The 1996 outburst of GRO J1655-40: disc irradiation and enhanced mass transfer

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Abstract. We show that the 1996 outburst of the X-ray binary transient system GRO J1655–40 can be explained by the standard dwarf-nova type disc instability, followed by an episode of enhanced mass transfer from the secondary if the mass transfer rate in GRO J1655–40 is within a factor $\lesssim 10$ of the stability limit. We argue that irradiation of the secondary during the onset of the outburst driven by the thermal instability in the outer disc can increase the mass transfer rate above the minimum value required for stable accretion. This will then produce the period of near-constant X-ray emission seen in this system. This scenario can also explain the observed anti-correlation between the optical and X-ray fluxes. It is generally accepted that optical emission in low-mass X-ray binaries is produced by irradiation of the outer disc by X-rays. There is also strong circumstantial evidence that in order for the outer disc to see the irradiating flux, it must be warped. Depending on the warp propagation mechanism, either a burst of mass from the secondary or viscous decay are likely to decrease the degree of warping, thereby causing the decrease in the observed optical flux while the X-ray flux remains constant or even increases, exactly as observed in GRO J1655–40. Finally, the decrease of the disc warping and, therefore, irradiation will cause the disc to become unstable once again, terminating the outburst.

Key words: stars: binaries: close – stars: individual: GRO J1655-40 – accretion, accretion disks – instabilities – X-rays: general

1. Introduction

The X–ray source GRO J1655–40 has several unusual characteristics. Though, like all soft X-ray transients, it is a low-mass binary system, its 1.7–$3.3 M_\odot$ secondary orbiting a 5.5–$7.9 M_\odot$ black hole (Shahbaz et al. 1999) is considerably more massive

than is typical in such systems (see e.g. a review by Tanaka & Shibazaki 1996). Its mass and spectral type (F3-F4) imply that the donor star is near (or just beyond) the end of its main-sequence life-time. In fact Kolb et al. (1997) and Kolb (1998) assert that it appears to be crossing the Hertzsprung gap, i.e. expanding towards the giant branch, which would imply a very large mass transfer rate, $\dot{M}_T \sim 10^{19}$ g s^{-1} (King & Kolb 1999). Even if the secondary star in GRO J1655–40 is still on the main sequence, as argued by Regös et al. (1998), the inferred mass transfer rate, $\dot{M}_T \gtrsim 10^{17}$ g s^{-1}, is orders of magnitude greater than $\dot{M}_T$ estimates in other X-ray transients (see e.g. Chen et al. 1997). Moreover, the values quoted above are close to the critical rate, above which the irradiated accretion disc in GRO J1655–40 would be stable with respect to the dwarf-nova type instability (van Paradijs 1996; see Dubus et al. 1999b for a most recent discussion of the critical rate for this instability), that is generally thought to be responsible for the transient behaviour of low-mass X-ray binary systems.

The outbursts themselves are also rather atypical. Like other Black Hole (Low Mass) X-ray Transient systems (BHXTs), GRO J1655–40 has been quiescent for more than 30 years before entering the active phase in 1994. However, contrary to the behaviour of 'conventional' BHXTs, the first outburst was followed in 1995 by two others which displayed hard X-ray spectra. Finally, after the last burst of emission in July/August 1995 the system settled into X–ray quiescence, with luminosity of $L_X \approx 2 \times 10^{32}$ erg s^{-1}.

This quiescent state ended around April 25, 1996 when a new, soft X–ray outburst began, which is the main subject of this paper. Orosz et al. (1997) obtained BVRI photometry close to the onset of the outburst and found the rise in X-ray flux delayed by 6 days with respect to the optical increase. Consequently, Hameury et al. (1997) showed that the rise to outburst, and in particular the X-ray 'delay', are very well described by the dwarf-nova type disc instability model (DIM) if the accretion disc is truncated at $\sim 5 \times 10^3\ R_S$ ($R_S = 2GM/c^2$ is the Schwarzschild radius). However, the success of this model is put into perspective by the subsequent behaviour of the system during the outburst, when, after the first local maximum,

the soft X-ray light curve rose to a higher luminosity 'flaring' plateau. The present theoretical understanding tells us that this type of light-curve cannot be produced based on the standard DIM (Hameury et al. 1998).

The behaviour of the optical luminosity during the 1996 outburst of GRO J1655–40 also seems to defy the generally accepted idea (based on a solid observational background) that in Low Mass X-ray Binaries (LMXBs) the optical emission from the accretion disc is due to reprocessing of X-rays in the outer disc. The fact that in GRO J1655–40 the optical flux decreases while the X-ray flux increases and then fluctuates around an approximately constant value is difficult to reconcile with the X-ray reprocessing model (Hynes et al. 1998). Finally, the list of unusual properties of GRO J1655–40 should be completed by the presence of a superluminal 'jet' seen during the 1994 outburst (Hjellming & Rupen 1995).

