OPTICAL VARIABILITY OF THE ACCRETION DISK AROUND THE INTERMEDIATE-MASS BLACK HOLE ESO 243-49 HLX-1 DURING THE 2012 OUTBURST

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ABSTRACT

We present dedicated quasi-simultaneous X-ray (Swift) and optical (Very Large Telescope, V-, and R-band) observations of the intermediate-mass black hole candidate HLX-1 before and during the 2012 outburst. We show that the V-band magnitudes vary with time, thus proving that a portion of the observed emission originates in the accretion disk. Using the first quiescent optical observations of HLX-1, we show that the stellar population surrounding HLX-1 is fainter than V ∼ 25.1 and R ∼ 24.2. We show that the optical emission may increase before the X-ray emission consistent with the scenario proposed by Lasota et al. in which the regular outbursts could be related to the passage at periastron of a star circling the intermediate-mass black hole in an eccentric orbit, which triggers mass transfer into a quasi-permanent accretion disk around the black hole. Further, if there is indeed a delay in the X-ray emission we estimate the mass-transfer delivery radius to be ∼10^{14} cm.

Key words: accretion, accretion disks – binaries: close – black hole physics

Online-only material: color figure

1. INTRODUCTION

Two varieties of black hole (BH) have been extensively observed: stellar mass (∼3–20 M☉) BHs and supermassive (∼10^6–10^9 M☉) BHs present in the cores of most galaxies. It is believed that stellar mass BHs are formed from the collapse of massive stars (e.g., Fryer 2003), but it is not yet clear how supermassive ones are formed. One model proposes that they are formed from the mergers of smaller mass (∼10^3–5 M☉) BHs, the so-called intermediate-mass black holes (IMBHs; e.g., Madau & Rees 2001). However, the observational evidence for these BHs has been, until recently, fairly weak.

One very good candidate is a 2XMM X-ray catalog source (Watson et al. 2009): 2XMM J011028.1−460421, serendipitously discovered as an off-nuclear X-ray source apparently associated with the galaxy ESO 243-49, 95 Mpc away (Farrell et al. 2009). Follow-up spectroscopy of the optical counterpart confirmed the association (Wiersma et al. 2010). Using the maximum unabsorbed X-ray luminosity of 1.1 × 10^{42} erg s^-1 (0.2–10.0 keV; Farrell et al. 2009) and the conservative assumption that this value exceeds the Eddington limit by at most a factor of 10 implies a minimum mass of 500 M☉. Modeling and Eddington scaling of the X-ray data indicate a mass of the order 10^4 M☉ (Godet et al. 2012a; Davis et al. 2011; Servillat et al. 2011) and recent radio observations provide a mass upper limit of 9 × 10^4 M☉ (Webb et al. 2012). This source, now known as ESO 243-49 HLX-1 or HLX-1 for short, is therefore a very good candidate IMBH.

Regular monitoring of HLX-1 with Swift has revealed flux changes by a factor of 50 in conjunction with simultaneous spectral changes in the same way as Galactic BH X-ray binaries (Godet et al. 2009; Servillat et al. 2011), thus strengthening the case for an accreting BH in HLX-1. It has become evident that HLX-1’s X-ray variability follows a fairly distinct pattern over ∼1 yr (Lasota et al. 2011; Godet et al. 2012a, 2012b). The fast rise exponential decay type light curve of HLX-1 outbursts is sometimes observed in Galactic black hole low-mass X-ray binaries (BHLMXBs). However, Lasota et al. (2011) showed that the HLX-1 outbursts cannot be explained by the same mechanism: the disk instability model (DIM; see Lasota 2001 for a review). In the framework of the DIM, the peak outburst luminosity requires the outer disk radius to be >10^{13} cm, incompatible with the observed decay time. For such a radius, the viscous decay time is >100 yr, whereas according to observations it is just a few months. The (apparently) periodic outbursts of HLX-1 can therefore not be attributed to a thermal-viscous disk instability.

