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The dwarf nova SS Cygni: what is wrong?

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ABSTRACT

Context. Since the Fine Guiding Sensor (FGS) on the Hubble Space Telescope (HST) was used to measure the distance to SS Cyg to be 166 ± 12 pc, it became apparent that at this distance the disc instability model fails to explain the absolute magnitude during outburst. It remained, however, an open question whether the model or the distance have to be revised. Recent observations led to a revision of the system parameters of SS Cyg and seem to be consistent with a distance of $d \gtrsim 140$ pc.
Aims. We re-discuss the problem taking into account the new binary and stellar parameters measured for SS Cyg. We confront not only the observations with the predictions of the disc instability model but also compare SS Cyg with other dwarf novae and nova-like systems.
Methods. We assume the disc during outburst to be in a quasi stationary state and use the black-body approximation to estimate the accretion rate during outburst as a function of distance. Using published analysis of the long term light curve we determine the mean mass transfer rate of SS Cyg as a function of distance and compare the result with mass transfer rates derived for other dwarf novae and nova-like systems.
Results. At a distance of $d \gtrsim 140$ pc, both the accretion rate during outburst as well as the mean mass transfer rate of SS Cyg contradict the disc instability model. More important, at such distances we find the mean mass transfer rate of SS Cyg to be higher or comparable to those derived for nova-like systems.
Conclusions. Our findings show that a distance to SS Cyg $\gtrsim 140$ pc contradicts the main concepts developed for accretion discs in cataclysmic variables during the last 30 years. Either our current picture of disc accretion in these systems must be revised or the distance to SS Cyg is ~ 100 pc.

Key words. accretion, accretion discs – instabilities – stars: individual: SS Cygni – stars: novae, cataclysmic variables –
stars: binaries: close

1. Introduction

Dwarf novae are weakly magnetized cataclysmic variables (CVs) showing quasi-regular outbursts, i.e., increased visual brightness of 2−5 mag for several days, which typically reappear on timescales of weeks to months (e.g. Warner 1995, for a review).

The standard disc instability model (DIM) assumes a constant mass-transfer rate through the whole outburst cycle and is successful in explaining the basic properties of dwarf nova outbursts. In general the rise to maximum and the decay of *normal* outbursts is well described by the standard version of the model. There are problems with quiescence. Superoutbursts, Z Cam-type outbursts, and the reproduction of the outburst cycle in general require DIM modifications (see Lasota 2001, for a review).

On the other hand the DIM is too simple to be a faithful representation of dwarf nova outbursts. It uses a 1+1D scheme and is based on the α-parameter description of viscosity. Although the news of the death of such an approach (Pessah et al. 2006) are exaggerated, its serious limitation have been well known for a long time.

It is therefore not surprising that the brightest and best observed dwarf nova SS Cyg has been a source problems for the DIM. Its various types of outbursts seem to require modulations of the mass-transfer rate and the anomalous outbursts remain unexplained (e.g. Schreiber et al. 2003). However, the main challenge comes from the distance to this system obtained from the HST/FGS parallax (Harrison et al. 1999). According to the DIM, at such a distance (166 ± 12 pc) the accretion disc of SS Cyg would be hot and stable and the system would not be a dwarf nova. Therefore such a distance, if correct, would seriously put in doubt the validity of the DIM. Indeed, Schreiber & Gänsicke (2002) concluded that either the DIM has to be modified and strongly enhanced mass transfer during outbursts plays an important role, or the distance of 166 ± 12 pc is wrong. Comparing detailed DIM simulations with the observations of SS Cyg, Schreiber et al. (2003) assumed $d = 100$ pc doubting the correctness of higher values.

Recently Bitner et al. (2007) observationally re-determined the parameters of SS Cyg and obtained values for the masses of the stellar components and the orbital inclination that differ significantly from those derived earlier. The new results are more reliable than earlier measurements because they do not rely on error-prone methods such as those based on the wings of emission lines to determine the mass ratio or those using a main sequence mass/radius relation to derive the orbital inclination (see Bitner et al. 2007, for a detailed discussion). Very important in the context of the DIM is the conclusion of

Bitner et al. (2007) that their results are consistent with a distance of $d \sim 140-170$ pc in line with the parallax measurement. This forced us to re-examine the problem.

The structure of the paper is as follows. In Sect. 2, applying the method of Schreiber & Gänsicke (2002) but using the revised system parameters of Bitner et al. (2007), we compare the predicted absolute magnitude and the accretion rate during normal outbursts with the value derived from observations. Thereafter we determine the mean mass-transfer rate from the observed outburst properties and again compare it with the predictions of the DIM (Sect. 3). The conclusion of these two investigations is that a distance of 166 ± 12 pc is incompatible with the DIM. In Sect. 4 we compare the mean mass-transfer rates of SS Cyg and other dwarf novae with HST/FGS-parallax measurements with those of several nova-like binaries. We show that at the HST/FGS parallax distance SS Cyg is *brighter* than some nova-like systems and conclude that being an outbursting system at such high luminosity SS Cyg must be a very special CV indeed. In the following (Sect. 5) we re-consider the possibility that in SS Cyg the mass-transfer rate increases during outbursts as this would lower the mean mass-transfer rate.

2. Accretion rate during outburst

One of the key-predictions of the DIM is that at the onset of the decline, i.e. when the cooling front forms at the outer edge of the disc, the disc is in a quasi-stationary outburst state and the mass accretion rate is close to the critical mass transfer rate given by

$$\dot{M}_{crit} = 9.5 \times 10^{15} \text{ g s}^{-1} R_{10}^{2.68} M_{wd}^{-0.89}, \tag{1}$$

where M_{wd} is the white-dwarf's mass is solar units and R_{10} the disc radius in units of 10^{10} cm (e.g. Hameury et al. 1998). The light curves of normal outbursts of SS Cyg show a plateau phase with nearly constant brightness before the onset of the decline. Therefore, according to the DIM, the accretion rate during outburst should be similar to the critical accretion rate. Assuming the outer radius of the disc to be close to the tidal truncation radius $R_{out} = 0.9 R_1$ with R_1 being the primary's Roche-lobe radius, we derive for the new parameters of SS Cyg (see Table 1)

$$\dot{M}_{crit} \sim 9.0-9.1 \times 10^{17} \text{ g/s}. \tag{2}$$

Clearly, we can derive the predicted absolute visual magnitude of a disc with this accretion rate. We follow Schreiber & Gänsicke (2002), i.e. we use the same equation to account for the inclination, assume the effective temperature to follow the radial dependence of stationary accretion discs and the annuli of the disc to radiate like black bodies. For the mass accretion rate given in Eq. (2) we than obtain $M_V = 3.76-4.37$ as the predicted absolute magnitude during outburst. On the other hand, using the observed visual magnitude, i.e. $m_V = 8.6 \pm 0.1$, we can determine the absolute magnitude as a function of distance. Figure 1 compares both values. The shaded region represents the absolute magnitude predicted by the DIM for the range of system parameters for SS Cyg recently derived by Bitner et al. (2007) summarized in Table 1. Also shown in Fig. 1 (solid horizontal line) is the predicted absolute magnitude when using the same system parameter as Schreiber & Gänsicke (2002), i.e. those given by Ritter & Kolb (1998) which are based on Friend et al. (1990). Apparently, the range of predicted absolute magnitudes significantly decreased due to the change of the system parameters. As a consequence of the revised inclination and mass of the white dwarf (see Table 1), agreement with the DIM now requires distances as short as $d \lesssim 100$ pc.

Table 1. Binary parameters of SS Cyg used by Schreiber & Gänsicke (2002) (based on Friend et al. 1990 and Ritter & Kolb 1998) and the new values recently derived by Bitner et al. (2007) (right column). Also given is the derived outer radius of the disc ($\sim 0.9 R_1$) in units of 10^{10} cm. Please note that the stellar masses (and therefore also R_{10}) can not be chosen independently from within their ranges as they are strongly constrained by the mass ratio.

	Ritter & Kolb (1998)	Bitner et al. (2007)
P_{orb}/hr	6.6	6.6
$M_{wd}/M_\odot$	1.19 ± 0.05	0.81 ± 0.19
$q = M_{sec}/M_{wd}$	0.70	0.683 ± 0.012
$i/^o$	37	45–56
R_{10}	5.73	4.7–5.5
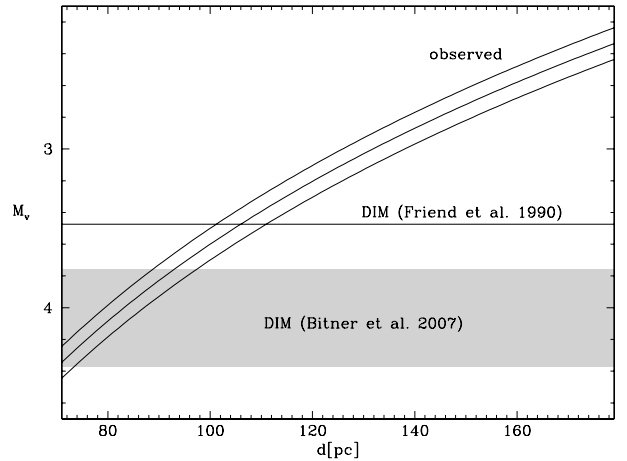
Fig. 1. The absolute magnitude at the onset of the decline derived from the observed magnitude of $m_v = 8.6 \pm 0.1$ as a function of distance and the absolute magnitude predicted by the DIM according to system parameters derived by Bitner et al. (2007) and Friend et al. (1990) (see Table 1).

To see how the discrepancy in the absolute magnitudes for a distance of 166 ± 12 pc correlates with accretion rates, we also compare the value of the critical accretion rate (Eq. (2)) with the accretion rate required to reproduce the absolute magnitude assuming SS Cyg is at $d = 166 \pm 12$ pc. We find that an accretion rate of

$$\dot{M}_{out} \sim 8.8-9.2 \times 10^{18} \text{g/s} \tag{3}$$

is required. This is *an order of magnitude* above the value predicted by the DIM (Eq. (2)). The value given above is also essentially higher (by a factor of ~ 2.5) than the one derived by Schreiber & Gänsicke (2002). The higher mass accretion rate is required because Bitner et al. (2007) found a higher value for the inclination and a lower value for the mass of the white dwarf.

3. The mean mass transfer rate

SS Cyg is among the visually brightest dwarf nova and a detailed long-term light curve exists. The mean outburst properties have been derived by Cannizzo & Mattei (1992, 1998) who analysed the AAVSO long term light curve. They find a mean outburst duration of $t_{out} = 10.76$ days, a mean cycle duration of $t_{cyc} = 49.47$ d giving a mean quiescence time of $t_{qui} = 38.71$ d. The mean duration of rise to outburst and decline from outburst are $t_{ris} = 0.5$ d and $t_{dec} = 2.5$ d respectively. Using these values we can now derive a value for the mean mass transfer rate from the observed visual magnitude during outburst. As in Sect. 2 we
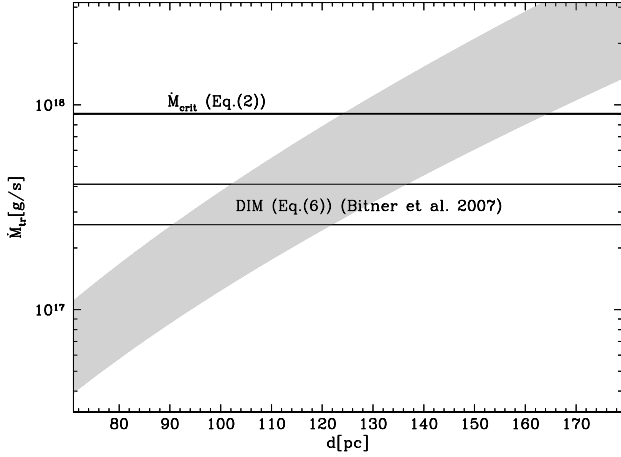
Fig. 2. The mean mass transfer rate of SS Cyg derived from the observed visual magnitude as a function of distance (shaded region) compared with the predictions of the DIM (horizontal lines). All values are calculated for the range of system parameters derived by Bitner et al. (2007). Agreement between DIM and observed visual magnitude requires a distance of $d \sim 100$ pc. At a distance of 166 pc the mean mass transfer derived from the observations is above the critical transfer rate and – according to the DIM – SS Cyg should be a nova-like.

will compare the value derived from the observations with the prediction of the DIM.

According to the DIM, the mean mass-transfer rate can be obtained from the relation

$$ t_{\mathrm{qui}} \approx \frac{\epsilon M_{\mathrm{D,max}}}{\dot{M}_{\mathrm{tr}} - \dot{M}_{\mathrm{in}}} \qquad (4) $$

where the fraction of the disc's mass lost during outburst is $\epsilon = \Delta M_{\mathrm{D}}/M_{\mathrm{D,max}}$ and $\dot{M}_{\mathrm{in}}$ is the accretion rate at the disc's inner edge. Usually $\dot{M}_{\mathrm{tr}} \gg \dot{M}_{\mathrm{in}}$ and $\epsilon \sim 0.1$. Taking

$$ M_{\mathrm{D,max}} = 2.7 \times 10^{21} \alpha^{-0.83} M_{\mathrm{wd}}^{-0.38} R_{10}^{3.14} \ \mathrm{g}, \qquad (5) $$

(see Lasota 2001), $\alpha = 0.02$, and the system parameters derived by Bitner et al. (2007) we obtain

$$ \dot{M}_{\mathrm{tr}} = 2.6\text{–}4.2 \times 10^{17} \ \mathrm{g/s}. \qquad (6) $$

The above value should be compared with the mean mass transfer rate derived from the observed visual brightness during outburst. Following again Schreiber & Gänsicke (2002, their Eq. (5)) but using the system parameters obtained by Bitner et al. (2007), we derive a mean mass transfer rate as function of distance. For $d = 166$ pc we obtain

$$ \dot{M}_{\mathrm{tr}} = 1.1\text{–}3.8 \times 10^{18} \ \mathrm{g/s}. \qquad (7) $$

The two values for the mean transfer rate, i.e. the one predicted by the DIM and the one derived from the observations are compared in Fig. 2. The grey shaded region represents the values required by $m_V = 8.6 \pm 0.1$ as a function of distance. The range of mean mass transfer rates predicted by the DIM (Eq. (6)) and the critical mass transfer rate (Eq. (2)) are shown as horizontal lines. Again, the discrepancy between DIM and HST/FGS parallax is obvious: according to the DIM, at 166 ± 12 pc SS Cyg should be nova-like system and not a dwarf nova. Even for $d \sim 140$ pc, the derived mean mass transfer rates are close to the critical value and one would at least expect Z Cam-like behaviour. Again, agreement with the DIM requires a distance of $d \sim 100$ pc.
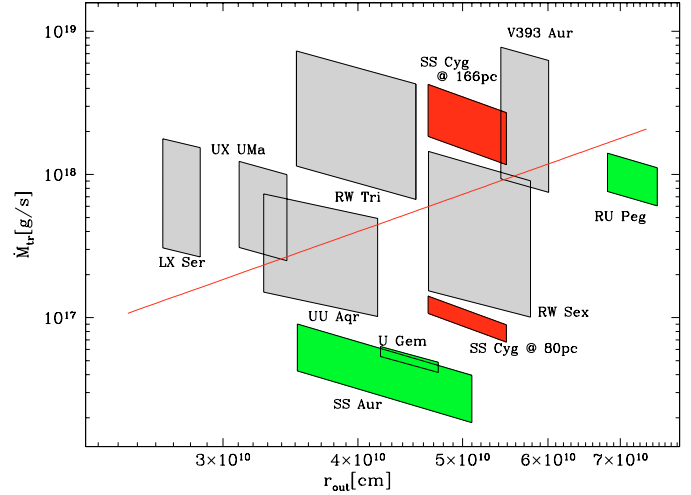
Fig. 3. The mean mass transfer rate of SS Cyg, three other dwarf novae with HST/FGS distance, and six well known nova-like CVs as a function of the outer radius of the disc during outburst. As binary parameters of SS Cyg we used again the values (and uncertainties) derived by Bitner et al. (2007). The parameters and distances used for the nova-likes are compiled and discussed in Table 1. Both, in order to make the plot easier to read as well as because the broad ranges of possible parameters do not represent well-determined values with certain errors, we use shaded boxes instead of error bars. The solid line represents the critical mass transfer rate according to Eq. (1) assuming $M_{\mathrm{wd}} = 1 \ M_{\odot}$. According to the DIM, this line should separate dwarf novae and nova-like systems. Interestingly, to reach agreement with this prediction for SS Cyg at $d = 166$ pc, the size of the disc needs to be similar to the one in RU Peg ($\sim 7 \times 10^{10}$ cm). Even for the maximum mass of the white dwarf ($M_{\mathrm{wd}} = 1.4 \ M_{\odot}$) this would require a disc larger than the Roche-lobe radius of the primary (6.8×10^{10} cm).

Although the recently determined parameters significantly increase the discrepancy between HST/FGS parallax and DIM prediction, the problem has been mentioned and discussed earlier. Schreiber & Gänsicke (2002) proposed as one possible solution a revision of the DIM by assuming an increased value of the critical mass transfer rate which would be equivalent to allowing for dwarf nova outbursts for higher mass transfer rates. However, as we will see in the next section the problem is not with the DIM. At 166 ± 12 pc the mean mass-transfer rate of SS Cyg is comparable or higher than that of nova-like binaries with similar orbital parameters but unlike SS Cyg these systems never show outbursts. If anything they show a so-called "anti-dwarf-nova" behaviour.

4. Comparing SS Cyg with nova-like CVs

There is an overwhelming evidence that the accretion disc is the site of dwarf-nova outbursts. The general picture of disc accretion in CVs is that below a certain mass transfer rate the disc is unstable and dwarf nova outbursts occur. For higher mass transfer rates, the disc is stable and the corresponding class of CVs are nova-like systems. In agreement with this picture, the mean absolute magnitudes of dwarf novae have been found to be lower than those of nova like systems (see Warner 1995, Fig. 9.8). To check whether this agreement remains for a distance to SS Cyg of 166 ± 12 pc, we compare the mean mass transfer rate derived for SS Cyg with those obtained for a set of well observed nova-like systems and three additional dwarf nova with measured HST/FGS parallax (see Tables 2 and 3).

Table 2. Binary parameters, distances, visual magnitudes, and extinctions of 6 nova-like systems.

Name	M_{wd}	M_{sec}	P_{orb}	d	i	m_V	A_V	Ref.
RW Tri	0.4–0.7	0.3–0.4	5.565	310–370	67–80	13.2	0.3–0.7	1, 2, 3, 4, 5
UU Aqr	0.6–0.9	0.2–0.4	3.92	250–350	76–80	13.6	0–0.2	5, 6
LX Ser	0.37–0.43	0.3–0.4	3.80	300–400	77–83	14.4	0–0.2	4, 5
RW Sex	0.8–1.3	0.55–0.65	5.88	150–250	30–40	10.8	0–0.2	5, 7
UX UMa	0.4–0.5	0.4–0.5	4.72	200–300	69–73	12.8	0–0.2	4, 5
V363 Aur	0.8–1.0	0.8–1.0	7.71	600–1000	68–72	14.2	0.3–0.5	4, 8

For some systems the values given in the literature differ significantly. To keep our results as independent as possible of uncertainties related to the system parameters of nova-likes, we always used a broad range of parameters. The values of A_V have been taken from Bruch & Engel (1994) and compared with Warner (1987) who quotes Bruch (1984). References: (1) McArthur et al. (1999), (2) Poole et al. (2003), (3) Groot et al. (2004), (4) Rutten et al. (1992, and references therein), (5) Vande Putte et al. (2003) (6) Baptista et al. (1994), (7) Beuermann et al. (1992), (8) Thoroughgood et al. (2004).

Table 3. Binary and light curve parameters of the four dwarf novae with HST/FGS parallax. The time the disc is in the quasi-stationary state during outburst t_{qs} is approximated as in Schreiber & Gänsicke (2002).

Name	M_{wd}	M_{sec}	P_{orb}	d	i	m_V(out)	A_V	t_{qs}/t_{cyc}	Ref.
SS Cyg	0.6–1.0	0.4–0.7	6.6	166 ± 12	45–56	8.5	0–0.2	5.8/49.5	1, 2, 3, 4
U Gem	1.0–1.3	0.45–0.5	4.25	90–100	67–71	9.3–9.6	0–0.1	5/118	4, 5, 6
SS Aur	0.6–1.4	0.38–0.42	4.39	175–225	32–47	10.7–10.9	0.1–0.3	5/53	4, 5
RU Peg	1.1–1.4	0.9–1.0	8.99	261–303	34–48	9.0–9.1	0–0.1	6/75	4, 7

Again, we used a rather broad range of parameters in order to avoid our conclusions depending on uncertain parameters. For completeness we added again the parameters ranges for SS Cyg according to Bitner et al. (2007). Please note that for SS Cyg M_{wd} and M_{sec} are constrained by $q = 0.683 \pm 0.012$. References: (1) Bitner et al. (2007), (2) Harrison et al. (1999), (3) Cannizzo & Mattei (1992), (4) Harrison et al. (2004), (5) Szkody & Mattei (1984) (6) Naylor et al. (2005) (7) Ak et al. (2002).

Figure 3 (inspired by Fig. 1 in Smak 1983) shows the derived mean mass transfer rates as a function of the outer radius of the disc during outburst. To avoid our results depending on uncertainties in the system parameters derived from observation we used rather broad ranges of parameters. The straight line represents the critical mass transfer rate for $M_{wd} = 1\,M_\odot$. Obviously, at a distance of 166 pc the mean mass transfer rate of SS Cyg is clearly above this limit as discussed earlier (Fig. 2). The other three dwarf novae are below the dividing line and the nova-likes have mass transfer rates higher than (or similar to) the critical rate. The striking point of Fig. 3 is the fact that the mean mass transfer rate of SS Cyg is larger (or as large) as those derived for nova-like systems with similar system parameters. In other words, if SS Cyg is indeed $d \gtrsim 140$ pc away, the difference between nova-like systems and the dwarf nova SS Cyg cannot be in the mean mass transfer rate. This conclusions represents a very important finding because it contradicts the generally accepted picture for accretion discs in CVs.

Clearly, one could argue that the distances to the nova-like systems might be systematically too small. However, the distance to RW Tri is based on a HST/FGS parallax and for the other systems we used very large upper limits for the distance. Hence, there is no easy way out of the problem. In the next section we will discuss a substantial revision of the DIM that might provide a solution.

5. Enhanced mass-transfer rate

Smak (2000), Lasota (2001), and Smak (2005) showed that enhanced mass transfer during outburst is required to explain the light curve of U Gem, especially the extremely long superoutburst in 1985. Moreover, modulations of the mass-transfer rate are necessary to explain outburst properties of SS Cyg itself (Schreiber et al. 2003) and it seems that there is growing evidence for enhanced mass transfer playing an important role in short orbital period dwarf novae of the SU UMa type (Schreiber et al. 2004; Smak 2004a, 2005; Sterken et al. 2007).

The mean mass-transfer rate is not an observed quantity but is calculated assuming constant mass-transfer rate over the cycle, hence, in case the mass transfer rate is significantly enhanced during outburst, our values are only upper limits. In addition, in the framework of the enhanced mass transfer scenario, the accretion rate during outburst and at the onset of the decline does not need to be the critical mass-accretion rate. Therefore, if evidence for a distance above $d = 140$ pc further grows, the enhanced mass transfer scenario might be considered a possible solution. The enhancement needed to put SS Cyg in the observed dwarf nova band is quite substantial. Assuming a mean mass transfer rate of $\dot{M}_{tr} = 1.5 \times 10^{17}$ g/s during quiescence, Schreiber & Gänsicke (2002) estimated the required mass transfer enhancement to be by about a factor of $\gtrsim 15$.

Taking into account the revisions of the system parameters according to Bitner et al. (2007), the required mass transfer enhancement reaches a factor of $\gtrsim 55$ for $d = 166$ pc. Even at a distance of $d = 140$ pc a factor of ~35 is required. Compared to mass transfer enhancements predicted for U Gem (factor 20−50, Smak 2005) or SU UMa superoutbursts (15−60, Smak 2004a) this seems to be plausible but one should keep in mind the model calculations by Smak (2004b) which seem to exclude irradiation induced enhancement for $P_{orb} \gtrsim 6$ h. However, if a distance to SS Cyg of 140−170 pc will be further confirmed in the future, considering enhanced mass transfer even in (some) long orbital period dwarf novae appears to be the most plausible mechanism to explain the observations.

6. Conclusions

The long term light curve of SS Cyg has been frequently used to constrain the disc instability model, in particular the viscosity parameter α. Now, it seems that we can learn something very

different but equally essential about accretion discs in CVs from analysing this particular system. SS Cyg is a dwarf nova and not a nova-like. It seems that the distance to SS Cyg is above 140 pc. If this will be further confirmed, then there is something we do not understand in this binary. The standard interpretation of mean mass transfer rates that are constant over the outburst cycle cannot be true and a difference in the mean mass transfer rate cannot be the only difference between nova-likes and (at least one) dwarf nova. This might mean that the standard DIM is in fact not adequate and has to be modified by including mass-transfer modulations. This is not a surprise to these authors (e.g. Schreiber et al. 2000; Lasota 2001; Buat-Ménard et al. 2001; Schreiber et al. 2004).

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