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THE MODULATED EMISSION OF THE ULTRALUMINOUS X-RAY SOURCE IN NGC 3379

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ABSTRACT

We report recent *Chandra* observations of the ULX in the elliptical galaxy NGC 3379 that clearly detect two flux variability cycles. Comparing these data with the *Chandra* observation of ~5 years ago, we measure a flux modulation with a period of ~12.6 hr. Moreover, we find that the emission undergoes a correlated spectral modulation, becoming softer at low flux. We argue that our results establish this source as a ULX binary in NGC 3379. Given the old stellar population of this galaxy, the ULX is likely to be a soft transient; however, historical X-ray sampling suggests that the current "on" phase has lasted ~10 yr. We discuss our results in terms of ADC and wind-feedback models. If the flux modulation is orbital, we can constrain the donor mass and orbital period at the onset of mass transfer within 1.15–1.4 $M_\odot$ and 12.5–17 hr, respectively. The duration of the mass transfer phase so far is probably ~1 Gyr, and the binary has been a soft X-ray transient throughout this time. These constraints are insensitive to the mass of the accretor.

Subject headings: galaxies: individual (NGC 3379) — X-rays: binaries

Online material: color figure

1. INTRODUCTION

Ultraluminous X-ray sources (ULXs) are nonnuclear X-ray sources observed in galaxies with X-ray luminosity in excess of 10^{39} ergs s^{-1}. This observational definition translates into bolometric luminosities that exceed the Eddington luminosity of typical stellar black hole binaries (BH mass $\sim 10\ M_\odot$), making these sources possible candidates for intermediate-mass black holes (IMBHs, with masses $\sim 20\ M_\odot$ and larger; see Long & Van Speybroeck 1983; Fabbiano 1989; Colbert & Ptak 2002). Alternatively, ULXs may represent a particular high accretion state of normal X-ray binary evolution, with possibly anisotropic (King et al. 2001) or super-Eddington emission (Begelman 2002), although other options have also been suggested (relativistic beaming [Koerding et al. 2002], young SNe [Fabian & Terlevich 1996], pulsars [Perna & Stella 2004]; see review in Fabbiano 2006). Various models for mass transfer from binary companions to black holes of either stellar or intermediate mass have been presented in the literature (e.g., Portegies Zwart et al. 2004; Rappaport et al. 2005; Hopman & Portegies Zwart 2005; Blecha et al. 2006; Madhusudhan et al. 2006; Patruno et al. 2006).

ULXs tend to be found in galaxies with a high star formation rate (e.g., the Antennae [Fabbiano et al. 2001], the Cartwheel [King 2004]), and are virtually missing in ellipticals, although in principle soft X-ray transients could appear as ULXs in these old populations (Piro & Bildsten 2002; King 2002). Irwin et al. (2004) conclude that "statistically" *Chandra* X-ray sources in E and S0 galaxies with $L_X > 2 \times 10^{39}$ ergs s^{-1} (~0.3–10 keV range) are likely to be background AGNs. However, a rare (although relatively faint) ULX was discovered in the inner regions of the elliptical galaxy NGC 3379 (Swartz et al. 2004; David et al. 2005). This source reached a peak luminosity of 3.5×10^{39} ergs s^{-1} (corresponding to the Eddington luminosity of a 25 $M_\odot$ BH) and was found to be variable by a factor of ~50%, with a clear minimum observed during the 30 ks *Chandra* exposure. Based on this time variability, David et al. (2005) suggested that the ULX may be a binary system with an orbital period of 8–10 hr and, based on this period and assuming that the secondary is filling its Roche lobe, estimated a mass of the companion star of $\sim 1\ M_\odot$.

As part of an ongoing *Chandra* legacy program, we are performing a series of deep monitoring observations of NGC 3379. The first of these new observations detected the ULX and showed that it varied both in flux and hardness ratio. In this paper we report these results, which in comparison with the archival *Chandra* data and a previous archival *ROSAT* observation, provide strong constraints on the nature of the ULX. We adopt a distance to NGC 3379 $D = 10.57$ Mpc throughout this paper, based on the surface brightness fluctuation analysis by Tonry et al. (2001). At the adopted distance, 1′ corresponds to ~3 kpc.

2. X-RAY OBSERVATIONS AND DATA ANALYSIS

NGC 3379 was observed for 85 ks on 2006 January 23 with the *Chandra* Advanced CCD Imaging Spectrometer (ACIS) (ObsID = 7073). The ACIS data were reduced as described in Kim & Fabbiano (2003) with a custom-made pipeline (XPIPE) specifically developed for the *Chandra* Multiwavelength Project (ChaMP; Kim et al. 2004), using the most up-to-date calibrations (CALDB 3.2.1). Removal of background flares reduced the effective exposure time of CCD S3 to 80.2 ks.