As shown by Lasota et al. (2011), an evolved (asymptotic giant branch) star on an eccentric orbit around the ∼10^4 M☉ BH, periodically delivering part of its mass to a permanently present accretion disk, can provide a viable explanation of the HLX-1 outbursts. This scenario has to take into account the outburst decay time which requires a disk radius (or a mass-transfer delivery radius) of <10^{12} cm, which implies a very eccentric orbit of the putative donor star. In this model the impulsive increase in mass transfer leads to a rise that is a fraction of the viscous time (≤0.1 t_visc) and then decays on ∼t_visc. The passage of the star at periapse may also lead to the excitation of waves in the disk that will enhance angular momentum transport (Spruit 1987). If such wave propagation mechanisms are at work during
the rise to outburst of HLX-1, the characteristic propagation velocity might be similar to that of the heating front according to the DIM (∼αc_s, where α ∼ 0.1 and c_s is the speed of sound). In such a case the outburst always starts in the outer disk and propagates inward.

In BHLMXBs the X-ray emission has been observed to lag the optical during outburst (Orosz et al. 1997; Jain et al. 2001; Buxton & Bailyn 2004; Wren et al. 2001) but, contrary to naive expectations, they are not thought to be produced from the outbursts starting at the outer disk edge and propagating inward (Hameury et al. 1997). The characteristic BHLMXB rise timescales (∼days) and the fact that delays between the rise of individual optical bands (e.g., Orosz et al. 1997) are also sometimes observed, suggest that the X-ray/optical tracks the size of the inner truncation radius of the quiescent disk. In LMXBs the heating fronts triggered by the thermal/viscous instability cannot propagate into the inner accretion-dominated accretion flow (ADAf; e.g., Dubus et al. 2001) which is invaded by the accretion disk on a viscous time. Typically the radii of the ADAF region corresponding to delays of a few days are ∼10^4 R_s (where R_s = 2GM/c^2), i.e., ∼10^{10} cm. The case of HLX-1 is different since its outbursts are not due to a thermal/viscous instability but to an impulsive increase of the mass transfer in the outer disk. Therefore, in principle, an observed delay between the rise of X-rays and the optical emission can be attributed to the distance between the two emitting regions.

In this Letter we examine dedicated quasi-simultaneous Swift X-ray and Very Large Telescope (VLT; V- and R-band) optical observations of HLX-1 before and during its 2012 outburst (Godet et al. 2012a) with the aim of constraining the properties of the rise-to-outburst mechanism. We also compare Gemini R-band data from the X-ray plateau phase and beginning of the X-ray decay, taken during the 2011 outburst. We examine the light curves for any evidence of a delay between the rise of X-rays with respect to the optical, which may provide information about the propagation of the perturbation at the outburst origin, as well as the disk structure.

2. OBSERVATIONS

2.1. Optical Data

We observed HLX-1 under the ESO program (089.D-0360(A), PI: Webb) on seven nights from 2012 August 11 to 2012 September 8, using the FORS2 instrument on the VLT; see Table 1. We employed two filters, the "v high" filter with an effective wavelength of 557 nm and a FWHM of 123.5 nm, and the "R special" which has an effective wavelength of 655 nm and a FWHM of 165 nm.10 The observations were carried out in service mode. Due to technical problems with the MIT CCDs (2 × 2 binning, 0′′.25 pixel^{-1}). The E2V CCDs provide much higher response in the blue compared to the MIT CCDs, but suffer from strong fringing above 650 nm and thus had an effect on the "R" observations. The latter four observations were taken with the MIT CCDs (2 × 2 binning, 0′′.25 pixel^{-1}). The seeing values, as determined from measuring the FWHM of stars in the images, are given in Table 1. The sky was always clear, but not necessarily photometric. We used IRAF version 2.16 (Tody 1986, 1993) to reduce and analyze the data. The raw images were trimmed, bias subtracted, and then flat fielded using the sky flats taken closest in time. Some residual fringing of the order 3%–4% remained after this step and was slightly higher for the R-band observations taken with the E2V CCDs. The observations on any one night in any particular filter were divided into two equal exposures to avoid saturating the host galaxy emission in the HLX-1 region. We then added the two exposures taken in the same filter on each night, to improve the signal-to-noise ratio.

