Observations of the quiescent X-ray transients GRS 1124–684 (=GU Mus) and Cen X–4 (=V822 Cen) taken with ULTRACAM on the VLT

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ABSTRACT

We present high time-resolution multicolour optical observations of the quiescent X-ray transients GRS 1124–684 (=GU Mus) and Cen X–4 (=V822 Cen) obtained with ULTRACAM. Superimposed on the secondary stars’ ellipsoidal modulation in both objects are large flares on time-scales of 30–60 min, as well as several distinct rapid flares on time-scales of a few minutes, most of which show further variability and unresolved structure. Not significant quasi-periodic oscillations are observed and the power density spectra of GRS 1124–684 and Cen X–4 can be described by a power-law. From the colour-colour diagrams of the flare events, for GRS 1124–684 we find that the flares can be described by hydrogen gas with a density of \( N_H \sim 10^{24} \) nucleons cm\(^{-2} \), a temperature of \( \sim 8000 \) K and arising from a radius of \( \sim 0.3 \) R\(_{\odot} \). Finally we compile the values for the transition radius (the radius of the hot advection-dominated accretion flow) estimated from quasi-periodic oscillations and/or breaks in the power density spectrum for a variety of X-ray transients in different X-ray states. As expected, we find a strong correlation between the bolometric luminosity and the transition radius.

Key words: accretion, accretion disc – binaries: close – stars: individual: GRS 1124–684 (=GU Mus) stars: individual: Cen X–4 (=V822 Cen)

1 INTRODUCTION

X-ray transients (XRTs) are a subset of low-mass X-ray binaries that display episodic, dramatic X-ray and optical outbursts, usually lasting for several months. More than 70 percent of XRTs are thought to contain black holes (Charles & Coe 2006). The black hole X-ray transients are known to exhibit five distinct X-ray spectral states, distinguished by the presence or absence of a soft black-body component at 1 keV and the luminosity and spectral slope of emission at higher energies; these are known as the quiescent, low, intermediate, high and very high states (Tanaka & Shibazaki 1996). The quiescent and low states can mostly be explained with the advection dominated accretion flow (ADAF) model (Narayan, McClintock & Yi 1996; Esin, McClintock & Narayan 1997). In the context of the ADAF model, properties similar to the low/hard state are expected for the quiescent state, as there is thought to be no distinction between the two except that the mass accretion rate is much higher and the size of the ADAF region is smaller for the low/hard state.

Similar to the transition between the low/hard and high/soft (thermal-dominant) state, where there is a reconfiguration of the accretion flow (Esin et al. 1997), there is also observational evidence for a state transition between the low/hard and quiescent states, in that the quiescent state power-law appears softer than in the low/hard state. In both these states, the ADAF model predicts that the inner edge of the disc is truncated at some large radius, with the interior region filled by an ADAF. Strong evidence for such a truncated disc is provided by observations of XTE J1118+480 in the low/hard state during outburst (Hynes et al. 2000; McClintock et al. 2001; Esin et al. 2001; Chaty et al. 2003), where the disc has an inner radius of >5 Schwarzschild radii.

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1 Based on observations made at the European Southern Observatory, Paranal, Chile (ESO program 075.D-0193)
Ray transient Cen X–4 in quiescence. These observations are also used to obtain lightcurves of GRS 1124–684, Cen X–4 and several comparison stars by extracting the counts using aperture photometry. The most reliable results were obtained using a variable aperture which scaled with the seeing. The count ratio of the target with respect to a bright local standard (which has similar colour to our target) was then determined. The magnitude of the target was then obtained using the calibrated magnitude of the local standard. As a check of the photometry and systematics in the reduction procedure, we also extracted lightcurves of a faint comparison star similar in brightness to the target.

The mean magnitude of GRS 1124–684 was $u'=21.49$, $g'=20.65$ and $i'=19.92$ and we estimate the photometric accuracy per exposure to be 16.4, 2.8 and 2.0 percent for the $u'$, $g'$ and $i'$ band respectively. For Cen X–4, the mean magnitude was $u'=18.69$, $g'=18.07$ and $i'=17.27$ and we estimate the photometric accuracy per exposure to be 5.9, 0.9 and 0.6 percent for the $u'$, $g'$ and $i'$ band respectively. The uncertainties only reflect the 1-σ statistical errors in the relative photometry.

