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Advection-Dominated Flows and the X-ray Delay in the Outburst of GRO J1655–40

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ABSTRACT

We show that the time delay between the optical and X-ray outbursts of the black-hole soft X-ray transient source GRO J1655–40, observed in April 1996, requires that the accretion flow in this object must consist of two components: a cold outer accretion disk and an extremely hot inner advection-dominated accretion flow (ADAF). In quiescence, the model predicts a spectrum which is in good agreement with observations, with most of the observed radiation coming from the ADAF. By fitting the observed spectrum, we estimate the mass accretion rate of the quiescent system and the transition radius between the disk and the ADAF. We present a detailed numerical simulation of a dwarf-nova type instability in the outer disk. The resulting heat front reaches the ADAF cavity promptly; however, it must then propagate inward slowly on a viscous time scale, thereby delaying the onset of the X-ray flux. The model reproduces the observed optical and X-ray light curves of the April 1996 outburst, as well as the 6-day X-ray delay. Further, the model gives an independent estimate of the quiescent mass accretion rate which is in very good agreement with the rate estimated from fitting the quiescent spectrum. We show that a pure thin disk model without an ADAF zone requires significant tuning to explain the X-ray delay; moreover, such a model does not explain the quiescent X-ray emission of GRO J1655–40.

Subject headings: accretion, accretion disks — black hole physics — X-rays: stars — stars: individual (GRO J1655–40)

1. Introduction

The binary X-ray source GRO J1655–40 (also called X-ray Nova Scorpii 1994) is a member of the class of so-called “Soft X-ray Transients” (SXTs) or “X-ray Novae”. In these systems, a low mass Roche-lobe-filling secondary star transfers mass through an accretion disk onto a compact object: a neutron star or a black hole. Compared to a neutron-star transient, a black-hole transient (BHT) generally has a larger X-ray outburst amplitude and a lower quiescent luminosity, which is a signature of a black hole’s event horizon (Narayan, Garcia & McClintock 1997). The mass of the black hole primary in GRO J1655–40 is $\approx 7.0M_{\odot}$ (Orosz & Bailyn 1997; hereafter OB).

GRO J1655–40 is an exceptional BHT because of its frequent outbursts in recent years. Most BHTs have recurrence times of decades or longer, whereas GRO J1655–40 has gone into outburst several times since its discovery on 1994 July 27 by BATSE on the *Compton Gamma Ray Observatory* (CGRO) (Zhang et al. 1994). Two subsequent outbursts occurred in late March 1995 (Wilson et al. 1995) and in July 1995 (Harmon et al. 1995). Following an extended period of X-ray quiescence, the source again went into outburst in April 1996, as discovered by the All-Sky Monitor (ASM) on the *Rossi X-ray Timing Explorer* (RXTE) (Remillard et al. 1996; Levine et al. 1996).

Thus GRO J1655–40 has remained active off and on for nearly three years. Other BHTs have shown X-ray and optical activity several months after an outburst; however, none of them have sustained their activity for more than about a year (e.g. Tanaka & Shibazaki 1996). The frequent outbursts of GRO J1655–40 in recent years may be due to an enhancement of the mass transfer rate, which is estimated to be relatively high, $2.2 \times 10^{17} \text{ g s}^{-1}$ (OB). One should however note (Ritter 1997) that this estimate is based on a formula of King, Kolb & Burderi (1996) which is valid for giants, but not for systems such as GRO J1655–40 which have not yet reached the giant branch. Systems with companions in the Hertzsprung gap should transfer mass at a very high rate ($\gtrsim 10^{19} \text{ g s}^{-1}$, Ritter 1997), since the secondary expands on a thermal time; this is obviously not the case now in GRO J1655–40, and no observational determination of the mass transfer rate is available at present. As it happens, the value given by OB is plausible, and we shall use it in the following. In any case, on longer timescales GRO J1655–40 behaves more like

other BHTs, since no outburst of the source has been reported in the previous 25 years. GRO J1655–40 is also distinguished by its radio outbursts, which are associated with superluminal expansion events (Tingay et al. 1995; Hjellming & Rupen 1995).

About 6 days prior to the most recent X-ray outburst of GRO J1655–40 (in April 1996), a remarkable optical precursor was observed (Orosz et al. 1997; hereafter ORBM). As shown in Figure 1, starting from an initially quiescent state, the optical intensities (BVRI) were observed to rise gradually for sev-

Fig. 1.— Observed optical and 2–12 keV X-ray light curves during the initial phase of the April outburst of GRO J1655–40 (From ORBM). For the sake of clarity, only one average data point per night is plotted. The B, V and I magnitudes are represented by triangles, squares and stars respectively. Time has been set to zero at an arbitrary point close to the onset of the outburst.

eral days and brighten by about 30% before the onset of the X-ray outburst. In this article, we examine only one aspect of the complex behavior of GRO J1655–40 in outburst, namely, the properties of the optical precursor and the X-ray outburst, and what they imply for models of quiescent BHTs and for the outburst mechanism. As argued by ORBM, the substantial delay between the optical eruption and the X-ray outburst (which we refer to hereafter as the “X-ray delay”) may provide support for the advection-dominated accretion flow (ADAF) model of the inner regions of the quiescent accretion disk.

One outburst mechanism that has been developed for SXTs is the mass transfer instability (Hameury, King & Lasota 1986); however, in general it cannot reproduce the characteristic timescales of SXTs and it has therefore been rejected (Gontikakis & Hameury 1993). It is now clear that the outburst mechanism must be due to a disk instability. A natural candidate for such an instability is the thermal (and viscous) instability resulting from abrupt changes in opacities when hydrogen becomes partially ionized. Such a mechanism explains successfully dwarf nova outbursts in the framework of the disk instability model (DIM) (see Cannizzo 1993 and references therein). The dwarf nova DIM has been extended to SXTs by Mineshige & Wheeler (1989) (see also Cannizzo, Chen & Livio 1995).

The DIM requires the quiescent accretion disk to be in a cold state; the accretion rate therefore has to be everywhere lower than a critical accretion rate $\dot{M}_{\text{crit}}(R) \propto R^a$ where $a \approx 2.6$ (see e.g. Ludwig, Meyer-Hofmeister & Ritter 1994). This in turn implies that the accretion rate onto the compact object required by the DIM is extremely low $\sim 10^6 \text{ g s}^{-1}$ (Mineshige & Wheeler 1989; Lasota 1996a). However, observations of X-ray emission from quiescent BHTs imply accretion rates which are several orders of magnitude higher (McClintock, Horne & Remillard 1995; Verbunt 1996; Narayan, McClintock & Yi 1996 (NMY); Narayan, Barret & McClintock 1997 (NBM); Robinson et al. 1997). A similar problem is encountered in some quiescent dwarf novae (see e.g. Lasota 1997). It is clear therefore that the standard DIM cannot apply to BHTs (Lasota 1996a,b); furthermore, in some cases it must be modified even to describe dwarf-nova outbursts (Meyer & Meyer-Hofmeister 1994; Livio & Pringle 1992).

A model for SXTs in quiescence was proposed by NMY in which the accretion flow occurs as a

thin disk only outside a transition radius $R_{\text{tr}} \sim 10^3$ Schwarzschild radii, while for $R < R_{\text{tr}}$ the flow forms an advection-dominated accretion flow (ADAF) (Abramowicz et al. 1995; Narayan & Yi 1994, 1995; for a recent review see Narayan 1997). In the NMY model, the observed X-rays are emitted with a very low efficiency by the ADAF while the UV and optical luminosity is produced by the outer disk. However, Lasota, Narayan & Yi (1996) pointed out that the NMY model is not self consistent because the outer disk is relatively hot and therefore subject to a thermal instability, contrary to the assumed stationarity (see also Wheeler 1996). More recently, NBM have shown that self-consistent models for the spectra of V404 Cyg and A0620–00 can be obtained by an ADAF that extends outward to $R_{\text{tr}} \sim 10^4$ Schwarzschild radii. For these models, the accretion disk is cool and the optical/UV flux is mostly supplied by synchrotron emission from the ADAF. In such a model, the transient outburst originates in the outer cold disk and is due to a dwarf-nova type instability.

In section 2, we discuss the consequences of the delay between optical and X-ray, and in section 3 we develop an ADAF model for GRO J1655–40 in quiescence. In section 4 we demonstrate that a time-dependent model of the outburst of GRO J1655–40 implies the existence of a two-component accretion flow. The parameters determined for this flow agree with the parameters independently determined in section 3.

2. Interpretation of the X-ray Delay: Evidence for a Two-Component Disk

2.1. The UV-Delay in Dwarf-Nova Outbursts

The X-ray delay observed in the outburst of GRO J1655–40 is analogous to the well known UV delay observed for dwarf novae (e.g. Warner 1995, and references therein). For dwarf novae the rise in the UV flux starts about 5 to 15 hours after the beginning of the optical outburst. In the framework of the standard disk instability model (DIM) one can interpret the UV-delay as due to an “outside-in” (or Type A) outburst. According to the DIM (e.g. Cannizzo 1993, and references therein), a thermal instability in the outer disk creates an inward propagating heat front. This front transforms the disk from a cold (quiescent) state to a hot state. Because the UV flux is mainly emitted close to the white dwarf, one expects a delay in its rise, a delay equal to the time it takes the

front to travel from the outer disk to the white dwarf. In the DIM, however, the calculated travel time of the front is much shorter than the observed UV-delay time (Pringle, Verbunt & Wade 1986; Cannizzo & Kenyon 1987). Thus, in its standard form the model fails to explain the UV-delay.

Two solutions have been proposed in order to rescue the DIM; both of them invoke a central “hole” in the accretion disk. At the edge of such a hole, an inward moving heat front would have to stop. The hole would then fill up on a viscous time scale, which is much longer than the heat front propagation time. Livio & Pringle (1992) suggested a mechanism for creating such a hole: they argued that at quiescent mass accretion rates, the magnetic field of a weakly-magnetized white dwarf can disrupt the inner accretion disk. They showed that such a model can reproduce the UV-delay observed in dwarf nova outbursts. This model cannot apply to systems in which the accreting object is a black hole, since a black hole cannot support a permanent magnetic field.

Meyer & Meyer-Hofmeister (1994) proposed a different scheme for quiescent accretion onto a white dwarf that also results in a central hole. They invoke inefficient cooling in the disk’s upper layers, which leads to the formation of a hot corona and ultimately to the evaporation of the inner disk. As a result, the inner accretion flow consists of a pure coronal plasma. A similar solution for quiescent SXTs has been independently proposed by NMY. In both cases, the hot inner flow provides a natural explanation for the hard X-ray emission observed in quiescent dwarf novae and SXTs.

Whether a hole is created by magnetic fields or by evaporation, the effect on the outburst of a dwarf nova is similar: when the heat front arrives at the inner edge of the truncated disk it cannot propagate any further; the (surface) density contrast slowly fills up the hole on a viscous time scale, thereby producing the required delay of the UV outburst.

Below we show that the observations of the April 1996 outburst of GRO J1655–40 imply the presence of a two-component accretion flow in this system, and that the parameters deduced from observations agree very well with a model comprised of an outer cold disk and an inner hot ADAF, as proposed by NBM.

2.2. The X-Ray Delay in the Outburst of GRO J1655–40

We assume that the April 1996 outburst of GRO J1655–40 was triggered by a dwarf-nova type instability in a standard cold disk, which extends from the transition radius R_{tr} to some outer radius R_{out} . This disk is most probably marginally stable with respect to this instability (e.g. Lasota et al. 1996), or it may be globally unstable (see below). Once the instability is triggered, the resulting heat front propagates with the speed $v_f \approx \alpha c_s$ (Meyer 1984), where c_s is the equatorial-plane sound speed in the hot phase. Thus, the time it takes for the front to travel a distance R_{out} is

$$t_f \approx \frac{R_{\text{out}}}{\alpha c_s} \sim 2.8 \alpha^{-1} R_{10} T_4^{-1/2} \text{ hr}, \quad (1)$$

where $T_4 = (T/10^4 \text{ K})$ is the central disk temperature, and R_{10} the radius in units of 10^{10} cm . If the instability starts at a sufficiently large radius, the front may take up to a day to reach the inner edge of the disk; this has been proposed by ORBM as the origin of the observed delay between the I, R, V and B light curves. Although very tempting, this explanation suffers from the fact that for any reasonable values of the radius and the primary mass, the effective temperature jumps to 10,000 – 11,000 K on a thermal time scale at the point where the instability sets in. At these temperatures, $B - V \sim 0$, $V - I \sim 0$, and the B, V and I magnitudes should increase simultaneously. Dilution of the disk light by the ADAF and secondary light does not alter this conclusion. Thus the disk instability model cannot easily account for a one day delay at optical/IR wavelengths.

It is interesting to note that the observations of ORBM do not quite cover the very initial rise of the outburst, since their first observation shows that the R, V and I fluxes have already risen, whereas the B flux remains at its quiescent value. This indeed implies the existence of a delay; however, the value obtained by ORBM assumes a linear extrapolation, which may overestimate the delay for two reasons. The initial rise could be very non linear, with a sharp increase of the optical light from the disk, in which case the delay could be only a few hours. Another possibility is that the mass transfer rate from the secondary may have significantly increased since the previous observation of the source in quiescence, one month prior to the outburst. In fact, it is quite plausible that such an increase could have triggered the thermal instability that caused the April 1996 out-

burst. In any case, such an increase in the mass transfer rate would not show up in the B-band because the quiescent temperature of the system does not exceed 6500 K.

When the heat front arrives at the transition radius R_{tr} where the dense (cold) disk ends, it cannot propagate any further towards the black hole; however, the resulting (surface) density contrast will propagate inward due to viscosity. The speed at which the density “front” propagates is

$$v_{\text{visc}} = \frac{\nu}{w}, \quad (2)$$

where ν is the kinematical viscosity ($\nu = \alpha c_s H$) and w is the scale of the density gradient. The density contrast will travel a distance R_{tr} in a time

$$t_{\text{vis}} = \frac{R_{\text{tr}}}{v_{\text{visc}}}. \quad (3)$$

The width w can be written as (see e.g. Cannizzo 1996)

$$w = \beta(HR)^{1/2}, \quad (4)$$

where we expect β to be $\lesssim 1$.

If we identify the observed X-ray delay with t_{vis} we can estimate the transition radius as

$$r_{\text{tr}} \approx 3.6 \times 10^4 \alpha^{4/3} t_{\text{X,d}}^{4/3} m_1^{-4/3} \beta^{-4/3} T_4, \quad (5)$$

where $r_{\text{tr}} = R_{\text{tr}}/R_S$, $R_S = 2GM/c^2$, $m_1 = M/M_\odot$ is the mass of the central black hole, and $t_{\text{X,d}}$ is the X-ray delay time in days. (Here and elsewhere we use the symbols R and r to refer to the radius in physical units and Schwarzschild units, respectively.) For $m_1 = 7$, $t_{\text{X,d}} \approx 5$ and $\alpha = 0.3$, one obtains $r_{\text{tr}} \approx 4.6 \times 10^3 \beta^{-4/3} T_4$ which shows that the transition between the hot ADAF and the cold outer disk occurs at $r_{\text{tr}} \sim 10^4$. Remarkably, this same value of the transition radius was deduced for models of two BHT by NBM in a completely independent way. Furthermore, in the next section we show that $r_{\text{tr}} \sim 10^4$ is close to the radius at which the outer disk becomes unstable to the dwarf-nova instability.

The outer disk radius in GRO J1655–40 is

$$r_{\text{out}} \approx 7.3 \times 10^5 m_1^{-2/3} P_{60}^{2/3} \approx 2 \times 10^5, \quad (6)$$

where $P_{60} = P_{\text{orb}}/60\text{h}$ is the orbital period.

3. ADAF Plus Cold Disk Model for GRO J1655–40 in Quiescence

We have seen in the previous section that the X-ray delay in the outburst of GRO J1655–40 requires that the quiescent state of the system must consist of a two-zone flow. The thin accretion disk can extend only down to a transition radius r_{tr} which has to be greater than a few thousand Schwarzschild radii. Inside this radius, the flow must either be absent or must have a much lower density than in the thin disk. This picture is very similar to the two-zone model proposed by NMY and NBM for fitting the spectral data of V404 Cyg and A0620–00 in quiescence; in that model, the flow inside the transition radius consists of an extremely hot two-temperature ADAF. Here we use the ADAF plus thin disk model to fit the spectral data on GRO J1655–40 in quiescence and thereby estimate some key parameters of the quiescent accretion flow.

We first select a set of system parameters for GRO J1655–40 that we use as inputs to our models for the source. These include the black hole mass, the binary inclination, the distance, and the velocity at the inner edge of the outer thin accretion disk. Second, we summarize the multiwavelength data (X-ray, optical and radio) that we use to constrain our models of the quiescent state. Finally, we use the spectral data to constrain the remaining parameters of the model.

The mass of the black hole in GRO J1655–40 and the inclination of the system are very well determined: we adopt $M_1 = 7 M_\odot$ and $i = 70^\circ$ (OB). In §2.2, we estimated the outer radius of the thin accretion disk to be $r_{\text{out}} \approx 2 \times 10^5$; in the spectral models we take $\log(r_{\text{out}}) = 5.0$. This parameter does not need to be determined very accurately since it has very little effect on the results. Based on studies of the radio jets, we adopt a distance of $D = 3.2$ kpc (Hjellming & Rupen 1995).

Dynamical and geometrical information about the thin accretion disk can be obtained from studies of the broad, double-peaked Balmer lines (Smak 1981; Horne & Marsh 1986), and from this the transition radius r_{tr} can be constrained. Of interest here is v_{in} , the projected velocity at the inner edge of the thin accretion disk. Estimates of this velocity have been inferred for several SXTs from orbit-averaged profiles of the H_α emission line (see NMY, and references therein).

GRO J1655–40 is a difficult case because of the

strong H_α absorption line present in the spectrum of the F subgiant secondary, and because of the relative brightness of the secondary. In order to obtain a useful spectrum at H_α , we formed a sum of 73 spectra that had been collected over a wide range of orbital phase in 1995 April-May when the system was near quiescence (Bailyn et al. 1995), and then subtracted the spectrum of the best-fitting F5IV star (Orosz 1996). In this way we measured the width of the H_α emission line and estimated $v_{\text{in}} \geq 1045 \text{ km s}^{-1}$. The inner edge of the thin disk, or equivalently the transition radius r_{tr} between the thin disk and the ADAF, is then estimated to be $r_{\text{tr}} = (c \sin i / v_{\text{in}})^2 / 2 \leq 3.6 \times 10^4$ (NBM). We present below models corresponding to a range of values of $\log(r_{\text{tr}})$ consistent with this constraint.

The multi-wavelength data, νF_ν vs. ν , are summarized in Table 1. To derive the optical flux (entry 5), it was necessary to subtract a large stellar component. We assumed that the residual (non-stellar) component contributed $5 \pm 2\%$ of the total light (OB); for the total optical flux from the system we used the apparent magnitude and reddening given in OB. The optical flux in the V band and its error bar are shown in Fig. 2.

Apart from the optical and BATSE data (entry 2), all the remaining data in Table 1 were obtained during an intensive campaign of observations of GRO J1655-40 in quiescence conducted in March 1996 by Craig Robinson and his collaborators (Robinson et al. 1997). All of the upper limits in Table 1 and below are quoted at the 3 sigma level of confidence. The OSSE flux limit (entry 1) corresponds to an intensity upper limit of 40 mCrab (100–600 keV). This is off-scale in Fig. 2 and is not plotted. GRO J1655-40 was detected by ASCA (entry 3) at an (unabsorbed) flux level of F_x (2–10 keV) = $(1.6 \pm 0.7) \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$; the photon power-law index (α) is estimated to be 1.5 ± 0.6 (Robinson et al. 1997). Both the flux (with its error bar) as well as the allowed range of spectral slope are indicated in Fig. 2. A stringent flux limit was obtained using the ROSAT HRI detector (entry 4): F_x (0.2–2 keV) < $6.1 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$ (3σ), assuming $\alpha = 2.1$ and $N_H = 5 \times 10^{21} \text{ cm}^{-2}$ (Robinson et al. 1997). This upper limit is indicated by the arrow in Fig. 2. Finally, the VLA limits on GRO J1655-40 (entries 6 & 7) correspond to a flux limit of 0.5 mJy at both 4.9 GHz and 8.4 GHz (not shown on Fig. 2).

The BATSE limit (entry 2) is an average over the

period 19–30 April 1996 and corresponds to a photon flux (20–200 keV) of $-0.0001 \pm 0.0024 \text{ ph cm}^{-2} \text{ s}^{-1}$ (assuming $\alpha = 2.8$), or an intensity limit of 26 mCrab. This is consistent with the OSSE limit. Recall, however, that the inferred start time of the X-ray rise at 2–12 keV is 25.4 ± 0.8 April 1996 (Orosz et al. 1997). So the BATSE limit includes a ~ 5 -day period when the 2–12 keV X-ray outburst was underway.

We have attempted to fit the quiescent spectral data on GRO J1655-40 using an ADAF plus thin disk model, analogous to the models described in NBM. The solid lines in Fig. 2 represent four models, where each model consists of a pure ADAF for radii $\log(r) < \log(r_{\text{tr}})$, and a thin accretion disk in the radius range $\log(r_{\text{tr}}) \leq \log(r) \leq \log(r_{\text{out}})$. The models

Fig. 2.— Quiescent spectrum of the non-stellar component of GRO J1655-40. The dot and error bar on the left represent the estimated V band flux of the quiescent accretion flow in GRO J1655-40, the arrow shows the upper limit on the soft X-ray flux as measured with ROSAT, and the dot on the right with error bar and “bow-tie” indicates the ASCA constraint on the X-ray flux and spectral index. The solid lines represent model spectra corresponding to an accretion flow consisting of an inner ADAF plus an outer thin disk. In each case, the mass accretion rate has been adjusted to fit the ASCA X-ray flux. From below (in the optical band), the four models have transition radii, $\log(r_{\text{tr}}) = 4.5, 4.0, 3.5, 3.0$, respectively.

TABLE 1
QUIESCENT SPECTRUM OF THE NON-STELLAR COMPONENT OF GRO J1655–40

Entry Number	Wavelength (Å)	$\log \nu$ (Hz)	$\log(\nu F_\nu)^a$ (ergs cm ⁻² s ⁻¹ Hz ⁻¹)	Observatory	Reference
1	0.05	19.818 ^b	<-9.49	CGRO/OSSE	1
2	0.17	19.258 ^b	<-9.44	CGRO/BATSE	1
3	2.3	18.123 ^c	-12.96	ASCA	1
M 4	16.6	17.258 ^b	<-12.59	ROSAT/HRI	1
5	5500	14.736	-11.24	CTIO	2
6	3.6x10 ⁸	9.924	<-16.38	VLA	1
7	6.1x10 ⁸	9.690	<-16.61	VLA	1

^aFlux limits are at the 3 σ level of confidence.

^bCentral frequency computed assuming a Crab-like spectrum with energy index $\alpha_E = 1.1$ (see NBM).

^cCentral frequency computed assuming $\alpha_E = 0.5$ (see Sect. 3).

REFERENCES.—(1) Robinson et al. (1997); (2) Orosz & Bailyn 1997

correspond to $\log(r_{\text{tr}}) = 4.5, 4.0, 3.5$ and 3.0 , respectively. The transition from the thin disk to the ADAF in these models occurs via evaporation into a corona, as described in NBM. The models assume equipartition between gas and magnetic pressure ($\beta = 0.5$ in the notation of NMY and NBM) and the viscosity parameter is taken to be $\alpha = 0.3$ in the ADAF region. It is assumed that a fraction 0.001 of the viscous energy directly heats the electrons in the ADAF (and the corona) while the remaining 0.999 of the energy goes initially into the ions (i.e. $\delta = 0.001$, see NBM for details). The shape and normalization of the computed spectra are quite insensitive to the values chosen for r_{tr} , β , α and δ (see Figures 3–5 in NBM).

In each model, only one parameter has been adjusted, namely the mass accretion rate. This has been optimized such that the model flux in the ASCA band agrees with the observed flux. Despite the large range of r_{tr} covered by the four models, the mass accretion rates vary very little from one model to another; in Eddington units, the accretion rates range from 0.0034 to 0.0037, which correspond to physical accretion rates of $\dot{M} = (3.4 - 3.7) \times 10^{16} \text{ g s}^{-1}$. Thus, the spectral models constrain the $\dot{M}$ of GRO J1655–40 in quiescence quite well. Technically, the models deter-

mine only the parameter combination $\dot{M}/\alpha$ and so $\dot{M}$ depends on a knowledge of α . However, the value of α in ADAFs is fairly well-constrained by the various studies done to date (Narayan 1997), and is unlikely to vary by more than a factor ~ 3 either way from the value we have assumed, $\alpha = 0.3$. This suggests that the above estimate of $\dot{M}$ in the ADAF is good to about a factor ~ 3 .

The models shown in Fig. 2 are consistent with all the measurements available at this time, including the OSSE and VLA limits (which are not shown in Fig. 2). Note, in particular, that the models fit the observed optical flux, predict the correct slope in the ASCA band, and lie below the ROSAT flux limit.

A rather obvious point is that the quiescent data are incompatible with any model which is based only on a thin accretion disk. The ROSAT and ASCA data clearly indicate that (1) the X-ray flux of GRO J1655–40 in quiescence lies below the optical flux, and (2) the X-ray spectrum is quite hard, with a photon index < 2.7 (2σ). A thin accretion disk model, with either a constant or variable $\dot{M}$ as a function of radius, cannot possibly reproduce such a spectrum. Thus, GRO J1655–40 is similar to A0620–00 and V404 Cyg (see

NMY and NBM), where again the quiescent spectra are found to be inconsistent with a pure thin disk model but are fitted well with an ADAF plus thin disk model.

Although the spectral fit does not help us to determine r_{tr} , it is possible to obtain a fairly strong constraint on r_{tr} by considering the stability of the outer thin disk (Lasota et al. 1996, NBM). Specifically, the outer disk will be unstable to the dwarf nova instability if it has an effective temperature greater than about 5000 K, and therefore the quiescent disk cannot exceed this temperature at any radius. The four models presented in Fig. 2, with $\log(r_{\text{tr}}) = 4.5, 4.0, 3.5, 3.0$, have maximum effective temperatures in their disks of $T_{\text{max}} = 1700, 3700, 8400, 20000$ Kelvin respectively. The requirement $T_{\text{max}} < 5000$ K thus provides the constraint $\log(r_{\text{tr}}) > 3.7$, or $r_{\text{tr}} > 5000$. Just prior to outburst, we expect the thin disk to be very close to the limiting value of T_{max} . We therefore estimate that GRO J1655–40 had its transition radius at $r_{\text{tr}} \sim 5000$, or $R_{\text{tr}} \sim 10^{10}$ cm, at the time of the April 1996 outburst.

4. Instability of the Outer Disk

In this section, we present numerical simulations of the dwarf nova instability in the outer disk of GRO J1655–40. We compare the results with observations of the early stages of the outburst, paying particular attention to the 6-day delay between the optical and X-ray outburst. We also compare the mass accretion rate implied by the outburst calculations with the quiescent $\dot{M}$ determined independently in the previous section. The calculations presented here have been done with the code described in Hameury et al. (1997).

In the following we assume that the mass transfer rate from the companion star, i.e. the accretion rate at the outer rim of the accretion disk, has the value given by OB, viz. $\dot{M}_{\text{transfer}} = 2 \times 10^{17} \text{ g s}^{-1}$. For this value of $\dot{M}_{\text{transfer}}$, the outer cold disk is unstable to the dwarf nova instability (see e.g. Ludwig et al. 1994), and so we are guaranteed that the code will produce an outburst.

We assume that the transition between the outer thin accretion disk and the ADAF is due to evaporation into a corona which gradually erodes matter in the disk as the cold inflowing material approaches the transition radius; such a model has been proposed for dwarf novae by Meyer & Meyer-Hofmeister (1994;

see also NMY & NBM). We have estimated the evaporation rate by the following approximate method. Narayan & Yi (1995) have derived that the maximum allowable mass transfer rate in the ADAF at small radii is $\dot{m}_{\text{ADAF,max}} = 0.3\alpha^2$ (in Eddington units) and that $\dot{m}_{\text{ADAF,max}}$ decreases at large radii ($r > 10^3$) (see also Abramowicz et al. 1995). Assuming that the mass transfer rate within the inner ADAF is equal to the maximum, and using $M_1 = 7M_{\odot}$, we adopt the the following approximate prescription for evaporation:

$$\dot{M}_{\text{ev}} = \frac{2.8 \times 10^{17}}{(1 + KR_{\text{tr},10}^2)} \text{ g s}^{-1}, \quad R_{10} \geq R_{\text{tr},10}, \quad (7)$$

where K is a constant which is adjusted so as to give the required value of the transition radius, and $R_{\text{tr},10}$ is the transition radius in units of 10^{10} cm. The local surface density evaporation rate is then related simply to the derivative of $\dot{M}_{\text{ev}}$ with respect to R , i.e.

$$\dot{\Sigma}_{\text{ev}} = \frac{1}{2\pi R} \frac{d\dot{M}_{\text{ev}}}{dR} = \frac{9 \times 10^{-4} K}{(1 + KR_{10}^2)^2} \text{ g s}^{-1} \text{ cm}^{-2}. \quad (8)$$

This prescription for the evaporation is numerically close to the formula given by Meyer & Meyer-Hofmeister (1994).

According to the dwarf nova DIM, the accretion rate in a quiescent disk must satisfy

$$\dot{M}(r) < \dot{M}_{\text{crit}}(r) = 9.6 \times 10^3 m_1^{1.73} r^{2.6} \text{ g s}^{-1}, \quad (9)$$

where we have taken $\dot{M}_{\text{crit}}$ from Ludwig et al. (1994). The disk first becomes unstable at its inner edge when $\dot{M}$ in the disk reaches the critical value near the transition radius. This triggers an inside-out outburst. Since most of the mass evaporation occurs close to the transition radius, the condition for the outburst is equivalent to the requirement $\dot{M}_{\text{ev}} = \dot{M}_{\text{crit}}$. For $KR_{\text{tr},10}^2 > 1$, we then find

$$R_{\text{tr}} = 3.3 \times 10^{10} K^{-0.43} m_1^{0.19} \text{ cm}. \quad (10)$$

As we showed in the previous section, GRO J1655–40 in quiescence requires a transition radius $\sim 10^{10}$ cm, which means that we require a value of K of order a few. In the detailed calculations presented below we have selected $K = 5$, which gives $R_{\text{tr}} = 10^{10}$ cm for the quiescent model just before outburst. In this model, the mass transfer rate feeding the ADAF prior to the onset of the instability is found to be $4.6 \times 10^{16} \text{ g s}^{-1}$, which is in excellent agreement with

the $\dot{M}$ in the ADAF estimated in Sect. 3 ($\dot{M} \sim 3.5 \times 10^{16} \text{ g s}^{-1}$ for $\alpha_{\text{ADAF}} = 0.3$) by fitting the spectrum of GRO J1655–40 in quiescence.

In the presence of evaporation the usual disk equation for mass conservation has to be modified as follows:

$$\frac{\partial \Sigma}{\partial t} + \dot{\Sigma}_{\text{ev}} = -\frac{1}{R} \frac{\partial}{\partial R} (R \Sigma v_R), \quad (11)$$

where Σ is the surface column density in the disk, and v_R is the radial velocity. Because the evaporation law is independent of Σ , evaporation results in a disk which is sharply cut off at the transition radius R_{tr} . We thus use as an inner boundary condition the relation

$$\dot{M}_{\text{disk}}(R_{\text{tr}}) = 0. \quad (12)$$

Once the outburst begins, the transition radius moves in and reaches R_{in} , the inner edge of the grid. When this happens, in order to avoid numerical complications, we switch to the standard inner boundary condition, $R = R_{\text{in}}$.

In the calculations presented here, the disk inclination was taken to be 70° , the outer radius of the disk was taken to be $4 \times 10^{11} \text{ cm}$, and the inner boundary of the grid was set at $R_{\text{in}} = 4 \times 10^8 \text{ cm}$. Our choice of the inner boundary corresponds to $R_{\text{in}} = 194 R_S$ rather than $3 R_S$, but this is merely for numerical convenience and does not affect any of the results presented here. Once the outburst gets underway and the thin disk extends inward to R_{in} , the time it needs to travel the additional distance to the black hole is quite short compared to the time it took to move from $R = R_{\text{tr}} = 10^{10} \text{ cm}$ down to $R = R_{\text{in}} = 4 \times 10^8 \text{ cm}$. Therefore, very little error is made by truncating the numerical simulation at R_{in} . The disk viscosity parameter α in the simulations varies between 0.035 on the cool branch and 0.15 on the hot branch.

Figure 3 displays the initial phases of an outburst seen in the numerical calculations. In this run, several outbursts have already occurred, so that the initial assumed density profile in the disc has been relaxed. The bottom panel shows the magnitude variations $-\Delta m = -m + m_0$ in the B, V and I bands, where m_0 accounts for the presence of diluting light originating essentially from the secondary (which dominates over the ADAF). For simplicity, we have assumed that m_0 is constant, and corresponds to a $48 L_\odot$ secondary with an effective temperature of 6500 K (OB). During quiescence, the disk is extremely faint—fainter than both the secondary and the ADAF—and contributes less than 1 % of the total light; however, in outburst,

its optical luminosity, although still smaller than that of the secondary, dominates the ADAF, justifying our assumption that m_0 is constant.

Fig. 3.— Results obtained by modeling the outburst in GRO J1655–40 by means of a dwarf-nova like instability in the outer thin disk. The upper panel shows the predicted X-ray flux expected to be observed by the RXTE ASM, the second panel shows the variation of the transition radius r_{tr} with time and the lower panel shows the variations of the optical B, V, and I magnitudes. In order to avoid numerical difficulties, the inner edge of the numerical grid was fixed at $4 \times 10^8 \text{ cm}$; however, when r_{tr} reaches this value, it is set to $3 R_S$ in the plot, which is more realistic.

The B, V, and I magnitudes decrease simultaneously in the calculations; this is independent of the magnitude of the diluting light m_0 . The slopes however are directly related to m_0 : for large diluting fluxes, the logarithm appearing in the definition of the magnitude can be linearized, and one has ($L(t) \ll L_0$)

$$-\Delta m = 1.09 \frac{L(t)}{L_0}, \quad (13)$$

where $L(t)$ is the disk luminosity and L_0 the luminosity of the companion plus the ADAF. The faster rise in the B band is thus simply due to the fact that $B-V = 0$ for a disk in the hot state, whereas most of the diluting light comes from the secondary with $B-V \sim 0.5$. This gives a factor ~ 1.5 between the slopes of the B and V magnitudes, as observed.

The middle panel in Fig. 3 shows the variation of the transition radius with time. Once the outburst begins, the mass accretion rate increases significantly and the evaporation is unable to keep up. The transition radius therefore decreases, slowly at first and then more rapidly as the characteristic viscous time decreases with decreasing radius. About 5 days after the start of the outburst, R_{tr} moves down to R_{in} , the inner boundary of the numerical grid. At later times, we assume that whatever accreted matter reaches R_{in} will continue down to the black hole in the form of a thin disk, and we calculate the X-ray luminosity accordingly.

The top panel in Fig. 3 shows the calculated X-ray light curve. This has been computed assuming that the emission from the ADAF has an efficiency of 0.1%, while the matter flowing through R_{in} in the thin disk has a standard efficiency of 10%. We assumed a conversion factor of 5.3×10^{35} ergs/count to relate ASM counts/s (2–12 keV) to X-ray luminosity (ergs/s). This simulation shows that it takes about 5 days for the transition radius to move from its initial value of 10^{10} cm to values small enough that X-rays can be emitted, in excellent agreement with the optical to X-ray time delay observed in the April 1996 outburst of GRO J1655–40 (ORBM). This explanation of the observed delay is the most outstanding success of the present calculations.

The simulations predict that the various optical bands should go into outburst simultaneously, whereas in the observations the outburst occurred first in the I band, followed by the other bands in the order R, V, and B, spread over a time range of about a day. The model does not reproduce the delays in the op-

tical bands, but, as explained in Sect. 2.2, this delay could result from an earlier increase in the mass transfer rate that occurred less than a month before the outburst, and could well have caused it. It is also worth noting that our optical light curves deviate significantly from linearity during the first two days, whereas the subsequent evolution shows an almost linear variation of the optical magnitudes. This suggests that it may be somewhat difficult observationally to identify the relative time of outburst in various optical bands.

Both the quiescent mass transfer rate into the ADAF and the inner disk radius are solely determined by the evaporation law. On the other hand, the X-ray delay corresponds to the time it takes to rebuild a standard inner disk, and is thus proportional to the mass of the disk, and inversely proportional to the mass transfer rate at the transition radius. This mass transfer rate depends essentially on α_h/α_c , the ratio of the Shakura-Sunyaev viscosity parameter in the hot and cold states of the disk. Therefore, an increase in K results in a smaller transition radius and a smaller ADAF luminosity; the corresponding shortening of the X-ray delay can in turn be compensated for by taking a smaller α_h , i.e. by increasing the viscous time.

The calculations described so far show that a two-component accretion flow model consisting of an outer thin disk and an inner ADAF explains most of the key observations of GRO J1655–40. It explains the quiescent spectrum of the source as well as the characteristics of the outburst, notably the X-ray delay. We argued in §3 that the quiescent spectrum of GRO J1655–40 cannot be explained by a pure thin disk. We now show that a pure thin disk model has difficulty in reproducing the outburst observations. We consider two models for which the thin disk extends down to $R_{in} = 4 \times 10^8$ cm.

The first model describes an inside-out outburst (solid lines in Fig. 4). The surface density in the outer parts of the accretion disk was adjusted such as to reproduce the correct slope of the X-ray and optical light curves, the viscosity being as in the previous model. For this reason, the agreement between the predicted and observed light curves is very good, better in fact than in the case of Fig. 3 for which such a fitting procedure was not performed, since we considered a relaxed case (i.e. after several outbursts) in order to minimize the number of free parameters. The X-ray intensity, which increases simultaneously

with the optical flux, is initially quite faint. Thus, the X-ray delay depends on the sensitivity of the X-ray detector; for example, the ASM would be unable to detect the X-rays during the first 1–2 days, and therefore the model predicts an X-ray delay of this order. The delay could be increased further by decreasing the viscosity parameter, which would slow the rise of the X-ray intensity. However, this would cause the rise in the optical flux to be unacceptably slow.

The second model (dashed lines in Fig. 4) describes an outside-in outburst. In order to obtain the longest possible characteristic times, and therefore the most optimistic scenario for the pure disk model, we started the outburst as far out in the ac-

Fig. 4.— Same as Fig. 3 but for outbursts in a thin cold disk extending down to 4×10^8 cm. The solid curve corresponds to an inside-out outburst; the dashed curves to an outside-in situation. In the latter case, matter was artificially added at 8×10^{10} cm to trigger the outburst.

cretion disk as possible. In long period systems like GRO J1655–40, the outer disk is always cold and stable; therefore to trigger the outburst we added some matter at $R = 8 \times 10^{10}$ cm. The outburst then began at $R = 7 \times 10^{10}$ cm. The viscosity was chosen such as to reproduce the observed X-ray delay ($\alpha_h = 0.10$): it takes 2.6 days for the heat front to reach the inner edge of the disk, and an additional 3.1 days for the mass accretion rate to reach 10^{16} g s $^{-1}$, the level at which the X-ray flux becomes detectable. Thus, this model reproduces the observed X-ray delay. However, the optical light curves are not in agreement with observations since most of the disk reaches a hot state before the heat front reaches the inner edge of the disk. Consequently, the optical flux increases too rapidly, on a thermal time scale, and then more slowly, on a viscous time scale. The observed optical light curve does not exhibit such a prominent two-phase behaviour, nor does it show such a rapid optical increase, features which are the signatures of an outside-in outburst.

It therefore appears difficult to reconcile the observations with a pure disk model. This might not be an insuperable difficulty, but it would most probably require making ad-hoc assumptions about the density profile in the disk and about the viscosity. Even if a candidate model could be contrived, one would also require an explanation for the quiescent X-ray flux that does not invoke accretion, since the whole disk must be in the low state and therefore the mass transfer rate has to be less than 5×10^6 g s $^{-1}$ at the last stable orbit. Such a small rate of mass transfer corresponds to a luminosity of less than 5×10^{26} erg s $^{-1}$, almost six orders of magnitudes below the observed quiescent luminosity. Together, the difficulty of building a viable model plus the near impossibility of explaining the X-ray flux in quiescence rule strongly against the pure disk model.

5. Conclusions

We have shown that both the X-ray spectrum observed in quiescence and the 6-day delay between the optical rise and the X-ray outburst in GRO J1655–40 imply that the accretion disk does not extend in its “standard” form all the way down to the last stable orbit; instead the inner part of the accretion flow is a hot ADAF. It is this ADAF region that is responsible for the X-ray emission detected by ASCA in quiescence. The outer parts of the disk, located

at distances larger than about 10^{10} cm in quiescence, are cold and subject to the same thermal and viscous instability as in dwarf novae. After the instability has been triggered, a heat front propagates inward. When this heat front reaches the transition radius, the divide between the thick disk and the ADAF region, it cannot propagate in further until it rebuilds the inner part of the disk on a viscous time scale (about a week). Because the efficiency of energy release in the ADAF region is very low, the X-ray outburst starts only when the dense parts of the disk can penetrate far enough in, close to the marginally stable orbit, to allow an efficient transformation of gravitational energy into radiation.

We have also shown that both in quiescence and during the initial outburst the observed properties of GRO J1655–40 are not consistent with a pure locally cooled thin accretion disk without an ADAF component. If one wishes to invoke such a model, one has to (1) accept that the quiescent X-ray emission is not linked to accretion, and (2) tune the viscosity and the initial surface density of the disk with some care.

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REFERENCES

- Abramowicz, M. A., Chen, X., Kato, S., Lasota, J.-P., & Reguev, O. 1995, *ApJ*, 438, L37
- Bailyn, C. D., Orosz, J. A., McClintock, J. E., & Remillard, R. A. 1995, *Nature*, 378, 157
- Cannizzo, J. K. 1993, in *Accretion Disks in Compact Stellar Systems*, ed. J.C. Wheeler, (Singapore: World Scientific), 6
- Cannizzo, J.K. 1996, in *Cataclysmic Variables and Related Objects*. Proceedings of IAU Coll. 158, ed. A. Evans & J. H. Wood (Dordrecht: Kluwer), 135
- Cannizzo, J.K., Chen, W., & Livio, M., 1995, *ApJ*, 454, 880
- Cannizzo, J. K., & Kenyon, S. J. 1987, *ApJ*, 320, 319
- Gontikakis, C., & Hameury, J.-M. 1993, *A&A*, 271, 118
- Hameury, J. -M., King, A.R., & Lasota, J.-P. 1986, *A&A*, 161, 71
- Hameury, J. -M., et al. 1997, in preparation
- Harmon et al. 1995, *IAU Circular # 6205*
- Horne, K., & Marsh, T. R. 1986, *MNRAS*, 218, 761
- Hjellming, R. M., & Rupen, M. P. 1995, *Nature*, 375, 464
- King, A. R., Kolb, U., & Burderi, L. 1996, *ApJ*, 464, L127
- Lasota, J. -P., 1996a, in *Compact Stars in Binaries*. Proceedings of the IAU Symposium 165, ed. J. van Paradijs, E. P. J. van den Heuvel & E. Kuulkers (Dordrecht: Kluwer), 43
- Lasota, J. -P., 1996b, in *Cataclysmic Variables and Related Objects*. Proceedings of IAU Coll. 158, ed. A. Evans & J. H. Wood (Dordrecht: Kluwer, 385)
- Lasota, J. -P., 1997, in *Accretion Phenomena and Related Outflows*, Proceedings of IAU Coll. 163, ed. D. Wickramasinghe, L. Ferrario & G. Bicknell, in press
- Lasota, J. -P., Narayan, R., & Yi, I. 1996, *A&A*, 314, 813
- Levine, A. M. et al. 1996, *ApJ*, 343, L33
- Livio, M., & Pringle, J. E. 1992, *MNRAS*, 259, 23P
- Ludwig, K., Meyer-Hofmeister, E., Ritter, H., 1994, *A&A*, 290, 473
- McClintock, J. E., Horne, K., & Remillard, R. A. 1995, *ApJ*, 442, 358
- Meyer, F. 1984, *A&A*, 131, 303
- Meyer, F., & Meyer-Hofmeister, E. 1994, *A&A*, 288, 175
- Mineshige, S. & Wheeler, J.C. 1989, *ApJ*, 343, 241
- Narayan, R. 1996, *ApJ*, 462, 136
- Narayan, R. 1997, in *Accretion Phenomena and Related Outflows*, Proceedings of IAU Coll. 163, ed. D. Wickramasinghe, L. Ferrario & G. Bicknell, in press
- Narayan, R., Barret, D., & McClintock, J. E., 1997a, *ApJ*, in press (NBM)

- Narayan, R., Garcia, M., & McClintock, J. E. 1997b, ApJ, 478, L79
- Narayan, R., McClintock, J. E., & Yi, I. 1996b, ApJ, 451, 821 (NMY)
- Narayan, R., & Yi, I. 1994, ApJ, 428, L13
- Narayan, R., & Yi, I. 1995, ApJ, 452, 710
- Orosz, J. A. 1996, private communication
- Orosz, J. A., & Bailyn C. D. 1997, ApJ, 477, 876 in press (OB)
- Orosz, J. A., Remillard, R. A., Bailyn C. D. & McClintock, J. E. 1997, ApJ, 478, L83 (ORBM)
- Pringle, J. E., Verbunt, F., & Wade R. A. 1986, MNRAS, 221, 169
- Ritter, H. 1997, private communication
- Robinson, C. R. et al. 1997, in preparation
- Remillard et al. 1996, IAU Circular # 6393
- Smak, J. 1981, Acta Astron., 31, 395
- Tanaka, Y., & Shibazaki, N. 1996, ARA&A, 34, 607
- Tingay, S.J. et al. 1995, Nature, 374, 141
- Verbunt, F. 1996, in Compact Stars in Binaries. Proceedings of the IAU Symposium 165, ed. J. van Paradijs, E. P. J. van den Heuvel & E. Kuulkers (Dordrecht: Kluwer), 333
- Warner, B., 1995, Cataclysmic Variable Stars. (Cambridge: Cambridge University Press)
- Wheeler, C. J. 1996, in Relativistic Astrophysics, eds. B. Jones & D. Markovic (Cambridge: Cambridge University Press) in press (astro-ph/9606119)
- Wilson, C.A. et al. 1995, IAU Circular # 6152
- Zhang, S. N. et al. 1994, IAU Circular # 6046