NGC 3379 had been previously observed with *Chandra* ACIS (ObsID = 1587) for 30 ks on 2001 February 13 (David et al. 2005). We have retrieved these data from the *Chandra* archive,

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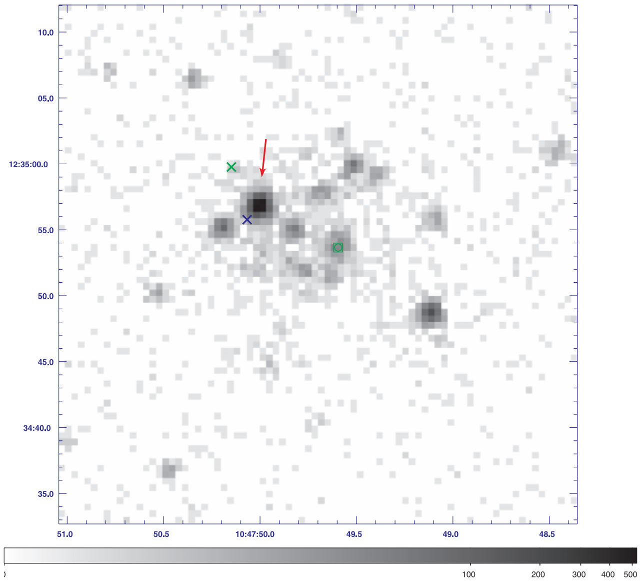

FIG. 1.—*Chandra* X-ray image near the center of NGC 3379 (*green square*; from 2MASS), with ULX (*red arrow*), nearest GC (*blue cross*), and nearest background galaxy (*green cross*) marked.

and we have reprocessed them to be consistent with CALDB 3.2.1. These corrections take into account time-dependent variations of the ACIS response (QE, CTI, gain) and make the reprocessed data directly comparable with 7073. These data were then reduced with the same procedures used for observation 7073.

Prior to *Chandra*, NGC 3379 had been observed with the *ROSAT* HRI for 24 ks on 1996 February 8. David et al. (2005) used these data to conclude that the ULX was then at a luminosity comparable to that in observation 1587, although the source in the *ROSAT* data is confused with nearby X-ray emission. We have retrieved the HRI data from the HEASARC *ROSAT* archive and reestimated the X-ray flux of the ULX, confirming the result of David et al. These three data sets were obtained at 5 yr intervals, spanning 10 yr, and provide a good baseline for a variability study (see § 2.2).

Detailed data analysis was performed using the tools in CIAO, version 3.3.

2.1. *Average Fluxes and Position of the ULX*

The central part of the *Chandra* ACIS-S 7073 image, which includes the ULX, is shown in Figure 1. We measure an average flux of $(2\text{–}3) \times 10^{-13}$ ergs s^{-1} cm^{-2} from the ULX (see Table 1), at a position of (R.A., decl.) = $(10^{\mathrm{h}}47^{\mathrm{m}}50.^{\mathrm{s}}0, 12^\circ34'56.''8)$ (J2000.0), identical to that published by David et al. (2005) from the 1587 data. Based on simulations developed for the ChaMP project (M. Kim et al. 2006, in preparation), we estimated a centroid statistical error of $0.''1$; typical *Chandra* absolute astrometry has $0.''3$ uncertainty. The position of the ULX is $6.''5$ northeast from the 2MASS position of the nucleus of NGC 3379 given by NED.

It is highly unlikely that the ULX is a background interloper not associated with NGC 3379. Based on the $\log N - \log S$ relation determined by ChaMP (Kim et al. 2004), we calculate a probability of $\sim 10^{-5}$ for such a bright X-ray source ($f_X = 2 \times 10^{-13}$ ergs s^{-1} cm^{-2}), within the central region of NGC 3379, to be the chance detection of a background source. We also compared the position of the ULX with a list of background galaxy positions, identified by A. Kundu (2006, private communication) in the *Hubble Space Telescope* (*HST*) WFPC2 image that covers the center of NGC 3379 and includes the ULX. The nearest background galaxy is 4″ away from the ULX (this comparison was done by referring the *HST* and *Chandra* positions to the same astrometric frame by matching globular cluster and X-ray source positions; see below). Moreover, the pattern of variability of the ULX (§ 2.2) suggests an X-ray binary.

We can also exclude a Galactic interloper. A binary with a white dwarf accretor, i.e., a foreground AM Her object, would put a severe limit on the optical magnitude of the companion. Roche geometry, together with the observed period (if orbital), implies that the companion has a mean density close to solar (see also David et al. 2005). For stable mass transfer the companion must have a mass no greater than the accreting white dwarf, i.e., no more than about 1 $M_\odot$, requiring its radius to be about 1 $R_\odot$. Normal stars cannot have effective temperatures less than the Hayashi line, i.e., about 3000 K, implying a companion luminosity $> 0.06\ L_\odot$ and thus a minimum optical brightness for the system. We can compare this with the observed optical flux limit. This gives a lower limit on the distance, which we can compare with the distance to the "edge" of the Milky Way along that line of sight. From the *HST* WFPC2 data we estimate a limit of $V = 25$ mag for the optical counterpart to the ULX. This gives us a distance limit of 30 kpc. Given the Galactic coordinates of NGC 3379, this lower limit on the distance puts the source beyond the outer boundaries of the Milky Way. Moreover, the corresponding minimum X-ray luminosity, 4×10^{34} ergs s^{-1}, makes it extremely unlikely that this is an AM Her system. This luminosity is far higher than any known object of this type (e.g., Ramsay et al. 1994). The result is even stronger in that, in order for the white dwarf to be phase-locked to the orbital motion

