of the NuSTAR observation in 2015, the accretion rate through the boundary layer must have been lower than that through the UV emitting portions of the accretion disk. Alternatively, the boundary layer may already have been partially optically thick in 2015 September. In the paragraphs that follow, we take these possibilities in turn.

If the entirety of the boundary layer of T CrB was optically thin at the time of the NuSTAR2015 observation, in which case its full luminosity would have been expected to appear in the hard X-rays, we need an explanation for the observational result that the boundary layer was significantly less luminous than the Keplerian disk at that time. Perhaps the brightening of T CrB started in the outer disk (either due to an increased mass transfer rate from the donor or due to an outside–in disk instability), and the increase in the local accretion rate was propagating inward through the disk, similar to the familiar
heating wave of the disk-instability model, creating a delay between the UV and X-ray brightenings. To quantify the magnitude of any such delay, we start by making a rough estimate of the location of the UV emitting region in the accretion disk. A 20,000 K blackbody has a spectral shape that peaks in the UV, and a spherical source with a radius of $10^{10}$ cm has a blackbody luminosity of just over $1.0 \times 10^{34}$ erg s$^{-1}$. The inferred UV luminosity of $\sim 3.5 \times 10^{34}$ erg s$^{-1}$ therefore implies that the UV emission has a radius of less than $2 \times 10^{10}$ cm (a temperature significantly lower than 20,000 K would imply a larger radius for the same total luminosity, but much of the emission would shift into the optical range). In the case of a symbiotic system, this corresponds to the inner region of the disk, although comparable to the total size of a CV disk. For this scenario to explain the low $L_{\text{UL}}/L_{\text{disk}}$ ratio during the optical rise, the heating wave must have reached the $R \sim 10^{10}$ cm region of the disk but not yet reached the boundary layer. In fact, judging by the later Swift$_{2015}$ observation as well as the low-time-resolution Swift BAT light curve, the delay between the heating wave reaching the inner part of the Keplerian disk and the boundary layer would have been at least 60 days. This is significantly longer than the duration of the transition we observe in dwarf novae, which takes about 2 days (see e.g., Wheatley et al. 2003). Therefore, we disfavor this scenario.

The alternative is that the boundary layer of T CrB was partially optically thick at the time of the NuSTAR$_{2015}$ observation. In this scenario, we must explain why the X-ray characteristics of T CrB were so different in 2015 (NuSTAR$_{2015}$ and 2017 (XMM-Newton observations; hereafter XMM-Newton$_{2017}$). The boundary layer of T CrB was demonstrably fully optically thick in 2017, based on three characteristics (Luna et al. 2018a). Most importantly, we directly observed a soft, optically thick, blackbody-like X-ray emission component. We also found that the hard X-ray flux was dramatically lower than in prior observations. Finally, the hard X-ray component was significantly softer than in prior observations, with $kT_{\text{max}}$ of about 13 keV. The latter two characteristics of the boundary layer in 2017 are frequently seen in dwarf novae in outburst (see Mukai 2017 for a review). Given that the boundary layer was fully optically thick in 2017 and inconsistent with being fully optically thin in 2015, we favor the scenario in which it was partially optically thick in 2015.

With T CrB showing evidence for a partially optically thick boundary layer in 2015, it is worth asking whether X-ray observations at that time revealed any direct evidence of soft, blackbody emission from the boundary layer, or a decrease in the temperature of the hard X-ray component (both of which are associated with optically thick boundary layers). Unfortunately, we were not sensitive to blackbody emission at the expected level. The upper limit on the luminosity of a blackbody component in 2015 (during the NuSTAR$_{2015}$ observation), based on Swift$_{2015}$ XRT data and taking the

![Figure 4. Schematic view of the inner accretion disk and at the different stages that lead to the current superactive state. (a) Inner accretion disk and boundary layer state before 2014 April, when $\log \dot{M} \leq 10^{-9} M_\odot$ yr$^{-1}$. (b) State as of 2015 September, with $\log \dot{M} = 4 \times 10^{-9} M_\odot$ yr$^{-1}$, when NuSTAR+Swift observations suggest that the boundary layer started its transition to the optically thick regime. (c) Superactive state, with most of the boundary layer being optically thick, as observed with XMM-Newton in 2017 February (Luna et al. 2018b).](image-url)
temperature we derived from the XMM-Newton\textsuperscript{2017} data, is $2 \times 10^{34}$ erg s$^{-1}$. Whereas this upper limit on any blackbody X-ray emission in 2015 is more than an order of magnitude lower than the 2017 soft X-ray luminosity of $L_{bb} = 6.6 \times 10^{35}$ erg s$^{-1}$ (derived from the XMM-Newton\textsuperscript{2017} spectrum), it is of the same order as the inferred UV Keplerian disk luminosity in 2015, and if the effective temperature in 2015 was lower than during the XMM-Newton\textsuperscript{2017} observation, an even higher luminosity soft component could have been hidden. Regarding the hard X-ray component in 2015, however, we can clearly see that it was not significantly softer or fainter than that recorded in 2006 (Suzaku\textsuperscript{2006}). T CrB therefore showed very different behavior than dwarf novae in outburst. In dwarf novae, the emergence of the soft X-ray component, UV brightening, the reduction in hard X-ray luminosity, and the softening of the hard X-ray spectrum all occur suddenly at a single transition point, as was famously seen during the rise to the outburst peak in the dwarf nova SS Cyg (Wheatley et al. 2003).