In this paper we argue that the puzzling behaviour of this system can be readily reconciled with the DIM, if we take into account the fact that the mass transfer rate in GRO J1655–40 is likely to be rather close to the stability limit. In this case, irradiation of the secondary during an outburst may be enough to increase the mass transfer rate by a factor of a few and thereby push the system into the stable regime. This scenario and its expected effect on the observed X-ray light curve are discussed in detail in Sect. 2. Furthermore, in Sect. 3 we speculate that the reason the optical flux does not rise with increasing X-ray luminosity is a reduction in the amplitude of the outer disc warping. Using a flared planar disc 'approximation' to describe a warped disc, we show that as a result, the intercepted X-ray flux and therefore the observed optical emission is reduced. We further suggest in Sect. 4 that the flattening of the outer disc and a consequent decrease in X-ray irradiation may also be responsible for the ultimate end of the stable accretion phase, by raising the stability criterion. We conclude with a final discussion and a summary in Sect. 5.

2. The X–ray outburst

Following Shahbaz et al. (1999), in our estimates below we assume that GRO J1655–40 contains a $7\,\mathrm{M_\odot}$ black hole and that the mass ratio between the primary mass M_1 and the secondary mass M_2 is $q \equiv M_2/M_1 = 0.33$. We also adopt a distance to the system of $3.2\,\mathrm{kpc}$ (Hjellming & Rupen 1995).

Fig. 1a shows the progress of the 1996 X-ray outburst of GRO J1655–40. The ASM (2-12 keV) 'soft' X-ray flux began to rise 6 days after the start of the optical outburst and 15 days later attained a maximum corresponding to $\sim 0.12L_\mathrm{Edd}$ (hereafter we use spectral fits by Sobczak et al. 1999 to convert ASM fluxes to bolometric luminosity values), where $L_\mathrm{Edd} = 1.25 \times 10^{38}M/\mathrm{M_\odot}$ erg s^{-1} is the Eddington luminosity. After ~ 12 days of a roughly exponential decline which followed the first maximum, the soft X-ray flux fell by about 30%. It then began to rise again, and after about two months from the onset of the outburst, reached a strongly flaring plateau with total luminosity varying around $\sim 0.17L_\mathrm{Edd}$. This flaring state, which Sobczak et al. (1999) identify with the very high spectral state,
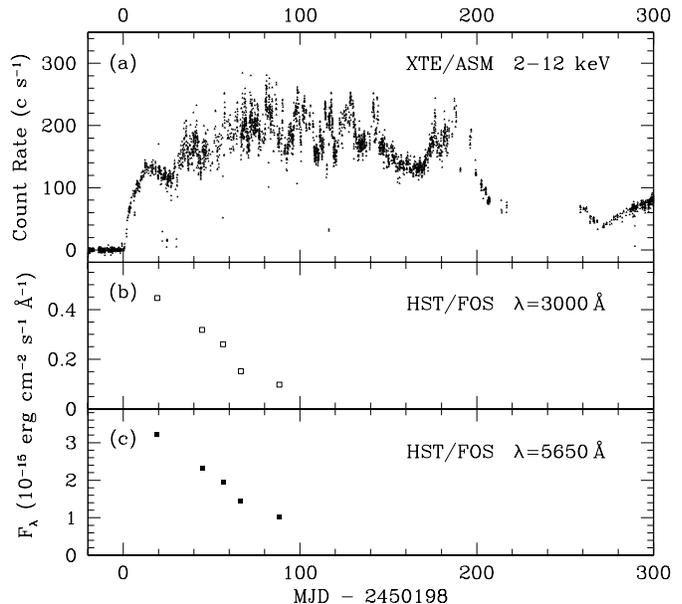

Fig. 1a – c. X-ray (**a**), UV (**b**) and optical (**c**) light-curves (Sobczak et al. 1999; Hynes et al. 1998) of the 1996 outburst of GRO J1655–40. A comparison of the three panels clearly shows anti-correlation between the observed optical (and UV) fluxes and soft X-ray count rates. The data on panels **b** and **c** has not been corrected for interstellar reddening. Note that the flux scales in panels **b** and **c** supersede those in Fig. 3 of Hynes et al. (1998) which were in error.

continued roughly until day 200 of the X-ray outburst. Over the next ~ 70 days the luminosity fell to less than a third of its peak value. Note that this local minimum was followed by a ~ 150 day long reflare, which we do not try to address in this paper (but see Sect. 4). Our goal here is to apply the (modified) DIM to the main 1996 outburst of GRO J1655–40 since, as discussed above, this model was successfully used to describe the beginning of this event. Various type of 'reflares' (observed also in dwarf novae) do not have a clear explanation in the context of the DIM (see e.g. Hameury, Lasota & Warner 2000). One can speculate that the long rise-time of the GRO J1655–40's reflare could be due to an inside–out outburst from a non–truncated disc, while its flat-topped lightcurve suggests a quasi–steady accretion phase. However, in view of incomplete optical coverage and uncertainties in models discussed below, we feel that an attempt at serious modeling of the reflare would be pure guesswork.

It is very suggestive that the e-folding rise time of $\lesssim 1$ day and the e-folding decay time of ~ 35 days, observed in the first 27 days of the X-ray outburst of GRO J1655–40, are characteristic of the so-called FRED-type light curves seen in many X-ray transients (see e.g. Chen et al. 1997). The rise and decay (see Figs. 1[b] and 1[c]) of the optical and UV luminosity also follow the pattern of a FRED outburst with an e-folding decline time close to ~ 73 days, considerably longer than that for X-rays. This behaviour naturally follows from the DIM in which the outer regions of the accretion disc are irradiated by the X-rays from the inner region (King & Ritter 1998; Dubus et al.

1999a). One could conclude, therefore, that GRO J1655–40 was producing a 'normal' X-ray transient outburst when, on day 27 a new event occurred which stopped the decline of the X-ray flux. In what follows, we will argue that the change in the outburst pattern was due to an increase in the mass transfer rate, which moved the system parameters into the range corresponding to stable accretion for an X-ray irradiated disc.

The minimum mass transfer rate necessary for a stable, steady-state accretion in an X-ray irradiated disc may be written as (Dubus et al. 1999b)

$$\dot{M}_{\mathrm{crit}}^{\mathrm{irr}} \approx 2.8 \times 10^{18} \left(\frac{R_{\mathrm{out}}}{5.3 \times 10^{11} \mathrm{cm}} \right)^{2.1} \times$$
$$\left(\frac{\mathcal{C}}{5 \times 10^{-4}} \right)^{-0.5} \mathrm{g \, s}^{-1}. \qquad (1)$$

Here the phenomenological 'parameter' (in reality a function of radius and time, see Sect. 3) $\mathcal{C}$ provides a simple description of the disc irradiation properties through:

$$T_{\mathrm{irr}}^4 = \mathcal{C} \frac{\dot{M} c^2}{4\pi\sigma R^2}, \qquad (2)$$

where T_{irr} is the irradiation temperature. $\mathcal{C} = 5 \times 10^{-4}$ is the value that represents best the average irradiation flux intercepted by the the outer disc regions in LMXBs (see Dubus et al. 1999b[1]). We assumed that in outburst the disc outer radius R_{out} expands to 90% of the primary Roche lobe radius (Smak 1999b), so that

$$R_{\mathrm{out}} = 5.3 \times 10^{11} \left(\frac{M_1}{7 \mathrm{M}_\odot} \right)^{1/3} \mathrm{cm} \qquad (3)$$

Let us note, however, that if the outward propagating heat front (Hameury et al. 1998) did not reach the outermost disc regions, the disc expansion would be negligible, and its outer edge would extend only to $\sim 70\%$ of the Roche lobe radius.

The critical accretion rate given by Eq. (1) is very uncertain, as discussed in Dubus et al. (1999a), and should be considered an order of magnitude estimate only. For the accretion in an irradiated disc to be stable the mass-transfer rate from the secondary has, therefore, to be larger than $\sim 10^{18}$ g s^{-1}. For GRO J1655–40 this corresponds to $\dot{M}_{\mathrm{T}} \sim 0.1 \dot{M}_{\mathrm{Edd}}$ ($\dot{M}_{\mathrm{Edd}} = L_{\mathrm{Edd}}/0.1c^2$).

Since $L \sim 0.2 L_{\mathrm{Edd}}$ during the plateau phase of the outburst, the observations are entirely consistent with a *stable* disc accreting at $\dot{M} = \dot{M}_{\mathrm{T}} \sim 0.2 \dot{M}_{\mathrm{Edd}}$. For our arguments to work, however, the mass transfer rate from the secondary must be smaller than critical value of $0.1 \dot{M}_{\mathrm{Edd}}$ quoted above, since otherwise GRO J1655–40 would not be a transient, at least according to the DIM. So what is known about $\dot{M}_{\mathrm{T}}$ in this system?

Estimates of the mass transfer rate in GRO J1655–40 quoted in the literature differ by three orders of magnitude. At the high end, Kolb et al. (1997) and King & Kolb (1999) argue that the secondary star in GRO J1655–40 is crossing the Hertzsprung

gap between the main sequence and the red giant branch, and is therefore undergoing a rapid envelope expansion (on a time scale $\sim 10^7$ years). They conclude that this implies a mass transfer rate of order $M_2/(10^7 \mathrm{y}) \gtrsim 10^{19} \mathrm{g \, s}^{-1}$. Obviously, taken at face value, this result suggests that GRO J1655–40 cannot be a transient system. Regös et al. (1998) show, however, that the type F3-F4 donor can still lie on the main sequence if convective overshooting at the core–envelope boundary is taken into account in stellar modeling. The presence of such (or equivalent) mixing is expected for main–sequence stars in the relevant mass range (see Regös et al. 1998 and references therein). Based on this argument, Regös et al. (1998) derive a considerably lower value for the mass transfer rate in GRO J1655–40, estimating that $\dot{M}_{\mathrm{T}} \sim 10^{17} - 10^{18}$ g s$^{-1} \approx 0.1 - 1.0 \times \dot{M}_{\mathrm{crit}}^{\mathrm{irr}}$. If this estimate is correct, the quiescent accretion disc in GRO J1655–40 is still unstable, though with the mass transfer rate rather close to the critical one. In this case, an increase in $\dot{M}_{\mathrm{T}}$ by a factor of a few during the outburst would stabilize the accretion, and produce the 'plateau' in the light curve, just as observed during the 1996 outburst. Interestingly, Hameury et al. (1997) showed that the spectrum of GRO J1655–40 in quiescence as well as its rise to outburst in 1996 can be very well modeled using the standard DIM operating in a truncated disc, assuming that the mass transfer rate is 2×10^{17}g s^{-1}, within the range considered plausible by Regös et al. (1998).

These relatively high values of $\dot{M}_{\mathrm{T}}$ are somewhat difficult to reconcile with the estimate of van Paradijs (1996), who used the standard method of deducing the mass transfer rates in X-ray transients by dividing the mass accreted during the outburst by the recurrence time. By estimating the total emission observed during the 1994–1995 period of activity and assuming a recurrence time of > 30 years van Paradijs (1996) obtained $\dot{M}_{\mathrm{T}} \lesssim 8 \times 10^{15}$g s^{-1} (see also Menou et al. 1999a). However, the validity of this method for the recent outburst cycle of GRO J1655–40 is questionable, since the observed outbursts clearly do not occur with even rough regularity. Between August 1995 and April 1996 GRO J1655–40 was in true quiescence so the recurrence time for the 1996 outburst was only 9 months. The relevant mass transfer rate may then be estimated by dividing the mass accreted during the 1996 outburst (which was roughly 4×10^{24}g, assuming the standard 10% radiative efficiency) by this recurrence time. The result, $\dot{M}_{\mathrm{T}} \approx 2 \times 10^{17}$g s^{-1}, is in reasonable agreement with convective overshooting models of Regös et al. (1998). This, of course, does not resolve the problem of the pre–1994 phase, namely that no outbursts were observed during the preceding 30 years.

Overall we conclude that there is significant evidence pointing to the mass transfer rate in GRO J1655–40 being rather *close* to the stability limit of an irradiated disc, at least during the period directly preceding the 1996 outburst. Furthermore, we can confidently state that the transient nature of this system as well as the shape of the X-ray light curve seen in 1996 can be attributed to the dwarf–nova type disc instability only if $\dot{M}_{\mathrm{T}}$ in quiescence was below, but not too far from the critical mass transfer rate. The former condition is necessary to have outbursts at all, and the latter is desirable so that a reasonable increase in $\dot{M}_{\mathrm{T}}$ during

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[1] Dubus et al. write that this value is used 'by comparison with a formula extensively used in the literature' but in fact the numerical value of $\mathcal{C}$ is deduced from applications of this formula to observations.

the first part of the outburst is sufficient to stabilize the disc. In addition, the same value of $\dot{M}_\mathrm{T}$ is required to explain all the rise–to–outburst properties.

An obvious reason for an increase in $\dot{M}_\mathrm{T}$ is X-ray irradiation of the secondary star. According to Phillips, Shahbaz & Podsiadlowski (1999), X-ray heating strongly affects the vertical structure of the irradiated outer layers of the secondary. Assuming an X-ray luminosity of 1.4×10^{37} erg s^{-1}, they obtain for GRO J1655–40 a (maximum) ratio of the irradiating to the intrinsic stellar flux ~ 6.6. They were considering BATSE (20 -200 keV) X-ray fluxes observed during the March 1995 event, whereas during a typical outburst most of the energy is emitted in softer (2-20 keV) X-rays (Sobczak et al. 1999). At the first maximum in the 1996 outburst, the total X-ray luminosity was approximately 8 times larger than the value used by Phillips et al. (1999), so the flux ratio would instead be ~ 50 and the expected effect considerably larger. Thus, an increase of the mass-transfer rate due to irradiation should be expected. In addition, in a recent seminal article, Smak (1999a) showed that mass–transfer enhancements play a fundamental role in dwarf–nova outbursts (see Sect. 5) and therefore they should also be expected in X–ray transients.

As pointed out by Phillips et al. (1999) X-ray irradiation does not directly affect the vicinity of the L_1 point but heats up matter located higher in altitude. This will induce a delay, because the heated matter has to move to the Roche nozzle before falling onto the accreting object. Such a delay was observed in dwarf novae; when the heating of the secondary by UV and optical emission is clearly observed, brightening of the hot spot due to the increased mass transfer appears a few days after the outburst maximum (Smak 1995). If the increased mass-transfer rate is due to irradiation, this delay must be shorter than the disc viscous time, in order to keep $\dot{M}_\mathrm{T}$ approximately constant. In the opposite case, the light-curve would instead have an exponential shape (Hameury et al. 1988; Augusteijn et al. 1993; Hameury et al. 1997).

The disc viscous time is

$$
\begin{aligned}
t_\mathrm{vis} \approx & \frac{R^2}{\nu} = 320 \left(\frac{\alpha}{0.1} \right)^{-4/5} \left(\frac{\dot{M}}{10^{18}\mathrm{g\,s^{-1}}} \right)^{-3/10} \times \\
& \left(\frac{M}{7\mathrm{M_\odot}} \right)^{1/4} \left(\frac{R}{10^{11}\mathrm{cm}} \right)^{5/4} \mathrm{d},
\end{aligned} \quad (4)
$$

using the expression for midplane temperature given for the 'hot' Shakura & Sunyaev (1973) solution. At GRO J1655–40's outer disc radius this time is longer than the total duration of the 1996 activity (~ 500 days), at least for values of $\alpha \approx 0.1$ - 0.2 assumed in the DIM.

In our picture, irradiation of the secondary at the time of the first maximum in the X-ray light curve, would increase the mass transfer rate from the companion. To be consistent with observations, this increase should affect the accretion rate onto the black hole after about two weeks, a considerably shorter time period than t_vis above. In this case, however, the relevant time scale is not that given by Eq. (4), but instead the time it takes for a surface density front, created by a sudden increase

in mass transfer, to diffuse towards the inner disc regions. In the presence of a warp, matter transfered from the companion is fed to the disc not at the outer edge but at radius $\sim R_\mathrm{circ}/2$ (see e.g. Wijers & Pringle 1999), where

$$
R_\mathrm{circ} \approx 2.13 \times 10^{11} \left(\frac{M_1}{7\mathrm{M_\odot}} \right)^{1/3} \mathrm{cm} \quad (5)
$$

is the so called circularization radius corresponding to the specific angular momentum of the mass transferred through the L_1 Lagrangian point. The time in which this surface density excess will reach the black hole is then given by (Hameury et al. 1997)

$$
t_\mathrm{vis}^c \lesssim t_\mathrm{vis}(R_\mathrm{circ}) \frac{\delta R}{R_\mathrm{circ}} \quad (6)
$$

where δR is the width of the surface density contrast. A density excess with $\delta R/R_\mathrm{circ} \sim 0.1$ (see e.g. Frank et al. 1987) would diffuse to the central black hole in ~ 20 days in agreement with our scenario. As we pointed out above, this number should be considerably longer than the expected delay between irradiation of the secondary and the increase in mass transfer, as required to produce a flat light-curve. Although it is very difficult to estimate how long it takes for the heated matter to reach the L_1 point (see Hameury et al. 1993, for discussion of a related problem), a time of $\sim$ few days is reasonable in the sense that it would imply subsonic speeds.

Our explanation of the 'flat top' X-ray light-curve of GRO J1655–40 is very similar to the one proposed by King & Cannizzo (1998) for light-curves of Z Cam-type dwarf-nova systems (see their Fig. 2). These authors do not invoke irradiation to explain the increased mass-transfer rate, however, but attribute mass transfer variations to a starspot.

Interestingly, the King & Cannizzo (1998) model is more successful in our case than it is in explaining Z Cam 'standstills'. In Z Cam the luminosity is observed to stick at a constant level halfway down from maximum, whereas in light curves produced by King & Cannizzo the the 'standstill' is at a luminosity higher than the outburst maximum, as in GRO J1655–40. King & Cannizzo expect this to be the result of the high mass-transfer enhancement factor (6) used in their calculation. In reality, however, the mass-transfer rate corresponding to stable disc accretion is, by construction, always higher than the maximum outburst mass accretion rate. The reason (see e.g. Hameury et al. 1998) is that at outburst maximum, before the cooling wave begins to propagate, the accretion rate in the disc is almost constant, i.e. at the outer disc edge (or at the hot disc outer edge) it is close to the accretion rate corresponding to the critical surface density (Σ_min marking the end of the 'hot' branch of the S-curve representing disc equilibria). A stable mass-transfer rate must be larger than this value.

3. The optical light curve

There is now a general consensus that optical emission in persistent and transient (in outburst) low-mass X-ray binaries is due to reprocessing of X-rays by the outer disc (see e.g. van Paradijs & McClintock 1995). This is also the case for GRO J1655–40,

since a simple estimate of the expected optical flux from a non-irradiated disc which reproduces the observed X-ray emission falls short of the observed optical flux by roughly an order of magnitude (see Fig. 2). Moreover, as we pointed out in Sect. 2, the optical light-curve is entirely consistent with the decline from maximum during a typical FRED-type outburst in an irradiated disc. Longer UV and optical decline time scales (~ 73 days, as compared to ~ 35 days for the X-ray flux) are simply due to the fact that as the irradiating flux declines, the outer disc edge becomes cooler and the peak of the emission moves into the optical band, thus compensating for the decrease in the total emission from the outer disc.

However, this simple picture clearly cannot explain the behaviour of the optical flux at times later than ~ 30 days after the onset of X-ray outburst. At this time, X-ray flux begins to increase, while the optical and UV emission continues to decline. Here we argue how the scenario for the X-ray emission of GRO J1655–40 described in Sect. 2 can reconcile these observations with the X-ray reprocessing origin of the optical emission.

As shown by Dubus et al. (1999b) the outer regions of a planar accretion disc cannot intercept the X-rays emitted by a point source located at the midplane. Therefore, in order for the outer disc to be irradiated, it must be warped (the other possible way for the outer disc to see the X-rays - an extended irradiating source - fails to explain why the outer disc is effectively geometrically thick while the vertical equilibrium implies very thin discs).

The origin and propagation of warps in accretion discs is still an open question (see e.g. Pringle 1999). Here we consider two possible regimes: one with low viscosity, when the warp propagation relies on sound waves; and another with high viscosity, when the warp evolution is driven by diffusion. As we shall see, in both cases the warp amplitude in GRO J1655–40 is likely to decay during an outburst.

If the viscosity is low, i.e. if $H/R > \alpha$, where H is the half-thickness of the disc, the warp can propagate as a non–dispersive wave at approximately the speed of sound (Papaloizou & Lin 1995). This regime can be relevant if the outer disc regions are not affected by the propagation of the heat front during the outburst. In the standard DIM the heat–front passage changes the viscosity parameter α from a low, cold (~ 0.01) to a high, hot (~ 0.1) value. Therefore, if the heat front does not reach the outer disc it is conceivable (since we don't know the physical mechanism supposedly responsible for the change of α) that in the outer regions we would still have $\alpha \sim 0.01$, while $H/R \gtrsim 0.01$ (see e.g. Dubus et al. 1999b). In such a case the increased stream of mass transfered from the secondary deposits matter moving in the orbital plane at $\sim R_{\rm circ}/2$. Since various parts of the disc communicate efficiently through sound waves, this new component will exert a torque on the outer disc reducing the warp on a time scale of a few forced precession periods, where the precession period is ~ 40 days (Larwood 1998).

On the other hand, the whole disc could be in a high α state during an outburst. Since in a standard accretion disc $H/R \lesssim 0.05$ in the outer regions, $H/R \ll \alpha$ and the warp propagation is driven by viscous processes. The relevant vis-
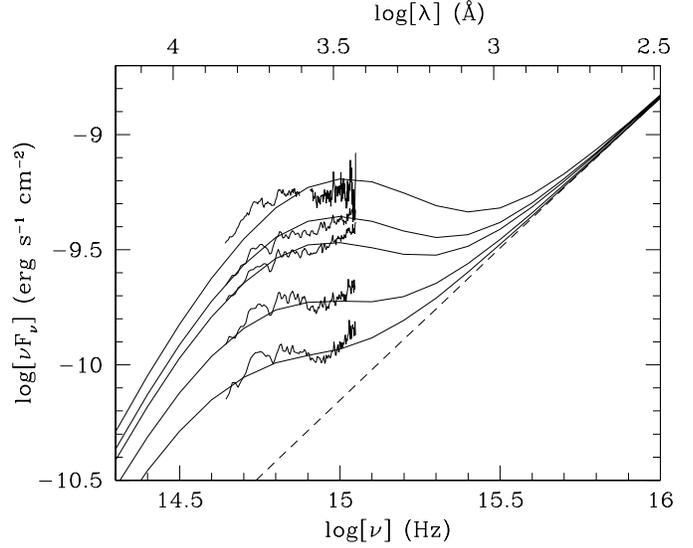

Fig. 2. The observed optical/UV spectra of GRO J1655–40 are plotted together with model spectra from a flared disc irradiated by X-rays emitted in the inner parts of the disc. The data were corrected for interstellar reddening, assuming $E(B-V) = 1.2$; we also subtracted the contribution from the secondary. The model spectra were calculated for $\dot{M} = 0.2 M_{\rm Edd}$ and disc size given by Eq. (3). Solid curves correspond to different values of the irradiation parameter at the outer disc edge, $\mathcal{C}_{\rm out}$; top to bottom $\mathcal{C}_{\rm out} = 6 \times 10^{-4}, 4 \times 10^{-4}, 3 \times 10^{-4}, 2 \times 10^{-4}, 0.8 \times 10^{-4}$. Dashed curve shows the spectrum of a planar (non-irradiated) disc.

cosity is the one corresponding to the vertical shear. The ratio of this kinematic viscosity coefficient to the standard (radial) one is approximately $1/2\alpha^2$, for $\alpha \ll 1$ (Papaloizou & Pringle 1983), and therefore the warp damping time is $t_{\rm damp} \approx 4\alpha^2 t_{\rm vis}$. At the outer disc edge of GRO J1655–40, $t_{\rm damp}$ is then about 100 days for $\alpha = 0.1$, in very good agreement with our scenario. Note that in this regime the increase of mass transfer would not affect the warp.

Pringle (1996) found that warp can be radiation driven. In such a case the warp's viscous decay could be prevented by irradiation. For this to happen, the growth rate of the radiative instability must be shorter than the viscous damping time $t_{\rm damp}$. This condition can be written as (e.g. Wijers & Pringle 1999):

$$\gamma_{\rm crit} > 3.21 \left(\frac{\eta}{0.1}\right)^{-1} \left(\frac{\alpha}{0.1}\right)^{-2} \left(\frac{M}{7M_\odot}\right)^{1/2} \times \left(\frac{R}{10^{11}{\rm cm}}\right)^{-1/2}, \qquad (7)$$

where η is the accretion efficiency and $\gamma_{\rm crit} \approx 0.1$ is the critical ratio of the radiative growth to the viscous damping times. One can see that for GRO J1655–40 the inequality above can be satisfied only for α values higher than the ones usually assumed in the DIM. Unless such values are assumed a warp will be viscously damped on a time–scale estimated above.

Whatever the mechanism of warp decay, it would result in the reduction of the irradiating flux intercepted by the disc, and

a consequent decrease in the observed optical flux from the system.

To illustrate this argument we calculated a series of optical spectra from uniformly accreting thin discs with varying degree of irradiation. The value of the mass accretion rate was chosen to reproduce the black body component of X-ray emission (Sobczak et al. 1999). In our simple treatment here we specify neither the origin nor the structure of the warp. However, since we need some description of the photosphere of the disc above the orbital plane as a function of radius, we use the prescription,

$$z = z_{\mathrm{out}}(R/R_{\mathrm{out}})^{9/7}, \tag{8}$$

chosen by analogy with formulae used in the literature, which (despite being based on an incorrect assumption about irradiated discs) seem to give a correct empirical description of the reprocessed X–ray flux (see Dubus et al. 1999b). All other properties of the warped disc, as far as irradiation is concerned, are described by $\mathcal{C}$, defined in Eq. (2). We use the prescription for irradiation of the outer disc by the inner disc edge (e.g. see Shakura & Sunyaev 1973; King & Ritter 1998), which combined with Eq. (8) above gives

$$\mathcal{C} = \mathcal{C}_{\mathrm{out}} \left(\frac{z/R}{z_{\mathrm{out}}/R_{\mathrm{out}}} \right)^2 = \mathcal{C}_{\mathrm{out}} \left(\frac{R}{R_{\mathrm{out}}} \right)^{4/7}, \tag{9}$$

where $\mathcal{C}_{\mathrm{out}} = \mathcal{C}(R_{\mathrm{out}})$. Note that for the disc–disc irradiation geometry, the strength of irradiation is quadratic in z/R, since it depends on the projections of both the emitting and irradiated annuli.

Of course the exact dependence of z on the disc radius is important in determining the shape of the optical spectrum. However, there are many other highly uncertain quantities in the calculation (e.g. radial profile of the albedo in the outer disc, angular distribution of the irradiating flux, details of radiative transfer in the atmospheres of irradiated discs) which all contribute significantly to the appearance of the disc in the optical band. In addition, we are using a flared planar disc 'approximation' to describe a warped disc. Since all these uncertainties are hidden inside our parameter $\mathcal{C}_{\mathrm{out}}$, the exact choice of $z(R)$ is not very important. As far as we are concerned, Eqs. (8) and (9) simply describe the distribution of the irradiating flux with radius and do not result from some assumed vertical disc structure. Note especially that we do not assume that the irradiated disc is isothermal or adopt a particular value for the disc aspect ratio at the outer edge.

The resulting spectra computed for different values of $\mathcal{C}_{\mathrm{out}}$ are shown in Fig. 2. For comparison we also plotted the deredened spectra of GRO J1655–40 observed (in order of decreasing flux) on May 14, June 8, June 20, June 30, and July 22, 1996 with *HST*/FOS red prism. (Note that these spectra correspond to the optical and UV data points shown in Fig. 1.) Since the contribution from the secondary is quite significant, especially at later times, we have subtracted from the data an estimate of the quiescent optical spectrum of GRO J1655–40, adjusted according to orbital phase (see Hynes et al. 1998 and Hynes 1999 for a fuller description of data processing). The broad hump centered

at $\log \nu \sim 14.8$ which remains after subtraction in the last two spectra has a similar spectrum to the secondary, and we suspect is probably due to a residual contribution from the companion. This suggests brightening of the secondary in outburst due to X-ray heating, supporting our irradiation scenario.

Though the model spectra are not intended as a formal fit to the data because of many simplifications in our calculation, the agreement between the five sets of spectra is fairly good. Fig. 2 shows qualitatively that by decreasing the degree of warping (as described by $\mathcal{C}_{\mathrm{out}}$), and therefore irradiation, of the outer disc, we can mimic the observed evolution of GRO J1655–40 in the optical band. Note how with decreasing $\mathcal{C}_{\mathrm{out}}$ the model optical spectra become softer, just as observed, even allowing for some residual contribution from the secondary in the data.

One should keep in mind that all model spectra shown in Fig. 2 were computed for a planar disc with $z \propto R^{9/7}$ and a fixed outer radius, given by Eq. (3). This means varying $\mathcal{C}_{\mathrm{out}}$ in our model corresponds simply to different values of the photospheric height at the outer radius. A more realistic description of the effects caused by enhanced mass transfer should, of course, include both changes in the disc profile (different functional form for $z(R)$) as well as possible changes in the disc outer radius. We feel that as long as we use a flared planar disc to approximate the effects of the warp, the exact disc shape is beyond the scope of this paper. Similarly, it is difficult to calculate the change in the outer radius of the disc from first principles. However, observations and numerical simulations of dwarf nova discs (e.g. Smak 1984; 1999b) show that at the onset of the outburst R_{out} expands by about 30% (from the canonical 70% to nearly 90% of the Roche radius) for a constant mass transfer rate from the companion. By comparison, simulations with enhanced mass transfer (say by a factor of 30) simply decrease this value to $\sim 25\%$, so the difference is too small to be constrained by the data.

4. End of the outburst

Because of many uncertainties in the physics of irradiation, it is very difficult to infer the time scale of the warp decay from the optical data. In both regimes considered in the previous section, our estimates of the decay time (a few forced precession times in the low viscosity case [Papaloizou & Terquem 1995; Larwood 1998] or the viscous damping time in a high viscosity case) are of the same order as the duration of the plateau phase of the outburst. It is therefore very tempting to speculate that the decay of the warp is not only responsible for the decline in the observed optical emission, but can also, by reducing heating through irradiation, terminate the outburst. Even if the mass transfer rate from the secondary remains high, a decrease in the irradiating flux can cause an increase in the minimum rate required for stable accretion (see Eq. 1) which is sufficient to bring the disc back into the unstable regime, and therefore, partially shut off the accretion in the inner disc where X-rays are produced. However, since the disc will most likely remain close to the stability limit, a very short period of mass accumulation at the outer edge is required to trigger the next outburst, just as

was observed for GRO J1655–40 in 1997 (e.g. Sobczak et al. 1999).

5. Discussion and conclusions

We have shown that X-ray and optical observations of GRO J1655–40 during its 1996 outburst can be reconciled with the standard disc instability scenario under the assumptions that the outer accretion disc is warped and that the primary 'standard' outburst triggers a burst of mass transfer from the secondary. In our picture, the enhancement in the mass transfer rate was sufficient to create a period of stable accretion, which was observed as a ~ 5 month plateau in the X-ray light curve. We have argued that this is entirely plausible, since available evidence is not inconsistent with the mass transfer rate in GRO J1655–40 being close to the stability limit of an irradiated disc. Thus a rather small enhancement in $\dot{M}_T$ is required to stabilize it. In addition, a burst of mass from the secondary is likely to decrease the warp amplitude in the outer disc. This effect explains why the optical light curve showed a decline as the X-ray flux was increasing, and can also account for the spectral evolution of the optical flux.

Warped disc physics is rather complicated and calculating the thermal–viscous instability in a warped disc (not to mention the effects of the enhanced mass transfer) is out of the question, at present. Because of this, the arguments presented in this paper are based on the calculations for planar discs and are necessarily of a qualitative nature. A lot more work is necessary before we can venture to make detailed quantitative comparisons between model predictions and what is observed.

It is also important to emphasize that although the overall ratio of X-ray to optical flux (determined by the value of $\mathcal{C}$ at the outer disc edge) is well constrained by observations, the detailed optical spectra of irradiated discs depend on many unknown parameters. While the angular distribution of irradiating flux may in some cases be deduced from detailed modeling of X-ray spectra, the exact shape of the disc as well as the X-ray albedo can only be determined from future theoretical calculations.

Despite these uncertainties, we believe that the picture presented here is realistic and is consistent with all the available data on the 1996 outburst of GRO J1655–40. One should perhaps view our result as a test of the hypothesis that this outburst was due to a dwarf–nova type disc instability. It is important to note that in our arguments we rely on only two major assumptions, which are both supported by extensive circumstantial evidence. Disc warping emerges as a natural conclusion from studies of X-ray irradiated outer discs, and a mass transfer increase during the outburst seems equally plausible when we consider irradiation of the secondary.

Similar modifications are also required in the application of the DIM to standard (U Gem – type) dwarf novae. In these systems there is clear observational evidence for irradiation–induced enhancement in the rate of mass transfer from the secondary (e.g. Smak 1995). Smak (1999a) studied the two types of 'inside–out' outbursts which are observed in dwarf novae: the 'narrow' and 'wide' ones. He showed, that their properties (various widths but similar amplitudes) can be explained if during the outburst the mass transfer rate is increased. Narrow outbursts correspond to moderate (factor 2) enhancements whereas wide outbursts correspond to major enhancements which temporarily put the accretion disc into the stable regime. It is, therefore, reasonable to expect that the variety of light curve types observed in X–ray transient systems may be due, at least in part, to mass transfer variations.

GRO J1655–40 is an exceptional system but is not the only one showing a 'flat top' outburst light curve (see e.g. Chen et al. 1997). One may hope, therefore, that such systems could be observed in a not too distant future. Multi-wavelength observations of such a transient event, in particular the correlation between X-ray and optical fluxes, could provide a useful test of our scenario.

At least one feature of the observed behaviour of GRO J1655–40 still remains a puzzle. If the mass transfer rate in quiescence is always close to the stability limit, it is unclear how this system could have sustained a > 30 years quiescence period. At such a high rate of accretion, the mass accumulation period at the outer edge of the disc would be very short (on the order of a few months to a year), with the successive outbursts following each other after a correspondingly short time. In fact, the behaviour observed in this system since 1994 should be the norm, rather than the exception. One possible explanation can be that during some periods accretion in GRO J1655–40 is non–conservative, e.g. King & Kolb (1999) propose that a lot of matter can be lost into a jet. However, more theoretical work as well as observations are required before we can assemble a comprehensive picture of this fascinating system.

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