TABLE 1

RESULTS

Data Set	Net Counts ± Error (1 σ)	Model	$T_{\rm in}$ (keV) or Γ	χ^2/dof	f_X(0.3–10 keV) (Unabsorbed) (10^{-13} ergs s^{-1} cm^{-2})	L_X(0.3–10 keV) (10^{39} ergs s^{-1})
7073 all	2462.4 ± 49.7	MCD	$1.41^{+0.09}_{-0.08}$	61.3/89	2.16	3.0
		Power law	$1.26^{+0.04}_{-0.04}$	68.4/89	3.35	4.7
7073 high	888.8 ± 29.9	MCD	$1.88^{+0.29}_{-0.22}$	12.7/35	3.16	4.4
		Power law	$1.09^{+0.07}_{-0.07}$	14.6/35	4.63	6.5
7073 low	310.1 ± 17.7	MCD	$1.07^{+0.12}_{-0.24}$	3.9/11	1.38	1.9
		Power law	$1.62^{+0.15}_{-0.15}$	2.6/11	2.21	3.1
1587 all	734.6 ± 27.2	MCD	$0.98^{+0.014}_{-0.47}$	25.1/29	1.17	1.6
		Power law	$1.79^{+0.08}_{-0.07}$	25.1/29	1.65	2.3
7073 (1587)[a]	758.9 ± 27.6	MCD	$1.13^{+0.06}_{-0.19}$	21.6/30	1.60	2.2
		Power law	$1.50^{+0.08}_{-0.08}$	20.6/30	2.49	3.5

[a] This spectrum was extracted from the 7073 observation at the same phase as the 1587 observation, i.e., during phase = 0.36–1.02. The count rate for 1587 was corrected for the ACIS QE variation so that it could be compared with that of 7073.

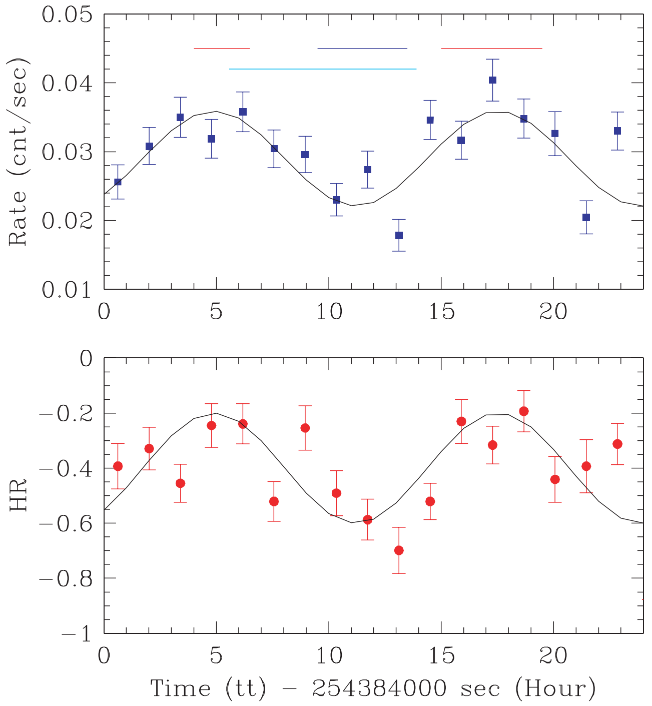

FIG. 2.—Light curve of the ULX. The count rate (*top*) and hardness ratio (*bottom*) are plotted against time (TT). In both plots, the black curve is the best-fit sinusoidal to the count rate light curve (see text). The red horizontal bars at the top of the figure indicate time intervals used for the high flux spectrum, the blue bar indicates the interval used for the low-state spectrum (see Table 1), and the cyan bar indicates the phase covered during the 1587 observation (see Fig. 3).