Whereas the transition of the boundary layer from optically thin to thick during the rise to the outburst peak of dwarf novae appears sharp, the transition from thick to thin during the decay is slower and perhaps also more complicated (Wheatley et al. 2003). We speculate that, perhaps, the optically thick boundary layer begins to emerge at one accretion rate, at which the characteristics of the residual hard X-rays are not immediately altered. The drop in hard X-ray luminosity and the softening of this optically thin component might happen at a higher accretion rate. Both changes appear to happen simultaneously during the rise of a dwarf-nova outburst because the accretion rate through the boundary layer increases so sharply in a matter of hours. In contrast, the accretion rate changes more slowly during outburst decay of dwarf novae, and in symbiotic stars, as demonstrated by the slow optical brightening of T CrB. In this interpretation, we caught the system at a very special time: after the initial emergence of UV emission from the optically thick boundary layer but before the optical depth had increased enough to have a dramatic effect on the properties of the hard X-ray component.

4.1. The Transition Accretion Rate, $\dot{M}_{\text{trans}}$

A major question for accreting WDs, particularly those accreting at rates of around $10^{-9} M_\odot$ yr$^{-1}$, is the accretion rates at which the boundary layer transitions (or begins to transition) from optically thin to thick ($\dot{M}_{\text{trans}}^1$) regimes and vice versa ($\dot{M}_{\text{trans}}^2$). These transition accretion rates are a function of $M_{\text{WD}}$ and are closely tied to the assumed structure of the boundary layer. Observational constraints on them can thus provide insight into boundary layer structure. Given that the timescale for the transition in one direction has been observed to be different from the timescale of the transition in the opposite direction in dwarf novae, it seems reasonable to suspect that the accretion rates for these transitions could also be different. However, only a few theoretical predictions of these thresholds exist. For the purpose of comparing observations with theory, we return here to the simple picture in which all the empirical indicators of a boundary layer transition from optically thin to thick for a particular system appear at a single accretion rate $\dot{M}_{\text{trans}}^1$, and all the empirical indicators of a boundary layer transition from optically thick to thin appear at a distinct, single accretion rate $\dot{M}_{\text{trans}}^2$. Narayan & Popham (1993) concluded that when $\dot{M} = 3 \times 10^{-10} M_\odot$ yr$^{-1}$ and $M_{\text{WD}} = 1 M_\odot$, the boundary layer is generally expected to be optically thin, hot, and a source of hard X-rays, with a transition from this regime starting at $\dot{M}_{\text{trans}}^1 \sim 3 \times 10^{-9} M_\odot$ yr$^{-1}$ (assuming a WD rotational speed of $\Omega = 0.5$). At $M \gtrsim \dot{M}_{\text{trans}}^1$, Narayan & Popham (1993) found the boundary layer to be optically thick.

Later, Popham & Narayan (1995) studied the optically thick solutions for the boundary layers in CVs and derived values of $\dot{M}_{\text{trans}}^2$ during the decay of an outburst for different values of $M_{\text{WD}}$. By assuming that the transition would occur at $\tau_a = 1$ (which includes opacity from free–free absorption from a fully ionized gas and electron scattering), the authors found that in a nonrotating WD, the transition would occur at a rate of $7.5 \times 10^{-7} M_\odot$ yr$^{-1}$ (for a $1 M_\odot$ WD). Taking a definition of $\dot{M}_{\text{trans}}^2$ with a slightly smaller optical depth, $\tau_a = 0.8$, yielded $\dot{M}_{\text{trans}}^2(\tau_a = 0.8) = 4.6 \times 10^{-8} M_\odot$ yr$^{-1}$ for the same WD mass. Suleimanov et al. (2014) found that these thresholds might be overestimated due to an underestimation of the Rosseland opacity which might have previously been underestimated by two orders of magnitude.

Assuming that the WD mass can be estimated from the maximum cooling flow temperature in the X-ray spectral model that we refer to as “Both,” we derive a mass for the WD in T CrB of at least 0.115 $\pm$ 0.03 $M_\odot$; in this case the theoretical models from Popham & Narayan (1995) predict an $\dot{M}_{\text{trans}}^1$ of about $4.6 \times 10^{-8} M_\odot$ yr$^{-1}$ (taking $\tau = 0.8$). The observations with XMM-Newton in 2017 (XMM-Newton\textsuperscript{2017}) indicated an accretion rate of $M \sim 6.6 \times 10^{-8}$ at that time (Luna et al. 2018a). Observations during the end of the current state will therefore be crucial to test the theoretical prediction for $\dot{M}_{\text{trans}}^1$

Observations of six dwarf novae compiled by Fertig et al. (2011) during quiescence and outburst showed that the observationally derived $\dot{M}_{\text{trans}}^1$ are much lower than the theoretical values predicted by Popham & Narayan (1995). Moreover, the $\dot{M}_{\text{trans}}^1$ for these six dwarf novae are different from each other, ranging from $\sim 1.6 \times 10^{-10} M_\odot$ yr$^{-1}$ in the case of SS Cyg to $\sim 1.2 \times 10^{-11} M_\odot$ yr$^{-1}$ in the case of U Gem. Note, however, that Fertig et al. (2011) implicitly assumed a single $\dot{M}_{\text{trans}}^1$, and took the highest recorded luminosity of the optically thin X-rays as corresponding to that $\dot{M}_{\text{trans}}^1$. If the emergence of an optically thick boundary layer and the decrease in luminosity of the optically thin X-ray component happens at different transition $M$, this procedure does not provide an unambiguous result. The behavior of U Gem is unusual for a dwarf nova, and is a case in point: it has simultaneously exhibited a detectable soft component from the optically thick boundary layer and an enhanced optically thin X-ray component during outburst (see, e.g., Mattei et al. 2000). During the 1993 December/1994 January outburst observed with the Extreme-Ultraviolet Explorer (EUVE) three times, the soft component persisted to an estimated accretion rate of $3 \times 10^{-10} M_\odot$ yr$^{-1}$ (scaled to a distance of 100 pc) so that could be taken as an indicator of $\dot{M}_{\text{trans}}^1$ (Long et al. 1996).

On the other hand, the hard X-ray component does not disappear in U Gem even when the accretion rate through the boundary layer exceed $5 \times 10^{-9} M_\odot$ yr$^{-1}$, if all outbursts of U Gem are similar to each other.
4.2. The Long-term Accretion Rate in T CrB and Implications for the Next Nova Eruption

We observed an increase in accretion rate of several orders of magnitude between 2004 and 2018 (Luna et al. 2018a). Other evidence, primarily from IUE spectra obtained between 1979 and 1989, suggests that the accretion rate is generally variable by at least an order of magnitude (Selvelli et al. 1992). Observations obtained with Galaxy Evolution Explorer using the far ultraviolet (FUV) (\(\lambda_{1528}\) Å; \(\Delta\lambda_{1442}\) Å) filter in 2006 July, show that the luminosity in the FUV filter was about \(L_{\text{FUV}} = 2.2 \times 10^{31} \text{(d/800 pc)}^2\) (deriving the flux in the FUV band using \(g_{\text{Photon}}\); Million et al. 2016). If this luminosity is roughly half of the available accretion luminosity, then the accretion rate at that time in 2006 was \(2.2 \times 10^{-10} M_\odot \text{yr}^{-1}\) (and with \(L_{\text{BL}}/L_{\text{disk}} \approx 1\), the boundary layer was optically thin). Theoretical nova outburst models, such those presented by Yaron et al. (2005), predict that for a WD with a mass of about \(1.0 M_\odot\), accreting at \(\sim 10^{-8} M_\odot \text{yr}^{-1}\), a nova outburst is produced every \(\geq 2 \times 10^5\) yr (see their Tables 2 and 3). The observed recurrence time of \(\sim 80\) yr in T CrB requires either a higher WD mass and average accretion rate, or a highly variable accretion rate. The episode of increased \(M\) reported in Luna et al. (2018a) might not have been unique, and similar events might have passed unnoticed.

5. Conclusions

The NuSTAR and Swift observations taken in 2015, during the rising phase of the current optical brightening allow us to estimate the accretion rate at which the boundary layer started to transition from an optically thin to an optically thick regime. This occurred at \(M_{\text{trans}} \approx 4 \times 10^{-9} (d/800 \text{ pc})^2 M_\odot \text{yr}^{-1}\). We found that the soft X-rays observed after the optical maximum in XMM-Newton2017 had not yet appeared during the observations in 2015, discussed here. However, the UV emission had already become as bright as after the optical peak. The ratio of UV to X-ray luminosities, which we take to be a proxy for the optical depth of the boundary layer (Luna et al. 2013), was much greater than 1 in 2015. Without the information provided by the later XMM-Newton2017 observation, we would have concluded that the boundary layer was mostly optically thick to its own radiation. However, the hard X-ray emission, which arises from the optically thin portion of the boundary layer, had not yet changed significantly. Even though the accretion rate through the disk had increased enough by mid-2015 that the Keplerian portion shone mostly in UV, the boundary layer took at least several tens of days more to undergo all of the changes usually associated with the transition to high state in dwarf novae. Our findings highlight how a key difference between symbiotic stars and cataclysmic variables—the size of the accretion disk—appears to impact phenomena close to the surface of the WD.

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