HLX-1 is immersed in the diffuse emission from the galaxy ESO 243-49 in all of the images. This must be subtracted to determine reliable flux values of HLX-1. We explored six different methods. Initially we tried point-spread function (PSF) matched image subtraction with spatially varying kernels, using the ISIS2 code (Alard 2000). However, this did not give sufficient control over the stars selected for the PSF fitting, which caused large residuals. We then tried the same method, but with the HOTPANTS codes,11 which gave more control over the stars selected and over the photometric errors. However, the proximity of HLX-1 to the very brightest parts of the host galaxy (close to non-linear count values) and the complex changes in host galaxy brightness on small spatial scales, results in systematic residuals in the subtracted frames (particularly along the long symmetry axis of the galaxy and near the nucleus) that strongly influence the HLX-1 flux determination. Changing the image section sizes and positions did not sufficiently negate this problem.

We also tried elliptical isophote fitting but were unable to fit and remove the diffuse emission effectively, as strong deviations of elliptical symmetry were apparent. We then tried two methods explored by Soria et al. (2012), first by using PSF-convolved physical model fits to the host galaxy as a whole, using the GALFIT codes (Peng et al. 2010) and subtracting this model. However, we found that a large number of model components were required to eliminate strong residuals near HLX-1, which in turn lead to large systematic errors associated with model degeneracy.

We next attempted surface fits to the local brightness profile and subtracted these from the diffuse emission, as explored in Soria et al. (2012). We excised postage stamp images containing HLX-1, with varying centroid coordinates and stamp sizes. We fitted polynomial surfaces to the light profile, excluding a

10 See http://www.eso.org/sci/facilities/paranal/instruments/fors/doc/VLT-MAN-ESO-13100-1543_v91.pdf.

11 http://www.astro.washington.edu/users/becker/hotpants.html
circular region around HLX-1. We used several radii of exclusion as well as a range of polynomial order values. However, both background residuals and source flux varied strongly with small variations in fitted image stamp and exclusion region. This is likely to be due to the high-order polynomial and small stamp size to adequately trace the strong variations in galaxy brightness (steep flux gradient) on small spatial scales. We therefore attempted to remove the steepest flux gradients by exploiting local symmetry, subtracting an image of the galaxy mirrored in the long axis, before performing local surface brightness fits in postage stamps (∼15′′ × 15′′ in size) around HLX-1. We then required much lower polynomial orders for the background fit, and residuals were robust to small changes in fit regions. This revealed HLX-1 clearly except for observations on August 11 and 14. For these observations, we added the data from the two nights in each filter. HLX-1 could then be identified.

We also reduced and analyzed the Gemini r′ filter (562–698 nm) presented in Farrell et al. (2013) and taken on four nights between 2011 August 31 and 2011 October 6. The detector pixel scale is 0.′′146 per pixel and we used a nine-point dither pattern repeated twice. We reduced and analyzed these data in the same way as the VLT observations.

