Voracious vortexes in cataclysmic variables

II. Evidence for the expansion of accretion disc material beyond the accretor’s Roche-lobe

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Abstract

Context. In our earlier paper we showed that the accretion disc radius of the dwarf nova HT Cas in its quiescent state has not changed significantly during many years of observations, remaining consistently large, close to the tidal truncation radius. This result is not consistent with the modern understanding of the evolution of the disc radius through an outburst cycle.

Aims. Spectroscopic observations of HT Cas during its superoutburst offered us an exceptional opportunity to compare the properties of the disc of this object in superoutburst and in quiescence.

Methods. We obtained a new set of time-resolved spectra of HT Cas in the middle of its 2017 superoutburst. We used Doppler tomography to map emission structures in the system, which we compared with those detected during the quiescent state.

Results. The superoutburst spectrum is similar in appearance to the quiescent spectra, although the strength of most of the emission lines decreased. Most of the line profiles are complex with a mix of absorption and emission components. He i in superoutburst was much narrower than in quiescence, whereas the profiles of other Balmer and He i lines did not change significantly. Doppler maps of the Balmer and He i lines are dominated by a bright emission arc in the right side of the tomograms, superposed on a diffuse ring of emission. The location of the leading arc on the Hβ, He i, and Si ii maps is consistent with Keplerian velocities at the tidal truncation radius. However, the bulk of the He λ emission has significantly lower velocities.

Conclusions. We show that the accretion disc radius of HT Cas during its superoutburst has remained the same size as it was in quiescence. Instead, we detected cool gas beyond the WD’s Roche-lobe, possibly expelled from the hot disc during the superoutburst.

Keywords. methods: observational – accretion, accretion discs – binaries: close – novae, cataclysmic variables – stars: dwarf novae – stars: individual: HT Cas

1. Introduction

Accretion discs are found in a wide range of astrophysical environments such as active galactic nuclei, young stellar objects, and interacting binary stars. In the accreting white dwarf (WD) systems known as cataclysmic variables (CVs), accretion discs play a major role in their overall behaviour. The discs in dwarf novae – a subclass of CVs – from time to time undergo outbursts. Short-period dwarf novae of the SU UMa-type show two types of outbursts: normal outbursts lasting a few days, and superoutbursts which have a slightly larger amplitude and a longer duration of a few weeks. The defining property of superoutbursts is the presence of superhumps, low-amplitude modulations with a period slightly longer than the orbital one (Warner 1995).

Superhumps are usually explained by the tidal instability of the accretion disc which grows when the disc expands beyond the 3:1 resonance radius \( R_{3:1} \). This causes the disc to become eccentric and precessing that initiates superhumps (see review by Osaki 1996). In CVs with low-mass donor stars, \( R_{3:1} \) is less than the tidal truncation limit \( r_{\text{max}} \). While the responsibility of the tidal instability for the superhump phenomenon is still under debate (Bisikalo et al. 2004; Hameury & Lasota 2005), there is a general consensus that during outbursts the accretion disc expands and then contracts with time (Lasota 2001; Osaki 2005; Hameury & Lasota 2005).

However, in our earlier paper we showed (Neustroev et al. 2016) hereinafter referred to as Paper I that the disc radius in the dwarf nova of the SU UMa-type HT Cas has not changed significantly during many years of observations, remaining consistently large, close to \( r_{\text{max}} \). Multi-epoch, time-resolved spectroscopic observations from Paper I were obtained between 1986 and 2005 in quiescence interrupted by several normal outbursts. This result is not consistent with the modern understanding of the evolution of the accretion disc through an outburst cycle described above. We also note that Paper I was mostly dedicated to studying the properties of emission structures in the system, of which the dominated source is the extended emission region in the leading side of the disc, opposite to the location of the hotspot from the area of interaction between the gas stream and the disc. This puzzling feature was detected in Doppler maps of many CVs, still its origin remains unclear. In Paper I we found that the leading side bright region is always observed at the very edge of the disc.

In the beginning of 2017, HT Cas experienced a very rare superoutburst (the previous one was observed in 2010, Kato et al. 2012) during which strong superhumps were detected (Enrique...
de Miguel, vsnet–alert 20570). This event offered us an exceptional opportunity to provide a crucial test for the theory. In the middle of the superoutburst (see Fig. 1), we obtained a new set of time-resolved spectra of HT Cas, which was analysed in a similar manner as our previous observations in quiescence (Paper I). Here we present a comparable analysis of the properties of the accretion disc and of its emission structures in HT Cas during its high and low states. We show a most striking result – the accretion disc radius has not changed in outburst. Instead, we detected cool gas beyond the WD’s Roche-lobe, possibly expelled from the hot accretion disc.

### 2. Observations and Data reduction

The spectroscopic observations of HT Cas were performed on 2017 January 17 with the Andalucia Faint Object Spectrograph and Camera (ALFOSC) mounted at the 2.5-m Nordic Optical Telescope (NOT) in the Observatorio de Roque de los Muchachos (ORM, La Palma, Spain). The data were obtained under perfect weather conditions with seeing 0.7–0.9′′, allowing us to use a narrow slit of 0.5″. The observations were taken with grism #19 in the wavelength range of 4410–6960 Å with a dispersion of 1.2 Å pixel$^{-1}$ and a corresponding spectral resolution of 2.9 Å. A total of 50 spectra with 120 sec individual exposures were obtained, covering one orbital period of the system. He-Ne lamp exposures were taken before, in the middle and after the observations of the target for wavelength calibration. In addition, we detected cool gas beyond the WD’s Roche-lobe, possibly expelled from the hot accretion disc.

### 3. Eclipse ephemerides and orbital phases

Eclipse ephemerides for HT Cas have been derived many times in the past (e.g. Feline et al. 2005; Borges et al. 2008). However, they have accumulated a significant error over time, resulting in a large discrepancy between the predicted and observed eclipse times. Because the time resolution of our spectroscopy is not sufficient to define an accurate zero-phase, we also used the AAVSO photometric observations of HT Cas during its superoutburst (Kafka 2017). Thus, we extracted 47 times of light minima between JD 2457765 and 2457775. A linear least squares fit to these times gives the following orbital ephemeris of the light-minima:

$$HJD_{\text{min}} = 245\,7765.23997(3) + 0.07364720309 \cdot E. \quad (1)$$

In this calculations, we adopted the value of the orbital period $$P_{\text{orb}} = 0.07364720309$$ d from Feline et al. (2005). The obtained ephemeris were used to calculate the orbital phases of the spectra.

### 4. Data analysis

Data analysis in this paper is mostly performed in a similar manner to that described in Paper I and we also used the same plot templates for figures. Thus, we advise the reader to consult Paper I for technical details of the analysis and compare the figures in this work with those of Paper I. Here we also use the same system parameters of HT Cas taken from Horne et al. (1991):

- $$M_1 = 0.61 \pm 0.04 M_\odot, \quad M_2 = 0.09 \pm 0.02 M_\odot, \quad q = 0.15 \pm 0.03,$$
- $$i = 81.0 \pm 1.0^\circ.$$
4.1. Averaged and trailed spectra

Figure 2 (top panel) shows the averaged and continuum-normalised out-of-eclipse spectrum, while the measured parameters of the most prominent spectral lines are present in Table 2. Although the superoutburst spectrum is quite similar in appearance to those observed in quiescence (see Figure 2 in Paper I), there are at least a few obvious differences. As in quiescence, the outburst spectrum shows double-peaked emission lines of the Balmer series and He i, nevertheless the relative to continuum intensities and the equivalent widths (EW) of these lines significantly lowered (compare Table 2 and Table 3 from Paper I). This results in the seeming appearance (C i i 4549, 4584, 5169, 5182, 5235, 5272 Å), and possibly a few of Fe i (44518 Å). An absorption core between emission peaks in the Balmer lines is above the continuum level, but in the He i lines it goes well below the continuum. The redshifted emission peaks are stronger than the blue peaks in all double-peaked emission lines. The iron lines seem to exhibit the absorption core peaks are stronger than the blue peaks in all double-peaked emission lines it goes well below the continuum. The redshifted emission lines it makes an impression that during these phases the blue peak is shadowed, becoming much weaker (Fig. 3). In emission lines it appears much narrower than in quiescence. It is not only evident from the peak-to-peak separation which decreased from ~1100 to 670 km s\(^{-1}\), but also from the full-width at half maximum (FWHM), which also decreased from ~2000 to 1450 km s\(^{-1}\). Since the dominant broadening mechanism of double-peaked emission lines is the Doppler shift due to Keplerian rotation of the accretion disc around the accretor (Horne & Marsh 1986), the observed narrowing of the He \(\alpha\) line suggests its origin during the outburst from a more extended area than in quiescence.

From the phase-resolved trailed spectra (Fig. 2 bottom panel), one can see that the absorption component of different lines, including the Balmer lines, varies with a similar radial velocity amplitude and in phase with each other, becoming broader at orbital phase ~0.3, when they are the most blueshifted. In emission lines it makes an impression that during these phases the blue peak is shadowed, becoming much weaker (Fig. 3). In mid-eclipse, the absorption components of the Balmer and He i lines are almost disappeared or even reversed into emissions.

4.2. Light curves

The flux-calibrated spectra were used to compute light curves for the emission lines H\(\alpha\), H\(\beta\), He i \(\lambda\)5876 and He ii \(\lambda\)4686. Similarly to Paper I we computed the light curves by summing the continuum-subtracted flux inside of ±2700 km s\(^{-1}\) window centered at the emission-line wavelengths. These light curves are shown in Fig. 4. In the bottom panel of Fig. 4 we show two AAVSO light curves, the phase-averaged one obtained between JD 2457765 and 2457775, and the light curve obtained during our spectroscopic observations.
Table 2. Parameters of the most prominent lines in the mean spectrum

| Spectral line | Relative intensity ($\%$) | EW (Å) | Peak-to-peak ($\text{km s}^{-1}$) |
|---------------|---------------------------|--------|-------------------------------|
| H$\alpha$     | 1.80/–                    | -27.8  | 670                           |
| H$\beta$     | 1.28/–                    | -8.0   | 1170                          |
| H$\gamma$    | 1.16/–                    | -4.9   | 1060                          |
| H$\delta$    | 1.15/–                    | -3.0   | 1250                          |
| He I 4471    | 1.04/0.85                 | +0.9   | 1300                          |
| He I 4713    | 1.02/0.97                 | –      | –                             |
| He I 4922    | 1.03/0.90                 | -0.2   | 1560                          |
| He I 5015    | 1.03/0.90                 | -0.2   | 1250                          |
| He I 5876    | 1.12/0.93                 | -2.0   | 1190                          |
| He I 6678    | 1.07/0.94                 | -1.6   | 1200                          |
| Fe II 4686   | 1.12/–                    | -4.7   | –                             |
| C $\text{n}$/N $\text{m}$ | 1.05/–             | -1.8   | –                             |
| Fe II 5169   | $\sim$0.94               | +0.6   | –                             |
| Si II 5669   | 1.01/–                    | -0.7   | 1300                          |
| Si II 6347   | 1.01/0.98                 | -0.2   | 1350                          |
| Si II 6371   | 1.01/0.99                 | -0.4   | 1200                          |

Notes. $a$ – a strong absorption core is present; $b$ – blend; $c$ – relative to continuum intensities are shown for both emission and absorption components if present.

Fig. 3. Trailed spectra (top panel) and averaged profiles (bottom panel) of the Fe II 5169 and He I 5876 lines. The spectra are averaged around the orbital phases 0.3±0.1 and 0.8±0.1.

Fig. 4. Light curves computed for the H$\alpha$, He II $\lambda$4686, H$\beta$ and He I $\lambda$5876 lines (top and middle panels). The bottom panel shows the AAVSO light curves. The black squares represent the phase-averaged data obtained between JD 2457765 and 2457775, while the blue circles show the light curve obtained during our spectroscopic observations.

By comparing the emission-line curves with figure 3 from Paper I one can conclude that the character of variability has significantly changed. In superoutburst it has shown single-wave modulations rather than double-wave seen in quiescence. However, the most striking difference is the increase of the Balmer and He I fluxes (not only the EWs) in mid-eclipse. It can be explained by assuming that the absorption line components were produced in the innermost parts of the optically thick accretion disc, which are eclipsed by the donor, whereas the emission line region is located more outward in the disc and/or possibly above the orbital plane. Figure 5 (left-hand panel) schematically demonstrates the system geometry in the middle of eclipse. As seen, the inner disc with its absorption spectrum is eclipsed around mid-eclipse phases, while the emission layer can still be seen. In this case it becomes the main contributor to the spectrum giving the raise of the total line flux.

4.3. Doppler tomography

The Doppler maps of the representative lines are shown in Figs 6 and 7. For the H$\alpha$ line we also show the trailed spectrum and its corresponding reconstructed counterpart (Fig. 6 middle and right panels). To calculate the map of the absorption line Fe II 5169, the latter has been first inverted. Similarly to Paper I, only out-of-eclipse spectra were used for tomography.

The appearance of the tomograms in superoutburst is quite unusual in general and significantly different compared to those in quiescence (see figures 6 and 7 in Paper I). No lines show evidence of spiral structures which are sometimes seen in Doppler maps of CVs in outburst (Steeghs et al. 1997). Although a diffuse ring of disc emission is still visible, the Balmer and He I maps are dominated by a bright emission arc in the right side of the tomograms. In Section 5 we show that this arc can probably
be regarded as an evolved emission region in the leading side of the accretion disc which we discussed in detail in [Paper I]. By analogy, hereafter we refer to this structure as the "leading arc". The latter follows the circle representing Keplerian velocities at the tidal truncation radius \( r_{\text{max}} \). In \( \text{H}\beta \), the leading arc is located inside the circle, and at the upper part it continues further to the negative x-velocities (Fig. 5). In addition, the \( \text{H}\alpha \) map shows a very bright, compact but slightly elongated emission component (in the following referred to as the "EEC") starting inside the bubble marking the Roche lobe of the donor star, and moving in the bottom-left direction for \( \sim 200 \text{ km s}^{-1} \). The EEC does not follow the predicted trajectory of the gas stream. In \( \text{H}\beta \), the EEC is much weaker than in \( \text{H}\alpha \) and it is not visible in other lines. In contrast, the \( \text{H}\beta \) and especially He \( \text{i} \) lines show another bright spot which is consistent with the trajectory of the gas stream \( (V_x, V_y) \sim (900, 500) \). A similar spot has been clearly seen in quiescence, and we identified it as the hotspot being located well inside the accretion disc [Paper I]. On overall, the emission structure in the Balmer and He \( \text{i} \) lines can be described as having a horseshoe shape with a gap in the third quadrant \( (V_x, V_y) \). Such a gap was also visible in some Doppler maps of HT Cas in quiescence.

The map of the Si \( \text{ii} \) 6347 line looks differently compared to other lines. In addition to the leading arc which is located at the same position as in the \( \text{H}\beta \) and He \( \text{i} \) maps, there is also another arc of a larger radius in the third quadrant.

The He \( \text{i} \) 4686 emission line does not have a clear double-peaked profile. As a result, its tomogram exhibits a rather diffuse distribution of emission with a compact bright spot in the fourth quadrant \( (V_x, V_y) \sim (900, 500) \). The latter can be identified as the hotspot located in the region where the gas stream hits the outer edge of the accretion disc. On the other hand, a single-peaked profile suggests non-Keplerian gas motions, e.g. perpendicular to the accretion disc. This indicates that at least part of the He \( \text{i} \) 4686 line is formed in the wind blowing from the disc.

The tomograms of absorption lines (e.g. Fe \( \text{ii} \) 5169) show a compact absorption area, which is associated with the absorption S-wave in the trailed spectra. In the maps it is shifted relative to the position of the WD in the bottom-left direction by a few hundred \( \text{km s}^{-1} \). A similar absorption pattern is also seen in most of emission line tomograms; it is possibly responsible for the appearance of the gap in the horseshoe emission structure.

5. Evidence for the emitting material outside the WD Roche-lobe

A direct comparison of the Doppler maps presented in Figs. 6 and 7 leads to the conclusion that the horseshoe emission structure consists of several components which are not necessarily physically linked. This allows us to discuss them separately.

The common component which is clearly seen in most of the tomograms is the leading arc. Its closer inspection reveals two distinct parts of similar brightness. This property, together with the location of the arc resemble the most prominent emission structure of the \( \text{H}\alpha \) Doppler maps of HT Cas in quiescence — the leading side bright region. The important finding of [Paper I] was that this region is always observed at the very edge of the disc, the radius of which is very close to \( r_{\text{max}} \) (see figure 12 in [Paper I]). In quiescence, however, this region is most obvious in the \( \text{H}\alpha \) line only. In \( \text{H}\beta \) it is much weaker, and almost undetectable in the He \( \text{i} \) lines. In contrast, in superoutburst the leading arc is the brightest region in all the \( \text{H}\alpha \), He \( \text{i} \) and Si \( \text{ii} \) lines. Moreover, in all these lines the arc is located almost exactly at the tidal truncation radius (Fig. 7 see also the right-hand panel of Fig. 8). This indicates strongly that the accretion disc of HT Cas in superoutbursts is hot \((\sim 15000 \text{ K}) \) until the tidally truncated radius.

Figure 8 compares the location of the leading arc and the leading side bright region visible in \( \text{H}\alpha \) in superoutburst and in quiescence (left-hand panel) to that found for the leading arc in He \( \text{i} \) lines in superoutburst (right-hand panel). What is extremely interesting is that the leading arc in \( \text{H}\alpha \) during the superoutburst was located inside \( r_{\text{max}} \) — the arc radius is about 100 \( \text{km s}^{-1} \) less than \( r_{\text{max}} \) — meaning that the disc, as it is seen in \( \text{H}\alpha \), extends beyond the tidally truncated radius. Although it is commonly accepted that the largest disc radius is determined by the tidal influence of the donor star — the viscous and tidal stresses become comparable at \( r_{\text{max}} \) — it is possible that \( r_{\text{max}} \) is not a hard limit and at some physical conditions the disc can extend beyond it (see e.g. [Papaloizou & Pringle 1977]). The problem is that in binaries with a low mass-ratio \( q \) there is still little room between \( r_{\text{max}} \) and the Roche-lobe surface. For example, in HT Cas, a binary with \( q=0.15 \), \( r_{\text{max}}=0.522a \), where \( a \) is the binary separation, whereas the Equatorial Roche lobe radius (in the direction perpendicular to the line of centres of the WD and the donor) is 0.558a (see figure 10 in [Paper I]). Assuming a circular Keplerian flow in the disc, the velocities at these two radii are different by just 3 per cent. However, the observed velocities of the \( \text{H}\alpha \) arc in superoutburst \((\sim 475 \text{ km s}^{-1}) \) are less than the velocity at \( r_{\text{max}} \) \((575 \text{ km s}^{-1}) \) by \( \approx 17\% \), which is translated into the distance \( \approx 1.5r_{\text{max}} \). This is larger than the distance from the WD to the inner Lagrangian point \((R_1=0.684a) \). meaning that it is not even theoretically possible to find a place inside the WD Roche-lobe where a \textit{Keplerian flow} can have the observed velocity. We believe that the observed \( \text{H}\alpha \) arc could only originate \textit{outside} the WD Roche-lobe.
In this respect, we must admit that the assumption of the circular Keplerian flow beyond the Roche-lobe cannot be correct in a strict sense. Indeed, it is known that even the outer parts of a large accretion disc are under gravitational influence of the donor star which distorts circular particle orbits (Paczynski 1977). On the other hand, in Paper I we discussed the expected deviation from a circular Keplerian flow and have concluded that for the orbit averaged spectra the assumption of circular Keplerian velocities is still reliable (see also Steeghs & Stehle 1999). Here we additionally note that the accurate tracing of \( r_{\text{max}} \) by the leading arc structure on Doppler maps of different emission lines that cover a range of excitation energies and temperatures further supports the assumption that the accretion disc behaves in a (quasi-)Keplerian fashion until its very edge. The appearance of the \( \text{H}\alpha \) emission in the lower-velocity region, in contrast with other, hotter lines, can be interpreted as tracing a cooling gas (\( \lesssim 10000 \) K) being expelled from the hot accretion disc beyond the accretor’s Roche-lobe. To place the \( \text{H}\alpha \) emission inside the WD Roche-lobe, one will need to assume significantly non-Keplerian orbits; the deviation from the Keplerian value must be no less than 15 per cent.

6. Other emission and absorption components

6.1. The elongated emission component (EEC)

The cool gas region visible in \( \text{H}\alpha \) envelopes the binary for at least 180° in azimuth and, visually, incurses at the top part of the tomogram to even smaller velocities. Nevertheless, it is not clear whether the EEC at the top of the Doppler map and the leading arc are physically linked. One side of the EEC coincides, on the Doppler map, with the Roche-lobe of the donor star. This allows us to speculate about a possible origin of this part of the EEC on the inner semi-sphere of the donor star which has possibly been irradiated by the WD and/or hot accretion disc regions. However, although the EEC is the brightest emission area seen in \( \text{H}\alpha \), its other part (a trajectory) cannot be associated with any structures of the binary system such as the gas stream or the hotspot, and none of hydrodynamical simulations predict an increase of the emission in this region. On the other hand, if the EEC is not locked in the rotating binary frame, then its small velocities suggest the out-of-the-accretors-Roche-lobe origin. We still have no physical explanation for this phenomenon.

6.2. Non-axisymmetrical absorption

The relative compactness of the absorption structure on Doppler maps suggests that its source is locked in the binary rest frame. Assuming Keplerian velocities, it is located on the opposite, from the donor star, side of the disc at azimuth \( \sim 110^\circ \). To be eclipsed by the donor, the absorption region must be situated close to the WD and it should not be very extended vertically (see Fig. 5 left-hand panel). This resembles a “dark spot” phenomenon observed in the nova-like UX UMa, which has been explained in the context of the stream-disc overflow model (see Neustroev et al. 2011, and references therein). However, this model cannot explain the depression of the blue peak of emission lines at orbital phases \( 0.3 \pm 0.1 \), when the absorption component is the most blueshifted (Fig. 3 upper-right panel). We believe that these two phenomena are not physically related to each other.

Such a depression might occur if the very edge of the accretion disc, perpendicular to the line of sight, is temporarily obscured by something in the foreground, for example by a thickened sector of the outer disc (Fig. 3 right-hand panel). This model is consistent with our hypothesis that the leading side bright region in quiescence (and the leading arc in outburst) is caused by irradiation of tidally thickened sectors of the outer disc by the WD and/or hot inner disc regions (see Paper I and figure 10 therein). See Section 7 for further discussion.

6.3. The hotspot

The canonical hotspot from the area of interaction between the gas stream and the disc is often one of the brightest emission components of dwarf novae in quiescence. This is, however, rarely visible during outbursts, when the hotspot cannot reach a high contrast to be detected on a background of the hot and luminous disc. Surprisingly, the hotspot in HT Cas in outburst is
Fig. 7. Doppler tomography for the Hβ, He ii 4686 (upper row), He i 5876 and 6678 (middle row), Si ii 6347 and Fe ii 5169 (bottom row) spectral lines. In addition to the marks described in Fig. 6, the predicted trajectory of the gas stream in the form of the curve has also been shown. For the Fe ii line, the map shows the distribution of the absorption component.
easily detected in most of emission lines (the only exception is Hα). However, only in He II the spot is located at the very edge of the disc whereas in other lines it is situated well inside the disc, at the distances from the WD of $R_{\text{hs}} \approx 0.23-0.29a$. These distances are consistent with those found for the hotspot visible in different lines during the quiescent state (Paper I). The difference is that in quiescence the hotspot velocities were close to Kepler velocities at the spot position (see the left-hand panel of Fig. 11 in Paper I), while during the superoutburst the velocities were close to the expected velocity of the gas stream at $R_{\text{hs}}$ (Fig. 7 and the right-hand panel of Fig. 8).

Following Skidmore et al. (2000) and Mason et al. (2000), we explained in Paper I the appearance of the hotspot inside the disc by a very low density of the outer disc regions which allows the gas stream penetrates deep into the disc. The occurrence of the hotspot at the same location during the superoutburst points to the same explanation, but it also suggests a relatively low temperatures in the region of the hotspot origin. The latter is not expected for the disc in the middle of the superoutburst when it is in an almost steady state. This indicates an inhomogeneous, non-axisymmetric structure of the disc, even of its inner parts.

7. Discussion

It is commonly accepted that variations of the outer disc radius in interacting binaries play an important role in understanding the structure and evolution of accretion discs. These variations are predicted by various models of discs (see, e.g., Smak 1984, Lasota 2001, Hameury & Lasota 2005), and they are adopted to explain superhumps which are observed during superoutbursts in SU UMa-type dwarf novae (Osaki 2005). Here we mention two important results obtained by Hameury & Lasota (2005). They found significant variations of the outer disc radius during an outburst (at least 20%), and that tidal torques which determine the outer radius at which the disc is truncated, must be important also well inside $r_{\text{max}}$.

In contrary to these claims, we have shown in Paper I that the disc radius of HT Cas and other CVs in quiescence is persistently large and is close to the tidal truncation radius. Moreover, in the present paper we demonstrate that during the superoutburst the disc radius of HT Cas remained of the same size, equal to $r_{\text{max}}$, which in short-period CVs is always larger than the 3:1 resonance radius. This result brings into question the standard explanation for the appearance of superhumps as a result of the disc radius expansion beyond the 3:1 resonance radius (Osaki 1996).

Furthermore, we have presented several lines of evidence indicating that the Hα emission which traces cooler lower-ionization gas than other Balmer and helium lines, most probably originated beyond the WD’s Roche-lobe. We propose that this cool gas was ejected from the leading side of the hot disc during the superoutburst. Moreover, the amount of expelled matter should be quite significant to be able to obscure the disc edge perpendicular to the line of sight (Fig. 5 right-hand panel). This hypothesis is consistent with predictions of numerical simulations, in which the appearance of the circumbinary envelope created by matter left the accretion disc and went outside the Roche-lobe has been noticed (see e.g. Bisikalo et al. 1998). An expansion of material outside the accretor’s Roche-lobe was predicted even for systems in the quiescent state. Synthetic Doppler maps of such simulations (Bisikalo et al. 2008) closely resemble the observed tomograms of HT Cas.

This result can have important implication for CV evolution theory which predictions are not fully supported by observations of the currently known CV sample. Indeed, the evolution of a CV is driven by angular momentum loss from the binary. According to the standard model, angular momentum loss in short-period CVs (below the period gap) is assumed to be driven solely by gravitational radiation (for details, see Knigge et al. 2011). However, the material that leaves the system carries with it the specific orbital angular momentum of the WD. This material is expected to flow out within the orbital plane of the system and thus can create and feed (continuously or occasionally, e.g. during outbursts) a circumbinary disc (CB). It has been shown that the inclusion of an angular momentum loss associated with a CB disc can significantly affect the evolution of CVs (Spruit & Taam 2001, Taam & Spruit 2001). In particular, Taam et al. (2003) have shown that even low fractional mass input rates into the CB ($\delta \sim 10^{-3}$) can promote the mass transfer between the binary components, increasing thus the evolution rate and heating the WD by the increased infall of material. Moreover, assuming even lower $\delta \sim 10^{-5}$ Willems et al. (2005) have demonstrated that this form of an angular momentum loss tends to smooth the predicted spike in the number of systems near the period minimum. Deeper discussion of a possible impact of a CB on the CV evolution is beyond the scope of this paper.

How significant and how common is mass outflow from the outer accretion disc in CVs and related objects? Some evidence for a possible expansion of accretion disc material beyond the Roche-lobe was already presented in the past for long-period nova-like CVs (see e.g. Hernandez et al. 2017). However, to the best of our knowledge, the observational confirmation of such an expansion in a short-period CV is obtained for the first time. It was possible because HT Cas is an eclipsing binary and its system parameters are known accurately enough, and because it exhibited emission lines during the superoutburst that is not common case. Unfortunately, only a few short-period CVs were observed spectroscopically during their superoutbursts and most of them are non-eclipsed. However, we noticed the presence of a horseshoe structure in the Hα Doppler map of SSS J122221.7–311525 (Neustroev et al. 2017). A notable narrowing of the Hα line during outbursts was also detected in black-hole X-ray binaries (see, e.g., Shahbaz et al. 2000). In a few other WZ Sge-type dwarf nova exhibiting double-peaked emission lines in superoutburst, a peak-to-peak separation of Hα was also significantly smaller than that of other lines (V1838 Aql – Hernandez Santisteban et al. 2019, TCP J21040470+4631129 – Tevssier 2019, Neustroev et al. 2019). A narrowing of the Hα line during outbursts was also detected in black-hole X-ray binaries (see, e.g., Shahbaz et al. 2000, Neustroev et al. 2014). These features probably indicate mass outflow from the outer disc. Unfortunately, the presented observations do not allow for a reasonable estimate of the mass-loss rate through the outer disc to be made. An attempt to estimate this parameter can be possibly made by applying numerical simulations.

2 Here we note the following discrepancies between the available models of CV evolution and the observations relevant to this paper: 1) the measured effective temperatures of WDs in short-period CVs show a large scatter and imply higher mass-transfer rates than predicted (Pala et al. 2017), 2) although the current empirical period distribution reveals a significant accumulation of systems near the observed common period gap (Gänsicke et al. 2009, Kato et al. 2017) that resembles the period-minimum spike predicted by CV population models (Kolb & Baraffe 1999), the width of the empirical spike is larger and the relative number of CVs at the period minimum is much smaller than predicted (Knigge et al. 2011, Pala et al. 2019).
8. Summary

We have analysed time-resolved spectroscopic observations of the dwarf nova HT Cas during its 2017 superoutburst with the aim of comparing the properties of the accretion disc in the system during superoutburst and in quiescence. The principal results of this study can be summarized as follows:

1. The superoutburst spectrum is similar in appearance to the quiescent spectra, although the strength of most of the double-peaked emission lines of the Balmer series and He II decreased. In addition, the high-excitation lines of He II 4686, C II 4267, and the Bowen blend were quite strong. However, the EW of He II 4686 is comparable in both the quiescence and outburst spectra. We also detected the emission lines of Si II which are rarely observed in CVs.

2. Most of the line profiles are complex with a mix of absorption and emission components. In the He I lines, the absorption goes well below the continuum. The iron lines are dominated by the absorption, or their emission component is very weak.

3. Hα in outburst was much narrower than in quiescence, whereas the profiles of other Balmer and He I lines did not change significantly.

4. A single-peaked profile of He II suggests that at least part of this line is formed in the wind blowing from the disc.

5. Doppler maps of the Balmer and He I lines are dominated by a bright emission arc in the right side of the tomograms, superposed on a diffuse ring of emission. This leading arc is probably an evolved emission region in the leading side of the accretion disc – the dominant emission source of the Hα line in quiescence.

6. In the Hβ, He I, and Si II lines, the leading arc is located at the tidal truncation radius, indicating that the disc radius during the superoutburst remained the same as in quiescence.

7. Doppler tomography of Hα revealed that the bulk of its emission, which traces cooler gas than other studied lines, is produced beyond the WD’s Roche-lobe. We interpret this as a signature of a cooling gas being expelled from the hot disc.

These unexpected findings bring into question the standard explanation for superoutbursts and the appearance of superhumps, and can have important implications for CV evolution theory.

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References

Bisikalo, D. V., Boyarchuk, A. A., Chechetkin, V. M., Kuznetsov, O. A., & Molteni, D. 1998, MNARS, 300, 39
Bisikalo, D. V., Boyarchuk, A. A., Kaigorodov, P. V., Kuznetsov, O. A., & Matsuda, T. 2004, Astronomy Reports, 48, 588
Bisikalo, D. V., Kononov, D. A., Kaigorodov, P. V., Zhitkin, A. G., & Boyarchuk, A. A. 2008, Astronomy Reports, 52, 318
Borges, B. W., Baptista, R., Papadimitriou, C., & Giannakis, O. 2008, A&A, 480, 481
Feline, W. J., Dhillon, V. S., Marsh, T. R., Watson, C. A., & Littlefair, S. P. 2005, MNARS, 364, 1158
Gänsicke, B. T., Dillon, M., Southworth, J., et al. 2009, MNARS, 397, 2170
Hameury, J. M. & Lasota, J. P. 2005, A&A, 443, 283
Hernández Santisteban, J. V., Echevarría, J., Zharikov, S., et al. 2019, MNARS, 486, 2631
Home, K. & Marsh, T. R. 1986, MNARS, 218, 761
Home, K., Wood, J. H., & Stenning, R. F. 1991, ApJ, 378, 271
Kafka, S. 2017, Observations from the AAVSO International Database, https://www.aavso.org
Kato, T., Isogai, K., Hambsch, F.-J., et al. 2017, PASJ, 69, 75
Kato, T., Maehara, H., Miller, I., et al. 2012, PASJ, 64, 21
Knudde, C., Baraffe, I., & Patterson, J. 2011, ApJ, 194, 28
Kolb, U. & Baraffe, I. 1999, MNARS, 309, 1034
Lasota, J.-P. 2001, New A Rev., 45, 449
Mason, E., Skidmore, W., Howell, S. B., et al. 2000, MNARS, 318, 440
Neustroev, V., Boyd, D., Berardi, P., et al. 2019, The Astronomers’ Telegram, 13009
Neustroev, V. V., Marsh, T. R., Zharikov, S. V., et al. 2017, MNARS, 467, 597

Fig. 8. Doppler maps combined of the tomograms for the Hα line in superoutburst and quiescence (left) and for Hα and the He I lines in superoutburst (right). The EEC, the brightest emission component in Hα is flattened to show other emission structures in more detail. The circular dashed lines represent Keplerian velocities at the tidal truncation radius $r_{\text{max}}$. 

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Neustroev, V. V., Suleimanov, V. F., Borisov, N. V., Belyakov, K. V., & Shearer, A. 2011, MNRAS, 410, 963
Neustroev, V. V., Veledina, A., Poutanen, J., et al. 2014, MNRAS, 445, 2424
Neustroev, V. V., Zharikov, S., & Michel, R. 2006, MNRAS, 369, 369
Neustroev, V. V., Zharikov, S. V., & Borisov, N. V. 2016, A&A, 586, A10 (Paper I)
Osaki, Y. 1996, PASP, 108, 39
Osaki, Y. 2005, Proceeding of the Japan Academy, Series B, 81, 291
Paczynski, B. 1977, ApJ, 216, 822
Pala, A. F., Gänsicke, B. T., Breedt, E., et al. 2019, arXiv e-prints, arXiv:1907.13152
Pala, A. F., Gänsicke, B. T., Townsley, D., et al. 2017, MNRAS, 466, 2855
Papaloizou, J. & Pringle, J. E. 1977, MNRAS, 181, 441
Shababz, T., Groth, P., Phillips, S. N., et al. 2000, Monthly Notices of the Royal Astronomical Society, 314, 747
Skidmore, W., Mason, E., Howell, S. B., et al. 2000, MNRAS, 318, 429
Smak, J. 1984, PASP, 96, 5
Spruit, H. C. & Taam, R. E. 2001, ApJ, 548, 900
Steehhs, D., Harlafits, E. T., & Horne, K. 1997, MNRAS, 290, L28
Steehhs, D. & Stehle, R. 1999, MNRAS, 307, 99
Taam, R. E., Sandquist, E. L., & Dubus, G. 2003, ApJ, 592, 1124
Taam, R. E. & Spruit, H. C. 2001, ApJ, 561, 329
Teyssier, F. 2019, The Astronomer’s Telegram, 12936
Warner, B. 1995, Cambridge Astrophysics Series, 28
Willems, B., Kolb, U., Sandquist, E. L., Taam, R. E., & Dubus, G. 2005, ApJ, 635, 1263