3 SHORT-TERM VARIABILITY

The optical lightcurves of GRS 1124–684 and Cen X–4 (Figure 1) show short-term variability/ﬂares superimposed on the secondary star’s weak ellipsoidal modulation. So if we want to determine the flux of the ﬂares, these “steady” contributions must ﬁrst be removed from the lightcurves. In order to isolate the short-term variability in each band we ﬁrst de-reddened the observed magnitudes using a colour excess of $E(B-V)=0.29$ (Cheng et al. 1992) for GRS 1124–684 and $E(B-V)=0.10$ for Cen X–4 (Blair et al. 1984) and adopting the ratio $A_V/E(B - V)=3.1$ (Cardelli, Clayton, & Mathis 1989), and then converted the Sloan AB magnitudes to flux density ($F_{\text{sloan}}=20.65$ and $E_{\text{sloan}}=17.27$ and we estimate the photometric accuracy per exposure to be 5.9, 0.9 and 0.6 percent for the $u'$, $g'$ and $i'$ band respectively. The uncertainties only reflect the 1-σ statistical errors in the relative photometry.

2 OBSERVATIONS AND DATA REDUCTION

Multi-colour photometric observations of GRS 1124–684 and Cen X–4 were obtained with ULTRACAM on the 8.2-m MELIPAL unit of the Very Large Telescope (VLT) at Paranal, Chile. The GRS 1124–684 data were taken during the nights starting 2005 May 9 to 10, whereas the Cen X–4 data were taken on the nights starting 2007 June 18 (see Table 1 for a log of the observations). ULTRACAM is an ultra-fast, triple-beam CCD camera, where the light is split into three broadband colours (blue, green and red) by two dichroics. The detectors are back-illuminated, thinned, E2V frame-transfer 1024×1024 CCDs with a pixel scale of 0.15 arcsec/pixel. Due to the architecture of the CCDs the dead-time is essentially zero (for further details see Dhillon et al. 2007). Our observations were taken using the Sloan $u'$, $g'$ and $i'$ filters with effective wavelengths of 3550 Å, 4750 Å and 7650 Å respectively.

The ULTRACAM pipeline reduction procedures were used to debias and flatfield the data. The same pipeline was also used to obtain lightcurves for GRS 1124–684, Cen X–4 and several comparison stars by extracting the counts using aperture photometry. The most reliable results were obtained using a variable aperture which scaled with the seeing. The count ratio of the target with respect to a bright region is expected to be larger. Here we report on our high-time resolution multi-colour optical observations of the black hole X-ray transient GRS 1124–684 and the neutron star X-ray transient Cen X–4 in quiescence. These observations are part of a ongoing campaign with ULTRACAM to obtain high-resolution photometry of X-ray binaries (Shahbaz et al. 2003).

| Object       | UT Date starting | UT Start | exp. time (s) | No.of images | Median seeing (range) |
|--------------|------------------|----------|---------------|--------------|-----------------------|
| GRS 1124–684 | 09/05/05         | 23:13    | 5.0/5.0/5.0   | 4005         | 1.5 (1.2–2.0)         |
| GRS 1124–684 | 10/05/05         | 00:17    | 5.0/5.0/5.0   | 3469         | 1.7 (1.3–3.0)         |
| Cen X–4      | 18/06/07         | 01:41    | 6.0/3.0/3.0   | 3296/6579/6579| 0.6 (0.45–1.2)        |
of 10–30 min. The parameters of the flares as defined by Zurita et al. (2002) are given in Table 2.

A look at the lightcurves of GRS 1124–684 shows short-term flare events which seem to occur regularly. In Figure 4 we show tick marks with representative intervals of 6.3 min. As one can see, some of the flare events seem to recur on a regular basis and the period appears to be stable on short time-scales. It is clear, however, that these events are not strictly periodic, and not strong enough to show up as QPOs in a log-log plot of the PDS (see section 4).

4 THE POWER DENSITY SPECTRUM

The flare lightcurves (i.e. the after subtracting the secondary star’s ellipsoidal modulation from the de-reddened lightcurves) of GRS 1124–684 and Cen X–4 show features which seem to be periodic. To see if this is true we computed the power density spectrum (PDS) of the data. To compute the PDS we detrended the data using the double sinusoid fit described in the previous section and then added the mean flux level of the data. Although the ULTRACAM sampling is perfectly uniform over short periods of time (tens of minutes), we use the Lomb-Scargle method to compute the periodograms (Press et al. 1992) with the same normalization method as is commonly used in X-ray astronomy, where the power is normalized to the fractional root mean amplitude squared per hertz (van der Klis 1994). We used the constraints imposed by the Nyquist frequency and the typical duration of each observation to limit the range of different frequencies searched.

The lightcurves of GRS 1124–684 and Cen X–4 shows features that are present in all three bands (see Figure 4). In order to determine the possibility of significant peaks above the red-noise level, we used a Monte Carlo simulation similar to Shahbaz et al. (2003). We generated lightcurves with exactly the same sampling and integration times as the real data. We started with a model noise lightcurve generated using the method of Timmer & Koenig (1995) with a power-law index as determined from the PDS of the observed data, and then added Gaussian noise using the errors derived from the photometry. We computed 5000 simulated lightcurves and then added the mean flux level of the data. Although the mean amplitude squared per hertz (van der Klis 1994). We used the constraints imposed by the Nyquist frequency and the typical duration of each observation to limit the range of different frequencies searched.

In Figure 5 the errors in each frequency bin are determined from the standard deviation of the points within each bin and the white noise level was subtracted by fitting the highest frequencies with a white-noise (constant) plus red-noise (power-law) model. The power-law index of the fit is also given.

5 THE ORIGIN OF THE FLARES

In an attempt to interpret the broad-band spectral properties of the flare, we compared the observed colours with the prediction for three different emission mechanisms, namely a blackbody, an optically-thin layer of hydrogen and synchrotron emission. We computed the given emission spectrum and then calculate the expected flux density ratios \( f_\alpha/ f_\beta \) and \( f_\gamma/ f_\alpha \) using the synthetic photometry package SYNPHOT (IRAF/STSDAS). Given the intrinsic model flux we can then determine the corresponding radius of the region that produces the observed de-reddened flux at a given distance.

Figure 6 shows the data for the flare events and the expected results for different emission models. For stellar flares the power-law index of the electron energy distribution~\( \sim -2 \) (Croby, Aschwanden & Schmitt 1993), which corresponds to a spectral energy distribution with index \( \alpha = -0.5 \) (\( F_\nu \propto \nu^{-\alpha} \)). However, the spectral energy distribution index observed in V404 Cyg (\( \alpha \sim -2.0 \)) implies a much steeper index for the electron energy distribution (Shahbaz et al. 2003), which may not be completely implausible given the extreme conditions around a black hole. Therefore in Figure 7 we show the power-law model for \( \alpha \) ranging from -2 to 2. We also show the very unlikely blackbody case, where the flares are due to blackbody radiation from a heated region of the disc’s photosphere. The most likely model for a thermal flare is emission from an optically thin layer of recombining hydrogen, which is essentially the mechanism generally accepted for solar flares. We therefore determined the continuum emission spectrum of an LTE slab of hydrogen for different baryon densities, \( N_H = 10^{21} \) to \( 10^{24} \) nucleons cm\(^{-2} \), and calculated the expected flux ratios.

For Cen X–4 the amplitudes of the flares are small and difficult to define. All we can say is that they arise from an optically thin region with \( N_H \sim 10^{21} \) to \( 10^{25} \) nucleons cm\(^{-2} \), a temperature of \( \sim 8,300 \) K and a radius of \( \sim 0.06 \) \( R_\odot \) (assuming a distance of 1.2 kpc; Chevalier et al. 1989). For GRS 1124–684 we can comment more because the flares are well defined; Figure 7 shows the data for the best resolved small and large flares for GRS 1124–684. The flare events can be described by hydrogen gas with a density of \( N_H \sim 10^{24} \) nucleons cm\(^{-2} \) and a temperature of \( \sim 8000 \) K, which corresponds to a radius of \( \sim 0.3 \) \( R_\odot \) (assuming a distance of 5.1 kpc; Gelino, Harrison, & McNamara 2001).

6 DISCUSSION

6.1 The origin of the flares

We can compare the flares in GRS 1124–684 to the flare properties determined in other quiescent black hole XRTs. The large flares in V404 Cyg are consistent with optically thin gas with a temperature of \( \sim 8000 \) K arising from a region with an equivalent blackbody radius of at least 2 \( R_\odot \) (Shahbaz et al. 2003). One should regard the equivalent radius estimate as a lower limit, because the emission mechanism is unlikely to be blackbody. Similarly for XTEJ1118+480, the short-term flares have a blackbody temperature of \( \sim 3500 \) K and an equivalent radius of \( \sim 0.10 \) \( R_\odot \). By isolating the spectrum of the flare event in A0620–00, we found that it could be represented by optically thin gas of hydrogen with radius 0.04 \( R_\odot \) and temperature 10,000–14,000 K (Shahbaz et al. 2003), which are consistent with the bright spot area and temperature. The
Balmer line flux and variations in A0620–00 suggests that there are two emitting regions, the accretion disc and the accretion stream/disc impact region. The persistent emission is optically thin and during the flare events there is either an increase in temperature or the emission is more optically thick than the continuum. For GRS 1124–684 we find that the flare events reach a maximum radius of ~0.3R_s, much larger than what is observed in A0620–00 (Shahbaz et al. 2003), XTE J1118+480 (Shahbaz et al. 2004) and Cen X–4 (section 5).

The flares GRS 1124–684 and Cen X–4 arise from various regions in the accretion disc that in total occupy 3.4% and 0.3% of the disc’s area respectively. Thus could be from the hotspot, but the Halpha Doppler maps of GRS 1124–684 and Cen X–4 do not show any evidence of a hotspot (Casaers et al. 1997; Torres et al. 2002). However, it should be noted that the optical state of quiescent transients are known to vary significantly from epoch to epoch (Cantrell et al. 2008).

### 6.2 The transition radius

Narayan et al. (1997) have shown that the X-ray observations of quiescent XRTs can be explained by a two-component accretion flow model. The geometry of the flow consists of an hot inner ADAF that extends from the black hole horizon to a transition radius r_tr and a thin accretion disc that extends from r_tr to the outer edge of the accretion disc. An ADAF has turbulent gas at all radii, with a variety of time-scales, ranging from a slow time-scale at the transition radius down to nearly the free-fall time close to the compact object. In principle, interactions between the hot inner ADAF and the cool, outer thin disc, at or near the transition radius, can be a source of optical variability, due to synchrotron emission by the hot electrons in the ADAF (Esin et al. 1997). For an ADAF the variability could be quasi-periodic and would have a characteristic time-scale given by a multiple of the Keplerian rotation period at r_tr. The ADAF model also predicts that r_tr should get larger as the inner disc evaporates during the decline from outburst.

To see if there is any observational evidence for this, we have compiled the values for r_tr estimated from spectral energy distribution (SED) fits, QPOs and/or breaks in the PDS for a variety of XRTs in different X-ray states (see Table 3). For J1118+480 during outburst there are several estimates for r_tr. The low/hard state X-ray PDS of J1118+480 (April 2000) shows a low-frequency break f_break at 23 mHz and a QPO at ~80 mHz (Hyves et al. 2003), which is approximately consistent with the relation observed in other sources (Wijnands & van der Klis 1999), most likely related to an instability in the accretion flow that modulates the accretion rate. The QPO frequency is most likely related to r_tr, which can be a source of quasi-periodic variability and r_tr can be estimated assuming the QPO frequency is the Keplerian rotation period at r_tr. The observed QPO frequency corresponds to r_tr=670 (t_K = 2πR/v_K = 2π(GM/R^3)^{-1/2} ~ (M/10 M_S)(r/100)^{3/2} s, where R is the absolute radius and r is in units of R_Sch)

For a cellular-automaton ADAF disc (Takeuchi & Mineshige 1997), the break-frequency is determined by the maximum peak intensity of the X-ray shots which is on the order of the size of the advection-dominated region, and corresponds to the inverse of the free-fall time-scale of the largest avalanches (Takeuchi, Mineshige & Negoro 1995) at r_tr. However, it should be noted that the break frequency depends not only on the size of the ADAF region but also on the propagation speed of the perturbation (Mineshige priv. comm.). Since the perturbation velocity should be less than the free-fall velocity, the free-fall velocity gives an upper limit to the size of the ADAF region. Thus equation 13 of Takeuchi et al. (1995) gives an upper limit to r_tr (r_tr < 10^{1/2}(f_{break} M_S)^{-2/3}). Thus the break frequency observed in J1118+80 during outburst corresponds to r_tr<5250. The SED fits gives r_tr~350, which is similar to value determined from the QPO to within a factor of 2; note that the variability/QPO could have a characteristic time-scale given by a multiple of the Keplerian rotation period at r_tr.

Figure 3 shows r_tr versus the bolometric X-ray luminosity (Campana & Stella 2000) for the sources listed in Table 3. One can see that there does exist a correlation (the corelation coefficient is -0.96) with a slope index of ~3.0. However, more observations of r_tr during different X-ray states are required.

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Table 3. The transition radius for various systems

| Object   | State           | Method  | $\log [R_{tr}/R_D]$ | $\log [L_X/L_{EDD}]$ | Reference          |
|----------|-----------------|---------|---------------------|-----------------------|--------------------|
| GU Mus   | ultrasoft       | SED     | -2.92               | -0.16                 | Misra (1999)       |
| J1118+480| low/hard        | SED     | -1.91               | -2.79                 | Chaty et al. (2003)|
| J1118+480| low/hard        | QPO     | -1.72               | -2.79                 | Hynes et al. (2003)|
| J1118+480| low/hard        | PDS break | -0.77            | -2.79                 | Hynes et al. (2003)|
| J1655–40 | quiescence      | Delay   | -1.51               | -5.25                 | Hameury et al. (1997)|
| V404 Cyg | quiescence      | QPO     | -1.29               | -4.89                 | Shahbaz et al. (2003)|
| A0620–00 | quiescence      | PDS break | -0.05            | -7.16                 | Hynes et al. (2003)|
| J1118+480| quiescence      | PDS break | -0.07            | -8.43                 | Shahbaz et al. (2005)|

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Figure 1. The de-reddened $u'$, $g'$ and $i'$-band lightcurves of GRS 1124-684 and Cen X-4 phase-folded using the ephemeris given in Casares et al. (1997) and Torres et al. (2002) respectively; orbital phase 0.0 is defined as inferior conjunction of the secondary star. The solid line is the fitted ellipsoidal modulation. At the bottom of each panel we also show the lightcurve of a comparison star of similar magnitude to the target, offset vertically for clarity.
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9 May 2005

10 May 2005

Figure 2. Top: The GRS 1124–684 flare de-reddened flux density $u'$ (top panel), $g'$ (middle panel) and $i'$-band (bottom panel) lightcurves obtained by subtracting a fit to the lower-envelope of the lightcurves shown in Figure 1. The uncertainties in the $u'$, $g'$ and $i'$ lightcurves are $4.3 \times 10^{-3}$ mJy, $1.2 \times 10^{-4}$ mJy and $2.0 \times 10^{-3}$ mJy respectively. Bottom: the flux ratio lightcurves binned to a time resolution of 150 s for clarity.
Figure 3. The top three panels show the Cen X–4 flare de-reddened flux density $u'$ $g'$ and $i'$-band lightcurves obtained by subtracting a fit to the lower-envelope of the lightcurves shown in Figure 1. The uncertainties in the $u'$, $g'$ and $i'$ lightcurves are $1.2 \times 10^{-3}$ mJy, $2.7 \times 10^{-3}$ mJy and $7.0 \times 10^{-3}$ mJy respectively. The bottom two panels show the flux ratio lightcurves binned to a time resolution of 135 s for clarity.
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Figure 4. A close-up of the $g'$-band lightcurve of GRS 1124–684. Short-term flare events seem to be periodic, but only over a few cycles. Vertical tick marks are shown with a representative interval of 6.3 min.

Figure 5. Detailed plot of some of the individual flares in the $i'$-band lightcurve of GRS 1124–684. Note that numerous flare events which last for a few minutes are not resolved. The solid point in the top left panels marks the typical uncertainty in the data.
Figure 6. From top to bottom: the $u'$, $g'$ and $i'$ PDS of the flare lightcurves of GRS 1124–684 taken on 9 and 10 May 2005 (left) and Cen X–4 taken on 18 June 2007 (right). The dashed line is a power–law fit. The slope of the power-law fit to the PDS is indicated in each panel.
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Figure 7. Colour-Colour diagram for the clearest small and large flare events in GRS 1124–684 and the large flare events in Cen X–4. The panels labelled "ALL" show all the data for that particular night, where the error bars have been removed for clarity. The dashed lines show optically-thin hydrogen slab models for different column densities and the open squares show the temperature in 1000 K units. The solid line shows a power-law model \( F_\nu \propto \nu^\alpha \) with indices \( \alpha=-0.5 \) and \(-1.5 \) marked as open circles. The dot-dashed line is a blackbody model where the asterisk shows the colour for a temperature of 6500 K.
Figure 8. The transition radius (accretion disc units $R_D$) versus bolometric luminosity (Eddington units $L_{\text{EDD}}$) for a variety of X-ray transients in different X-ray states. The filled circles are for systems in quiescence and the crosses are for systems in the low/hard state or in outburst. The $r_{tr}$ values have been determined from QPOs (crosses), breaks in the PDS (upper limit), fits to the spectral energy distribution (squares) or delays in the optical/X-ray outburst (stars): J1118+480 (Chaty et al. 2003; Shahbaz et al. 2005); A0620–00 (Hynes et al. 2003); J1655–40 (Hameury et al. 1997); V404 Cyg (Shahbaz et al. 2003); GRS 1124–684 (Mira 1997). The X-ray luminosities are taken from Campana & Stella (2000) and the orbital parameters from Charles & Coe (2006).