The VLT observations were not always carried out in photometric conditions, we give relative fluxes (compared to a non-variable field star) in Figure 1. These fluxes were calculated using the phot task in IRAF by means of aperture photometry. We used an aperture of 1.5 FWHM to extract the source counts and employed the IRAF task mkapfile to correct for aperture losses. We also used a larger annulus around the extraction region and within the region of low and stable background to determine a background level. We utilized the instrumental zero-point values calculated for the night our observations were made, and given on the FORS2 Web pages, along with the extinction and the color corrections. To verify the reliability of the fluxes and magnitudes extracted, we checked that the magnitudes of nine field stars did not vary over all the observations to within the magnitude errors. However, it should be noted that the R-band errors are slightly larger than the V-band errors, due in large part to the first three observations taken with the blue CCD that shows strong fringing in this band. We included stars as faint as HLX-1 and which were immersed in the diffuse galaxy emission. These objects were reduced in the same manner as HLX-1, and include one star that falls less than 4′′ from HLX-1, see Figure 2, which was therefore extracted from the same small postage stamp region. Only one object in the field was found to vary between observations, and this was HLX-1. The variability of HLX-1 can be seen in Figure 1, along with the relative R-band flux of a field star, to show the reliability of the data reduction and analysis.

2.2. X-Ray Data

The Swift X-Ray Telescope (XRT) photon counting data were processed using the Swift-XRT light-curve generator web interface, binned by observation (Evans et al. 2009). No X-ray source was detected at the position of HLX-1 for the observations made before MJD 56160. For these observations we calculated the 3σ upper limit, as explained in Evans et al. (2009).

Figure 1. Uppermost panel shows the relative “R special” flux of a field star and the comparison star used for the HLX-1 light curves. The middle two panels show the relative R- and V-band flux between HLX-1 and a comparison star. The errors are the percentage errors calculated from the photometry. The lower panel shows the Swift X-ray counts (0.2–10.0 keV) measured for HLX-1 over the same period. X-ray error bars are 1σ. The first three X-ray points are an average upper limit for the three observations. Wide time errors indicate that data on more than one day has been added.

(A color version of this figure is available in the online journal.)
3. RESULTS AND DISCUSSION

The X-ray and optical light curves can be seen in Figure 1. No X-ray source is detected before the observation on MJD 56160, which is consistent with the count rate observed in the low-hard state (e.g., Godet et al. 2012a). The X-ray count rate appears to commence a rise on MJD 56160; however, this point (0.0095 ± 0.0039 counts s⁻¹), which is shown in Figure 1 with its error bar at the 1σ level, has a count rate consistent with the low-hard state count rate if we consider an error bar at the 2σ level and with zero counts if we consider the 3σ error bar (Godet et al. 2012b). Therefore, there is only a hint that the outburst began on this day and it is only two days later (MJD 56162) that we can confidently say that the outburst began in X-rays, as discussed in Godet et al. (2012a) and Kong (2012). Fitting the X-ray data points, the outburst maximum (peak) is reached as discussed in Godet et al. (2012a) and Kong (2012). Fitting that we can confidently say that the outburst began in X-rays, began on this day and it is only two days later (MJD 56162) before the 2012 outburst commences. Lower left: ~5 days before the 2012 outburst peaks. Upper right: Gemini r’-band image. ~5 days after the 2011 outburst peak.

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The V-band flux also rises on MJD 56160. However, contrary to the X-rays, the relative V-band flux observed on that day (0.61 ± 0.24, 3σ error) is not consistent with the quiescent value (0.09 ± 0.04, 3σ error) at the 3σ level. Thus the optical rise may be interpreted to have commenced on MJD 56160, potentially before the X-ray, which would be indicative of an outside-in outburst and supporting the scenario proposed by Lasota et al. (2011); see Section 1.

The R band does not show a rise on the same timescale. This may be because the host stellar population (Farrell et al. 2012) dominates in the R band, whereas the disk dominates the V band, or that there is some other cool emission, for instance from a nebula (Soria et al. 2013). This is supported by the V-band magnitude which is very faint in the low state and increases with the outburst, see Table 2, whereas the R band is brighter initially.

The flux remains roughly constant in the VLT R-band observations. Farrell et al. (2013) also see little evidence for variability in the R band, using Gemini observations taken slightly later in the 2011 outburst (starting two weeks after the peak of the X-ray outburst that year). Our analysis of the same data also reveals no evidence for variability in relative flux compared to the same non-variable field star used for the VLT data, to within the observational errors. HLX-1’s relative flux in the Gemini data appears approximately 1 mag brighter in the R band, compared to the low level detected in the majority of the VLT R-band observations; see Figure 2 and Table 2. However, at the 3σ level, these two values are compatible. We verified that the observed difference in magnitude was not due to variability in the comparison star, by comparing it to a second non-variable field star. No variability is detected in the original comparison star in any of the VLT or Gemini observations.

We have estimated the R- and the V-band magnitudes for the VLT and Gemini data and they are presented in Table 2. The variability can also be visualized in Figure 2. We compare our estimated (because the conditions were not always photometric) magnitudes with previous observations, taken at different times through the 2009–2012 outbursts. It should be noted, however,
that the optical observations made before MJD 56160 are the first to be made during the low-hard state. The very low magnitude measured indicates that any host stellar population should have a maximum $V$-band magnitude of $\sim 25.1$ (taking into account the $V$-band errors). Due to the limited number of filters used in this study, it is difficult to constrain the nature of the underlying stellar population and the contribution of the accretion disc, as previously done by Farrell et al. (2012). However, the bright state data are consistent with the irradiated disc and an underlying stellar population presented in Farrell et al. (2012).

As shown above, there is a possibility that the $V$ band rises before the X-ray. Due to the sampling timescale of ~2 days, we can give an upper limit on the possible delay in the X-rays of <2 days. We estimate the mass transfer delivery radius that a delay of the order of one day corresponds to in the case of HLX-1.

If one assumes that the impulsive increase in the rate at which matter is delivered to the disk propagates as a density contrast, the viscous propagation time can be written as

$$t_{\text{prop}} \approx \frac{R(\Delta R)}{\nu} = \delta t_{\text{vis}}, \quad (1)$$

where $\Delta R$ is the width of the density contrast, $\delta = \Delta R/R$, $\alpha \ll 1$, $\nu = \alpha c_s^2/\Omega$ is the kinematic viscosity coefficient, and $\Omega_k = \sqrt{GM/R^3}$ is the Keplerian angular velocity (Hameury et al. 1997). Hence the distance the density contrast will go through is

$$R_d \approx 5.8 \times 10^8 t_d^2 \delta^{-1} \alpha_{0.1}^2 T_7^2 M_4^{-1} \text{cm}, \quad (2)$$

where $t_d$ is the delay time in days and $\delta = 9 \times 10^{-2}$, $\alpha_{0.1} = \alpha/0.1$, $T = 10^7T_7$ K is the midplane temperature and $M = (10^4 M_\odot)M_4$ the BH mass. Such a distance ($\sim 2 R_d$) is too short to constrain the properties of the accretion flow in HLX-1 if the rise to outburst is driven by viscosity. One could increase $R_d$ by making the density contrast sharper but since the assumed temperature ($10^7$ K) is already too high for an optical emitting region such playing with numbers is of little interest.

However, as mentioned above, the required HLX-1 disk size makes the viscous character of the rise to outburst extremely unlikely and the wave-propagation mechanism is certainly to be preferred. The sound crossing distance corresponding to one day is

$$R_{\text{sound}} \approx 3 \times 10^{11} T_5^{1/2} t_d \text{cm}, \quad (3)$$

where $T = 10^7T_5$ K. This radius of $\sim 3 \times 10^{11}$ cm can then be taken as an upper limit and might correspond to the distance between the optical and X-ray emitting regions if the density contrast propagates through waves. This radius is 2–3 mag smaller than the outer disk radius determined in Farrell et al. (2013).

One can conclude, therefore, that if the putative observed delay between the onset of HLX-1’s optical and X-ray outbursts results from the propagation of the density contrast created by an impulsive increase of mass transfer into an accretion disk, this propagation cannot be viscous but must be mediated by waves in agreement with the suggestion of Lasota et al. (2011).

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