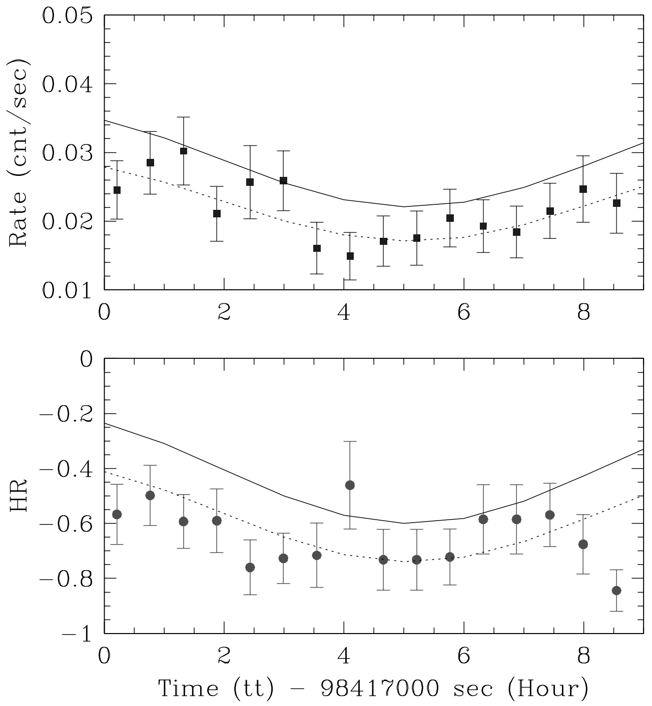

FIG. 3.—Same as Fig. 2, but showing the previous observation 1587 taken 5 years ago. The data have been corrected for the temporal variations of the ACIS quantum efficiency. The two sinusoidal curves are the best-fit sinusoidals from the entire ACIS data set (see text); the lower curve has the best-fit amplitude for the 1587 data set, and the upper curve has the best-fit amplitude for the 7073 data set. [*See the electronic edition of the Journal for a color version of this figure.*]

despite the wide separation implied by the detected period (see below), we require both a strong magnetic field and a low accretion rate, whereas the luminosity would imply an unprecedented high accretion rate. Given the flux, the X-ray luminosity would be too low for a Galactic X-ray binary with either a neutron star or a BH accretor, unless this system is in quiescence. The expected optical magnitude of the companion star would exclude this possibility in these cases as well.

The above considerations make a very strong case for the source to be a ULX in NGC 3379. Since two similarly luminous ULXs have been reported associated with globular clusters (GCs) in the elliptical galaxy NGC 1399 (Angelini et al. 2001), we have further examined the possibility of an association of the ULX with a GC in NGC 3379. To this end, we have cross-correlated the positions of X-ray point sources in NGC 3379 with optical GCs discovered in the *HST* WFPT2 images by Kundu & Whitmore (2001). Using six LMXBs that are clearly matched with GCs (within $1''$) and located nearly on-axis (within $\sim 1'$) but not very close to the galaxy center (galactocentric radii = $10''$–$60''$), we correct for a systematic offset of $0\farcs82$ (mostly in the R.A. direction). The remaining random offset is less than $0\farcs3$. Independently, A. Kundu et al. (2006, in preparation) determine GC X-ray source matches in a number of galaxies, including NGC 3379, and derive a relative astrometry with an uncertainty $<0\farcs4$. The nearest GC is found at $\sim 1\farcs35$ south-southeast from the ULX. Given the $0\farcs3$–$0\farcs4$ accuracy of the relative astrometry and the centroid statistical error of $0\farcs1$, the discrepancy between the ULX and the nearest GC position is $\sim 3\ \sigma$; we conclude that the ULX resides in the stellar field of NGC 3379.

2.2. *Flux and Spectra Variability*

During our new observation (7073), the ULX is variable both in flux and spectral hardness (Fig. 2). The flux light curve strongly suggests a periodic variability, covering two cycles. The peak X-ray luminosity (assuming the best-fit power-law spectrum; see below) is $L_X = (4\text{–}7) \times 10^{39}$ ergs s^{-1}, and the minimum luminosity is $L_X = (2\text{–}3) \times 10^{39}$ ergs s^{-1}. While the minimum is consistent with the measurement of David et al. (2005), the maximum luminosity is slightly larger than previously reported. Although this may be in part due to the limited phase coverage of the previous short observation, comparing the two observations, we find that the difference could be due to long-term variability (see Fig. 3, where we plot the data from the first Chandra observation [1587] with its best-fit curve from the joint fit described below, the lower dotted curve, and the best-fit curve with the best-fit amplitude of 7073 from the same joint fit).

Using the two *Chandra* observations taken 5 years apart, in the hypothesis that the observed variability is periodic, we estimated the period. We used the CIAO application Sherpa to fit simultaneously the two light curves with a sinusoidal curve plus a constant. We linked the period and phase = 0 epoch of two models to vary together, but allowed the amplitude to vary independently since the mean flux may vary, as suggested by the comparison of the two *Chandra* light curves (see Fig. 3). To perform this fit, we binned the data so as to have a minimum of 33 counts per bin, and we used χ^2 statistics. We obtain best-fit reduced χ^2 values of 3.3 for 14 dof (7073), 0.6 for 12 dof (1587), and 2.0 for 28 dof for the joint fit. We notice that most of the residuals are due to two low bins and the last point in the 7073 light curve. Excluding them, the reduced χ^2 values are 1.4 for 11 dof (7073) and 0.97 for 25 dof (joint). These discrepancies could well be due to our choice of model and to the presence of higher frequency components in the light curve, which are often observed in low-mass binaries (e.g., White et al. 1995). We find that the best-fit period for observation 7073 alone (taken in 2006) is 12.3 ± 0.5 ($1\ \sigma$) hr, or $12.7^{+0.8}_{-1.1}$ excluding the high residual points; as noted by David et al. (2005), the results for observation 1587 (taken in 2001) are much less constrained, with a possible period of 9^{+5}_{-2} hr. The joint fit results in a period of 12.6 ± 0.3 hr, or 12.7 ± 0.1 excluding the high residual points. The epoch corresponding to phase = 0 is either (in Terrestrial Time [TT]) 98,446,798 s in 2001 or 254,390,240 s in 2006.

Although David et al. (2005) could not detect any variability of the spectral properties, Figure 2 shows that the spectral hardness also varies along with the flux with a similar overall period, in the sense that the X-ray emission becomes harder at peak intensity, although there is substantial "flickering." These hardness ratios are defined as $(H - S)/(H + S)$, where H and S are the counts in the 0.5–2.0 and the 2.0–8.0 keV bands, respectively. The error bars are 1 σ, in Gaussian approximation; using a Bayesian approach (Park et al. 2006) that takes into account the asymmetric Poisson errors, the results are essentially consistent. Looking at the long-term behavior by comparing the average hardness ratio we measure in 7073 with that in 1587, in the same phase span, we find -0.48 ± 0.03 versus -0.64 ± 0.03, respectively. The average luminosities also differ by 23%. The lower luminosity emission is associated with a softer spectrum (see Fig. 3).

We fitted the ACIS spectra of observation 7073 to models for the entire observation and for two subsets obtained by extracting the data in two phase bins (observation time in TT seconds = 254,398,400–254,407,400 and 254,438,000–254,454,200) for the high flux and 254,418,200–254,432,600 for the low flux). In both cases, the spectra were extracted from a circular region of 3″ radius after excluding two nearby sources. The background was extracted locally from a surrounding annulus (radii 10″–20″), but the background is negligible. The results are summarized in Table 1 for two choices of spectral model: a multicolor disk model, used to fit spectra of black hole binaries and ULXs (e.g., Makishima et al. 2000), and a power law. Using more complex composite methods does not improve the fit statistics. However, in cases where high signal-to-noise data are available, it is clear that complex spectral models are needed to fit ULX spectra (e.g., Miller et al. 2003; Goad et al. 2006). These results should only be considered indicative of the ULX spectral parameters; a full-fledged spectral analysis requiring significantly higher signal-to-noise data will be postponed to a future time, after the completion of our monitoring program. In both cases, we performed fits freezing the absorption column (N_H) to the line-of-sight value of 2.78×10^{20} cm^{-2} (from COLDEN), and also leaving this parameter free to vary. In all cases, we obtain acceptable values of χ^2, but the range of N_H is largely undetermined; we only list the results for line-of-sight N_H in Table 1.

In general, the results of Table 1 follow the hardness ratio results: the MCD inner temperature of the accretion disk T_{in} appears larger (harder spectrum) in the high-flux data. Similarly, the power law tends to be flatter at high flux. The overall spectrum is softer in 1587, where the overall source flux was also lower, than in 7073 at the same phase (phase = 0.36–1.02). In all cases, uncertainties are at a 1 σ confidence level for one interesting parameter.

3. DISCUSSION

We have observed a full cycle of variability in the ULX in NGC 3379 that suggests that this source may be a periodic variable, with a period of ~12.5 hr. Although the shape of the light curve is somewhat uncertain, given the error bars, and possibly not sinusoidal, the minima are well defined over a 5 yr baseline. This variability strongly suggests that the ULX is an X-ray binary. Although the variability may be orbital, the present data cannot exclude low-frequency random variability with similar timescales observed in low-mass X-ray binaries. Future scheduled long observations of this source that will cover a number of variability cycles will allow us to reexamine this point. We also discovered that the spectral properties of the emission seem to undergo a correlated (although noisier) variability cycle, with softer emission observed at the minima of the light curve. Comparing our recent observation with the previous *Chandra* observation discussed in David et al. (2005), we have also found evidence of minor (~23%) long-term flux variability over a 5 yr span, in the sense that the ULX was dimmer in the year 2001 than in 2006, considering a comparable phase of the light curve. We also measure a softer X-ray hardness ratio (and spectrum) in the data of 5 years ago. Since the ULX is also visible in the archival *ROSAT* data (see also David et al. 2005), we conclude that the ULX may have been steadily emitting for ~10 yr. If we assume an isotropic emission at the Eddington limit, the peak L_X corresponds to $M_{BH} = 32\ M_\odot$.

This ULX appears not to be associated with a globular cluster. One could argue that the ULX may have been ejected from the neighboring cluster, or that the parent GC may have evaporated or been tidally disrupted (the ULX is only ~340 pc from the nucleus of NGC 3379); however, its large luminosity (a factor of ~10 higher than the Eddington limit for a neutron star accreting He-rich material; see Shakura & Sunyaev 1973) would be hard to explain in the GC formation scenario proposed by Bildsten & Deloye (2004) that LMXBs in ellipticals may be ultracompact objects with neutron star accretors formed in globular clusters. BH binaries in the field (see Ivanova & Kalogera 2006) may instead be very luminous sources, because of a higher Eddington limit during transient outbursts. Transient behavior here is very likely (see below) because of the relatively long binary period and the small donor mass, given the old age of the stellar population (see King et al. 1996).

Since the stellar population of NGC 3379 is old with an age of 9–10 Gyr (see the recent SAURON study of line strength maps by Kuntschner et al. [2006]; we confirm these result for the position of the ULX with a new look at the SAURON data), the donor star feeding the compact object must be of low mass, ~1 $M_\odot$. Thus the most likely interpretation is that the ULX is a soft X-ray transient in outburst (Piro & Bildsten 2002; King 2002). We note that the transient character of the source is expected for both stellar-mass and intermediate-mass black holes. The metallicity for NGC 3379 is estimated to be a factor of 1.5–2 higher than solar metallicity ($Z \sim 0.03$–0.04; Terlevich & Forbes 2002; Trager et al. 2000; Thomas et al. 2005). Assuming that the binary orbital period is 12.5 hr at Roche lobe overflow, we run stellar evolution calculations using an up-to-date stellar evolution code described in detail in Podsiadlowski et al. (2002), Ivanova et al. (2003), Kalogera et al. (2004), and Ivanova & Taam (2004). We find that the donor mass is very narrowly constrained in the range 1.1–1.15 $M_\odot$, given a galaxy age in the range 8–10 Gyr. This constraint is highly insensitive to the accretor's mass (values of 10, 100, and 1000 $M_\odot$ were examined). We further examine mass transfer simulations for such donor masses, and as expected, the calculated mass transfer rates are indeed lower than the critical values for transient behavior (critical rates derived by Dubus et al. [1999] were used).

However, most probably mass transfer did not start at the currently measured period of 12.5 hr. It is possible that it started at either (1) a longer period for a donor star more massive than 1.15 $M_\odot$ and the orbit has been shrinking due to magnetic braking and gravitational radiation, or (2) at a shorter period for a donor star less massive than 1.1 $M_\odot$ and the orbit has been expanding due to the donor's nuclear evolution. Our mass transfer simulations indicate that the latter hypothesis can be excluded because, for magnetic braking strengths typically used in the literature (Rappaport et al. 1983; Ivanova & Taam 2003), radial expansion due to nuclear evolution of stars less massive than 1.1 $M_\odot$ cannot overtake magnetic braking and drive orbital expansion. Therefore mass transfer for the observed system must have started at an orbital period longer than 12.5 hr; the initial donor mass must have been higher than 1.15 $M_\odot$, but low enough so that a significant convective envelope mass be present, and consequently magnetic braking be operational and strong enough to drive orbital contraction.

The requirement for the presence of a partially convective envelope constrains the initial donor mass to be lower than 1.3 and 1.4 $M_\odot$ for $Z = 0.03$ and 0.04, respectively (this limit is 1.25 $M_\odot$ for solar metallicity). We have examined a set of mass transfer calculations for initial donor masses up to 1.5 $M_\odot$ and initial orbital periods up to 18 hr. For $Z = 0.03$ and 0.04, we find that the properties of the ULX at the onset of mass transfer are further constrained to lie in the range 1.15–1.4 $M_\odot$ for the donor mass and 12.5–16 hr for the orbital period, for any accretor mass. In these ranges the maximum orbital period allowed decreases as the donor mass increases.

For properties outside these ranges, the binary expands instead of contracting either because the donor mass no longer has an outer convective envelope or the donor's radial expansion due to nuclear evolution dominates over magnetic braking. With these tight constraints on the binary properties at the onset of mass transfer, we are also able to constrain the duration of the mass transfer phase (i.e., the time from the mass transfer onset until the orbital period reaches the current measurement of 12.5 hr) to shorter than 1 Gyr (down to just about 10 Myr, if mass transfer starts very close to 12.5 hr). We note that for the highest donor masses in the accepted range (1.3–1.4 $M_\odot$) the total age of the system is 5–6 Gyr, somewhat shorter than the galaxy age estimated from the SAURON study; such a difference is acceptable, given the uncertainties associated with the galaxy age estimate. If we do not allow for this difference, then the donor mass would be even more narrowly constrained (1.15–1.25 $M_\odot$). Last we note that for the mass transfer sequences that satisfy all these constraints, the mass transfer rate remains below the critical rate for transient behavior throughout, consistent with more general theoretical expectations that bright sources in ellipticals should be transient (Piro & Bildsten 2002; King 2002; Ivanova & Kalogera 2006).

The maximum length of the outburst is set by the geometric size of the accretion disk: if the black hole mass is $\sim 30\ M_\odot$, a period of $\sim$12.5 hr implies an orbital separation of $\sim 6 \times 10^{11} (M/30\ M_\odot)^{1/3}$ cm, where $M \sim 30\ M_\odot$ is the total binary mass. This suggests a total disk mass before the outburst of $\sim 2 \times 10^{27}$ g, depending on the disk viscosity (King & Ritter 1998, eq. [8]). If the disk mass is consumed at the rate indicated by the ULX luminosity, the outburst could last $\sim$7 yr. This may indeed suggest that the variability we have detected may not be orbital, and that the orbital period may be longer. However, the viscosity is highly uncertain, and in addition the source may well be super-Eddington, i.e., actually consuming the mass faster than this rate. The length of the outburst could thus vary significantly from this estimate. Empirically one might expect it to be longer than that of A0620−00 (a few 100 days; see Tanaka & Lewin 1995) and shorter than that of GRS 1915+105 (10 yr and still going; see Fender & Belloni 2004), as the orbital period is between the two (6.5 hr and 33 days, respectively).

The source is never totally eclipsed, a behavior reminiscent of Galactic LMXBs (see White et al. 1995), but narrow eclipses may be hidden by the relatively low signal-to-noise ratio of the data. The light curve expected for a point X-ray source eclipsed by a companion would be flat (plus aperiodic modulations) apart from a very narrow total eclipse. A much more usual pattern of orbital modulation for LMXBs is shown by the so-called dippers and ADC (accretion disk corona) sources. In these binaries, the X-ray source is slightly extended and has a structure fixed in the orbital frame, creating a more complex periodic light curve. These sources are believed to have matter close to the accretor, which probably scatters the X-rays and makes an extended X-ray source component. In ADC sources the light curve does not have a deep narrow minimum, while in dippers it does (see, e.g., Frank et al. 2002, pp. 106, 107). The two classes differ only in inclination angle, the dippers having lower inclination than the ADCs.

The hardness ratio behavior seen for the NGC 3379 ULX seems to be opposite from what one usually sees in dippers. In ADCs we do not see the central point X-ray source, but only the scattered X-rays. Although these sources typically do not present an orbital modulation of the hardness ratio, the corona may have an uneven structure or there may be some intervening material responsible for partial absorption of the X-rays from the corona and possible reemission. Galactic ADC sources are intrinsically faint, because for low scattering optical depths τ, the scattered X-rays have luminosity of order τ times the central point source luminosity. Thus one usually expects the unseen central point source to be much brighter than the detected luminosity. In known ADCs, comparison of optical/X-ray ratios with face-on sources suggests that the central source is 10–100 times brighter than the observed (scattered) luminosity (White & Holt 1982; see Mason 1986 for a comparison of different X-ray binaries). In our case this would mean a true luminosity significantly higher than the $\sim 4 \times 10^{39}$ ergs s^{-1} we infer from the observed flux. However, for accretion rates near or above the Eddington rate, as is likely for our object, we must have $\tau > 1$ (King & Pounds 2003), so the extended source luminosity may be comparable to the (unseen) point source. Our object may thus give us insight into what happens when accretion is at or above the Eddington value, and indeed into the nature of the ULX phenomenon in general.

If the source is not an ADC, a different model that may apply is that of wind feedback (e.g., Basko et al. 1977 and references therein). In this model, illumination of the companion by X-rays from the compact object causes heating of the companion and promotes stronger stellar winds; at periastron the wind will have the effect to make the emission harder since it will act as an absorber. This model would be consistent with the observed lack of total eclipses and the smooth modulation of the light curve. A better defined X-ray light curve and spectral light curve are needed to firmly establish the nature of the source.

4. CONCLUSIONS

Our recent *Chandra* observations of the elliptical galaxy NGC 3379, in conjunction with archival *Chandra* and *ROSAT* data (see David et al. 2005), have led to the measure of a 12.6 ± 0.3 hr period in the variability of the luminous ULX present in this galaxy (Swartz et al. 2004). We also found correlated spectral variability, with the emission becoming softer in the minima of the light curve. Including our new data, this ULX has been detected with a similar average luminosity over a 10 yr time span.

Given the metallicity and the old age of the stellar population in NGC 3379 and assuming that the $\sim$12.5 hr period is that of the orbit, we are able to constrain the donor mass and orbital period at the onset of mass transfer within 1.15–1.4 $M_\odot$ and 12.5–17 hr, respectively. The duration of the mass transfer phase so far is probably $\sim$1 Gyr (although we cannot exclude that it is much shorter, about ∼10 Myr), and the binary has been a soft X-ray transient throughout this time. These constraints appear to be quite insensitive to the assumed accretor mass (10, 100, 1000 $M_\odot$).

The light curve and spectral behavior may be consistent with an ADC binary, although in this case the intrinsic luminosity may be significantly higher than suggested by the detected flux. This source may thus give us some real insight into what happens in super-Eddington accretion and thus possibly into the ULX phenomenon in general. However, the spectral modulation of the light curve is not typical of ADC sources and may alternatively suggest a wind-feedback model (e.g., Basko et al. 1977).

To really constrain the nature of this ULX, significantly better light curve and spectra are needed, for a more accurate comparison with well-studied Galactic binaries and for firmly establishing that the detected variability is indeed orbital, and not a low-frequency random variation. If the ULX continues to shine in the upcoming year, our *Chandra* legacy program will provide the needed data.

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REFERENCES

Angelini, L., Loewenstein, M., & Mushotzky, R. F. 2001, ApJ, 557, L35

Basko, M. M., Sunyaev, R. A., Hatchett, S., & McCray, R. 1977, ApJ, 215, 276

Begelman, M. C. 2002, ApJ, 568, L97

Bildsten, L., & Deloye, C. J. 2004, ApJ, 607, L119

Blecha, L., et al. 2006, ApJ, 642, 427

Colbert, E. J., & Ptak, A. F. 2002, ApJS, 143, 25

David, L. P., Jones, C., Forman, W., & Murray, S. S. 2005, ApJ, 635, 1053

Dubus, G., Lasota, J., Hameury, J., & Charles, P. 1999, MNRAS, 303, 139

Fabbiano, G. 1989, ARA&A, 27, 87

———. 2006, ARA&A, in press

Fabbiano, G., Zezas, A., & Murray, S. S. 2001, ApJ, 554, 1035

Fabian, A. C., & Terlevich, R. 1996, MNRAS, 283, L95

Fender, R., & Belloni, T. 2004, ARA&A, 42, 317

Frank, J., King, A., & Rayne, D. 2002, Accretion Power in Astrophysics (3rd ed.; Cambridge: Cambridge Univ. Press)

Goad, M. R., Roberts, T. P., Reeves, J. N., & Uttley, P. 2006, MNRAS, 365, 191

Hopman, C., & Portegies Zwart, S. 2005, MNRAS, 363, L56

Irwin, J. A., Bregman, J. N., & Athey, A. E. 2004, ApJ, 601, L143

Ivanova, N., Belczynski, K., Kalogera, V., Rasio, F. A., & Taam, R. E. 2003, ApJ, 592, 475

Ivanova, N., & Kalogera, V. 2006, ApJ, 636, 985

Ivanova, N., & Taam, R. E. 2003, ApJ, 599, 516

———. 2004, ApJ, 601, 1058

Kalogera, V., Henninger, M., Ivanova, N., & King, A. R. 2004, ApJ, 603, L41

Kim, D-W., & Fabbiano, G. 2003, ApJ, 586, 826

Kim, D.-W., et al. 2004, ApJS, 150, 19

King, A. R. 2002, MNRAS, 335, L13

———. 2004, MNRAS, 347, L18

King, A. R., Davies, M. B., Ward, M. J., Fabbiano, G., & Elvis, M. 2001, ApJ, 552, L109

King, A. R., Kolb, U., & Burderi, L. 1996, ApJ, 464, L127

King, A. R., & Pounds, K. A. 2003, MNRAS, 345, 657

King, A. R., & Ritter, H. 1998, MNRAS, 293, L42

Koerding, E., Falcke, H., & Markoff, S. 2002, A&A, 382, L13

Kundu, A., & Whitmore, B. C. 2001, AJ, 121, 2950

Kuntschner, H., et al. 2006, MNRAS, 369, 497

Long, K. S., & Van Speybroeck, L. P. 1983, in Accretion Driven X-Ray Sources, ed. W. Lewin & E. P. J. van den Heuvel (Cambridge: Cambridge Univ. Press), 117

Madhusudhan, N., Justham, S., Nelson, L., Paxton, B., Pfahl, E., Podsiadlowski, Ph., & Rappaport, S. 2006, ApJ, 640, 918

Makishima, K., et al. 2000, ApJ, 535, 632

Mason, K. O. 1986, in The Physics of Accretion onto Compact Objects, ed. K. O. Mason, M. G. Watson, & N. E. White (Berlin: Springer), 29

Miller, J. M., Fabbiano, G., Miller, M. C., & Fabian, A. C. 2003, ApJ, 585, L37

Park, T., et al. 2006, ApJ, in press (astro-ph/0606247)

Patruno, A., et al. 2006, MNRAS, 370, L6

Perna, R., & Stella, L. 2004, ApJ, 615, 222

Piro, A. L., & Bildsten, L. 2002, ApJ, 571, L103

Podsiadlowski, P., Rappaport, S., & Pfahl, E. D. 2002, ApJ, 565, 1107

Portegies Zwart, S., Dewi, J., & Maccarone, T. 2004, MNRAS, 355, 413

Ramsay, G., Mason, K. O., Cropper, M., Watson, M. G., & Clayton, K. 1994, MNRAS, 270, 692

Rappaport, S. A., Podsiadlowski, Ph., & