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Properties Of Accretion Disks

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Accretion Discs in Cataclysmic Variable Stars

B. Warner

Astronomy Department, University of Cape Town, Private Bag, Rondebosch 7700, South Africa

Abstract. An overview is given of the spatial and time-dependent properties of the accretion discs in cataclysmic variable stars.

1. Introduction

For nearly three decades it has been possible to claim that the best objects for studying accretion discs are the cataclysmic variable stars. In them, quite often most or all of the observable flux originates in discs; some are eclipsing and many show changes in disc structure on accessible time scales. With the advent of direct imaging by HST of accretion discs around protostars it is perhaps important to stress that CV discs still provide the greatest range of disc phenomena, and although the enviable spatial resolution available in protostellar discs will certainly lead to important advances in understanding of steady state discs, it is in CVs that the richest sources of time-dependent phenomena are accessible.

CV discs span a range of radius from $\sim 5 \times 10^9$ cm in the ultrashort period He-rich AM CVn binaries to $\sim 5 \times 10^{12}$ cm in ~ 200 d orbital period recurrent novae such as T CrB. The majority of CVs have orbital periods $1\frac{1}{2}$ - 10 h and disc radii $\sim 2 - 10 \times 10^{10}$cm. Their radial temperature distributions typically range from few $\times 10^4$ K in their inner regions to $\sim$ few $\times 10^3$ K in the outer regions of the largest discs. Typical masses are $\sim 10^{-10} - 10^{-9}$ $M_\odot$.

Time-dependent luminosities cover the observed range from <1 sec (flickering) through dwarf nova outbursts on time scales of days to high-low state changes of luminosity on time scales of months or years. These latter variations result from changes in mass input $\dot{M}$ into discs, but allow observation of the variations of disc structure when all parameters other than $\dot{M}$ remain constant. There is also evidence that changes of $\dot{M}$ occur on times $\geq 10^2$ y, resulting in different appearances of otherwise similar systems. Rates of mass input cover $\sim 10^{-7} - 10^{-12}$ $M_\odot y^{-1}$, and can on occasion switch off altogether. The discs themselves may be steady state, with mass transfer through the disc $\dot{M}$(d) balancing the input, as in most nova-like variables, or may be non-steady in building up mass ($\dot{M}(d) < \dot{M}$) as in dwarf novae in quiescence, or draining out mass ($\dot{M}(d) > \dot{M}$) as in dwarf novae at maximum of outburst. Transitions between these states can occur through variation in $\dot{M}$ or through instabilities in the discs themselves.

Furthermore, there is a variety of interactions of discs with their environment: irradiation from the central source, collision with the stream, tidal stress and magnetic stress from the secondary star, generation of winds, boundary effects where the disc meets the primary - or its magnetosphere. All of these can be variable in importance if $\dot{M}$ from the secondary star changes significantly.

The following sections illustrate some of these phenomena and their interpretation.

2. 'Steady State' Discs

Truly steady state discs would be very boring, but no CV disc has been observed to be that steady. The quiescent discs of dwarf novae (DN) have $T_{eff}(r) \sim$ constant (e.g. Z Cha: Wood *et al.* 1986) and are far from steady state (Mineshige & Wood 1989), being in the process of building up mass between outbursts. The high $\dot{M}$(d) discs of nova-likes and nova remnants are closer to steady state, but there are subtle observed departures: the observed $T(r)$ are slightly flatter than predicted in systems with orbital period $P_{orb} > 3.9$ h and considerably flatter for $3 < P_{orb} < 4$ h (Rutten, van Paradijs & Tinbergen 1992; Horne & Steining 1985; Baptista, Steiner & Cieslinski 1994). This might indicate that the central parts of the discs are missing (e.g. Wood, Abbott & Shafter 1992), perhaps because of clearance by the magnetosphere of the primary (Casares *et al.* 1996). Furthermore, some high $\dot{M}$(d) systems show brightness modulations ~0.7 mag with quasi-periods of tens of days (see Table 1 of Warner 1995c), and variation of 1 mag or more on time scales of years is probably universal (see Warner 1995a, p.p. 242 and 473). The former modulations may be disc instabilities (see Section 3) and the latter are probably variations of $\dot{M}$ (Section 5).

3. Thermal Instabilities

The disc instability model of dwarf nova outbursts is well established (e.g. Cannizzo 1993a); in essence, high $\dot{M}$(d) and very low $\dot{M}$(d) discs can be stable, but in a region where energy is transferred partially convectively the question of disc structure has a multiple choice answer and the disc responds by cycling between unstable 'hot' and 'cool' states. The transitions between states are effected by heating and cooling fronts that traverse the disc.

There are a number of well determined observational properties of DN that find quantitative explanation in the disc instability model - with the caveat that until recently the Shakura-Sunyaev viscosity parameter α required to explain the DN phenomena had to be selected by hand (with $\alpha_{hot} \sim 0.3$ and $\alpha_{cold} \sim 0.03$). However, the dynamo model of Tout and Pringle (1992), which generates effective α's of the correct magnitude, has recently been successfully incorporated into a time-dependent disc code, and gives realistic looking dwarf nova outbursts (Armitage, Livo and Pringle 1996).

The rate of fall of disc luminosity in a DN outburst, found to be correlated with P_{orb} (Bailey 1975; van Paradijs 1983; Warner 1995a), results from the combination of constant velocity of transition front with larger discs in the more widely separated, longer P_{orb} systems. In a given system, however, the rate of rise can vary according to where the heating front starts out; whereas cooling fronts are always launched inwards from the outer edge of the disc.

A clear correlation between luminosity at maximum of outburst and disc size, which shows as an $M_v(max) - P_{orb}$ relationship (Warner 1987, 1995a) and as an upper limit to the luminosity of outbursts of a given system (e.g. SS Cyg: Cannizzo 1993b), has been explained by Cannizzo (1993b). At outburst maximum the disc is close to a steady state, for which $\dot{M}(d) \propto r^{3/4}\ \Sigma(r) = r_d^{3/4}\Sigma(r_d) =$ const, where r_d is the disc radius and Σ is surface density. Then since the outburst starts when the disc mass has reached an upper limit where somewhere $\Sigma(r) = \Sigma_{max}(r)$, at which point it rapidly adjusts towards the steady state and $\Sigma(r_d)$ is not very much larger than $\Sigma_{min}(r_d)$ (and when it falls to the latter value the cooling front is launched), $\dot{M}(d)$ near maximum of outburst is essentially only a function of (r_d) (and hence P_{orb}).

The $M_v(max) - P_{orb}$ relationship is valuable for distance determinations, but requires some approximate knowledge of disc inclination (Warner 1987).

The DN outburst rise and fall time scales provide the means for deducing α_{hot}. The interval between outbursts gives α_{cold}, but depends also on $\dot{M}$. It has been claimed (Smak 1993; Osaki 1994) that, even though $\dot{M}$ is very low, $\alpha_{cold} \ll 0.01$ in WZ Sge which has outbursts only every 30 years. However, if the centre of the disc is missing, truncated by the magnetosphere of the primary, removing access to outbursts triggered from the inner disc, then it is possible to obtain decade outbursts without α_{cold} being extremely low (Warner, Livio & Tout 1996). WZ Sge has many of the signatures of a fast magnetic rotator.

Dwarf nova outbursts illustrate transitions between non-equilibrium low $\dot{M}(d)$ discs and short-lived near-equilibrium high $\dot{M}(d)$ discs. The Z Cam stars provide transitions into and out of equilibrium discs: if $\dot{M}$ increases and becomes greater than $\dot{M}(crit)$ while the system is in outburst, then it can settle into an equilibrium state. When $\dot{M}$ falls below $\dot{M}(crit)$ it transits back to the low state. If the $\dot{M}$ variations are caused by magnetic cycling in the secondary (Warner 1988), then some quasi-periodicity of Z Cam standstills would be expected; this has not been investigated fully. It is of interest that many months of accretion onto the primary at $\dot{M} \simeq \dot{M}(crit)$ at standstill does not heat it sufficiently to irradiate the secondary and produce self-sustaining $\dot{M} > \dot{M}(crit)$; however, as with normal DN, Z Cam stars have $P_{orb} \geq 3.7\ h$, which evidently gives a binary separation too large for irradiation-induced mass transfer to be dominant.

An important and well-studied object is UU Aqr with $P_{orb} = 3.9$ h. From eclipse mapping this has a distance of 200 pc, $i = 78°$ and $\dot{M} = 10^{9.0\pm0.1}\ M_\odot\ y^{-1}$ (Baptista, Steiner & Cieslinski 1994, Baptista, Steiner & Horne 1996), which gives $M_v(d) = 5.5$ - 5.8 from the observed $m_v = 13.5$ -13.8 and $A_v = 0.1$ mag. This system is just at $\dot{M}(crit)$ and its 0.3 mag range of brightness is shown to result from variations in $\dot{M}(2)$. With a measured $T_{eff}(r_d) \simeq 6000$ K it is very near to triggering DN outbursts. A slightly larger reduction of $\dot{M}$ should turn it into a Z Cam star with outbursts reaching $M_v(max)$, i.e. $m_v \simeq 12.8$. This could account for the occasional isolated observations at $m_v \simeq 13.0$ (Volkov, Shugarov & Seregina 1986) and implies that UU Aqr is a Z Cam star in extended standstill. The measured temperature of the primary in UU Aqr is 34 000 K, which agrees with the $T_{eff}(1)$ - $\dot{M}(1)$ relationship (Warner 1995a, Figure 9.9). This is too low a temperature to provide substantially enhanced $\dot{M}$, in agreement with the expectation for Z Cam stars at standstill. The ~ tens of days brightness modulation in some high $\dot{M}$ systems may be a direct result of $\dot{M} \sim \dot{M}(\mathrm{crit})$, which can produce a stable inner disc with unstable outer disc (Lin, Papaloizou & Faulkner 1985) or may be the result of irradiation of the inner disc by the primary (Tuchman, Mineshige & Wheeler 1990; Warner 1995c).

4. Tidal Stresses

As gas passes through the disc and reaches the primary, its angular momentum is transferred out through the disc and is returned to the secondary via tidal stresses at the edge of the disc. This tidal interaction determines the radius of the disc, and is a function both of mass ratio $q = M_2/M_1$ and rate of mass transfer $\dot{M}(1)$ onto the primary. In quiescent DN discs the radius $r_d/a \simeq 0.30$, but these are not in equilibrium; in high $\dot{M}(1)$ $(=\dot{M}=\dot{M}(\mathrm{d}))$ equilibrium discs the radii are in general close to the tidal truncation radius (Harrop-Allin & Warner 1995). This is in agreement with the general finding that quiescent DN discs have much lower viscosity than high $\dot{M}(\mathrm{d})$ discs.

For $q \geq 0.22$ the tidal truncation radius is smaller than the radius r_{31} at which a 3:1 orbital resonance occurs between particles in the disc and the secondary star. Therefore for $P_{orb} \geq 3$ h the maximum disc radius achieved during a DN outburst should not access the 3:1 resonance, but shorter period systems can experience strong perturbation of the outer disc when they are in high $\dot{M}(\mathrm{d})$ states. One consequence of this is that the disc becomes elliptical and precesses with a period $\sim$ 2 d (Whitehurst 1988; Hirose, Osaki & Mineshige 1991).

Observationally this is seen as 'superhumps', at the difference frequency between the orbital and precession frequencies, during superoutbursts of short orbital period DN (known collectively as SU UMa stars) and in high $\dot{M}$ equilibrium discs at short P_{orb} (Warner 1975, 1995a,b). According to Osaki (1989), a superoutburst occurs when the accumulation of mass and angular momentum in a disc (only small fractions of which are transferred to the primary during normal outbursts) becomes sufficient for the outer radius in an outburst to reach the 3:1 resonance, thereby stressing the outer disc into a high viscosity state (which keeps the whole disc in the high state) until about half the disc mass has been drained. At superoutburst maximum r_d is therefore larger than in normal outbursts, so a superoutburst is both more luminous and of longer duration. Angular momentum is extracted from the outer parts of the disc faster than it flows from the inner regions, which shrinks the mean radius of the disc and probably accounts for the decreasing amplitude and increasing period of the superhumps on the 'plateau' of superoutburst. Observationally, at the initial, brightest part of supermaximum, visual brightnesses m_v(supermax) are typically 0.75-1.0 magnitude brighter than m_v(max) (but a few are 2-3 mag brighter), and decays at $\sim$ 0.1 mag d^{-1} for about 10 d, until m_v(max) is reached, at which time the superoutburst declines at the same rate as a normal outburst. In both observations (Warner 1995a,b) and simulations (Osaki 1996) m_v(end) at the end of the plateau is closely equal to the mean m_v(max) of ordinary outbursts, i.e., $M_v(\mathrm{end}) = \bar{M}_v(\mathrm{max})$. It is possible to check this latter relationship in a few cases (the example of WZ Sge was already given in Warner 1995a, p. 194): Sproats *et al.* (1996), from infrared fluxes of the secondaries, have deduced distances of several SU UMa stars and find they mostly lie well above the $M_v(\max)$ - P_{orb} relationship. However, correction for inclination and for $\bar{m}_v(\max)$ - $m_v(\text{supermax})$ where possible brings these into agreement (and in any case, the $M_v(\max)$ - P_{orb} relationship as originally established (Warner 1989) used $\bar{M}_v(\max)$ for the SU UMa stars - if $m_v(\text{supermax})$ had been used they would have departed from the relationship in the same way as those of Sproats *et al.*, who appear to have chosen the brightest value of m_v, i.e., $m_v(\text{super})$, for their calculations). This result extends the applicability of the $M_v(\max)$ - P_{orb} relationship: in those systems where only superoutbursts are observed it can be used as an $M_v(\text{end})$ - P_{orb} relationship.

The reason for the equality of $M_v(\text{end})$ and $M_v(\max)$ is that a cooling front is launched from the outer edge of the disc when $\Sigma(r_d)$ falls to $\Sigma_{min}(r_d)$. Provided r_d is similar in the two circumstances then $\dot{M}(\text{d})$ and $M_v(\text{d})$ will be similar. The simulations (Osaki 1996) show that $r_d(\text{end}) \simeq \bar{r}_d(max)$.

For studying thermal and tidal instabilities the recently discovered V1159 Ori stars (named here after the first to be recognised - Jablonski & Cieslinski 1992 - and studied in detail - Patterson *et al.* (1995a) - rather than the later discovered ER UMa and RZ LMi (Kato & Kunjaya 1995; Robertson *et al.* 1995)) provide unexpected ease of observation. With normal outbursts every $\sim$4 d and superoutbursts as frequent as every 19 d, these are relatively high $\dot{M}(\sim 5 \times 10^{16}\text{gs}^{-1})$ for P_{orb} as short as $1\frac{1}{2}$h. They appear never to reach a stable quiescent state, probably because both cooling and heating fronts are transitting at the same time. They evidently have $\dot{M}(\text{d}) \sim \dot{M}(\text{crit})$ and are the short P_{orb} analogues of Z Cam stars, unable to reach standstills because of the destabilising effect of the tidal stress (Warner 1995b, Osaki 1996). The discovery of an eclipsing V1159 Ori system would enable application of the full range of diagnostic techniques - e.g., eclipse mapping and r_d determinations throughout the normal and supercycles. An intensive one month international campaign on such a star may well generate results more complete and coherent than all the work done on SU UMa stars in the past two decades.

Even higher $\dot{M}(\geq 10^{17}\text{gs}^{-1})$ systems of short orbital period are becoming known: the nova-like BK Lyn (PG0917+342) has an absorption line spectrum and low amplitude superhumps (Skillman & Patterson 1993), the nova remnants CP Pup and V1794 Cyg (O'Donoghue *et al.* 1989; White, Honeycutt & Horne 1993; Patterson, private communication) and possibly the recurrent nova T Pyx (Schaefer *et al.* 1992) have high $\dot{M}$ - probably because of irradiation of the secondary of the nova-heated primary - and have superhumps indicative of precessing discs. Finally, 'negative superhumps' (i.e., photometric modulations at periods shorter than P_{orb}) are known which may indicate tilted discs, with retrogressing nodes (Patterson 1995). Positive and negative superhumps may be simultaneously present in AM CVn (Patterson, Halpern & Shambrook 1993).

5. Variable Mass Transfer

The observed absolute visual magnitudes of discs are shown in Figure 1. Although the standard theory of orbital angular momentum loss by gravitational waves and magnetic braking gives essentially a unique relationship between $\dot{M}$ and P_{orb}, it is clear that at all P_{orb} there is some spread of $\dot{M}$, amounting to sev-

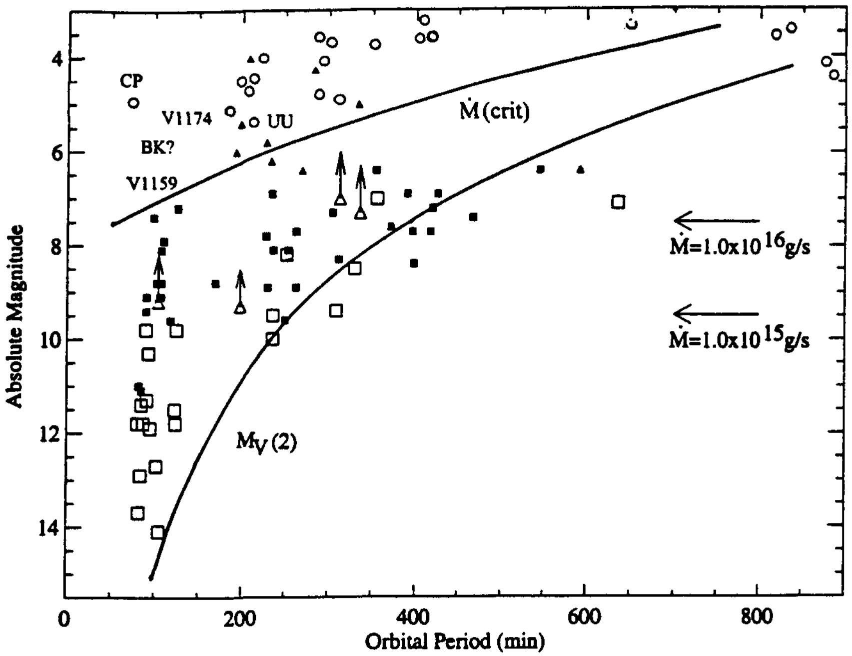

Figure 1. Absolute magnitudes of CV discs - combining data from Warner (1987) and Sproats, Howell & Mason (1996). Dwarf novae: open and solid squares; Nova-likes: open and solid triangles; Nova remnants: open circles. The positions of the V1159 Ori stars, CP Pup, BK Lyn, UU Aqr and V1794 Cyg are shown. The solid lines are the absolute magnitude of the secondary and the critical mass transfer rate for disc thermal instability.

eral orders of magnitude for small P_{orb}. The locus of secondary star brightness M$_v$(2) in Figure 1 might suggest that we lose the lower $\dot{M}$ systems at longer P_{orb}, but such systems would have large amplitude DN outbursts which would greatly outshine the secondary, so the lack of such systems is unlikely to be a selection effect. The spread of M$_v$(d) for $3 \leq P_{orb} \leq 6$ h has been explained by irradiation-enhanced $\dot{M}$ from the secondary (Wu, Wickramasinghe & Warner 1995a), and in particular the highest $\dot{M}$ ($\sim 2 \times 10^{-8}$ M$_\odot$y^{-1}) systems in Figure 1 are nova remnants where radiation from the hot primary is responsible for the high $\dot{M}$. Ignoring these, there is a maximum $\dot{M} \sim 1 \times 10^{-8}$ M$_\odot$y^{-1} in CVs (Warner 1987, 1995a) which is a result of saturation of the irradiation feedback mechanism. The stability analysis shows that no systems with $\dot{M} < \dot{M}$(crit) are expected with P_{orb} below about 4 h, explaining the rarity of DN in the P_{orb} = 3-4 h range. In the $3 \geq P_{orb} \geq 4$ h range the VY Scl star phenomenon is observed, with transitions between high and low $\dot{M}$ occurring on time scales of days to months. This also is understood in terms of irradiation induced instability of $\dot{M}$ (Wu, Wickramasinghe & Warner 1995b). The possible supression of full amplitude DN outbursts in the low state by irradiation of the disc by the hot ($\geq 5 \times 10^4$ K) primary has been pointed out (Warner 1995c). Variations in brightness of high $\dot{M}$(d) systems on time scales of years cannot readily be attributed to discs themselves, and are better understood as sensitive indicators of small variations of $\dot{M}$, probably resulting from cycling of the magnetic dynamo in the secondary stars (Applegate 1992; Warner 1988). Variations of $\dot{M}$ can be expected to have interesting observable effects in CVs with magnetic primaries, few of which have so far been recognised. These include (a) the formation of a disc immediately after a nova outburst because of a high irradiation induced $\dot{M}$ which is able to compress the primary's magnetosphere sufficiently, (b) the transition from disced to discless polar as the post-nova $\dot{M}$ decreases, (c) the transition from disced to discless and *vice versa* in intermediate polars as $\dot{M}$ falls to a low state and returns, (d) systems that have $\dot{M}$ just at the critical rate for disc/discless transition that (in analogy wih Z Cam stars) make moderately frequent moves between the two states.

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Discussion

S. Balbus: Is there a single example one can point to in a CV system in which one can infer an $R^{-3/4}$ temperature law?

J. Smak: The peculiar, flat T vs R distributions obtained with the MEM technique are largely an artefact resulting from the assumption of a flat disk. Real disks have finite z-thickness and at inclinations close to 90° the edge of the disk partly obscures its inner, concave surface. (in fact, the degree of this spurious flatness is well correlated with inclination). Systems with $i = 60 - 70°$ do indeed show $T \sim R^{-3/4}$.

K. Beuermann: Could you comment on the mechanism which drives the high mass-loss rate in the ultrashort-period system labelled PS in your figure and on the longevity of their high $\dot{M}$?

B. Warner: CP Pup and V1974 Cyg are nova remnants in which the high rate of mass transfer presumably arises from irradiation of the secondary by the hot primary. BK Lyr is not a known nova, but may be prehistoric. These temporary phases of high mass transfer probably last hundreds of years, but do not affect the long term average rate of orbital evolution.

A. King: If you irradiate steadily, the secondary star will expand to a slightly larger radius. During this phase the mass transfer ratio will rise somewhat. However, the star will not continue to expand, after about 10^5 yr the mass transfer ratio will return to normal.

F. Ringwald: Which one is the eclipsing Z Cam star?

T. Naylor: It was EM Cyg, studied by E.L. Robinson and company some years ago.

M. Różyczka: Is there any evidence for the presence of jets in cataclysmic variables?

B. Warner: There is strong evidence for bipolar winds in the high luminosity systems, but not for collimated jets.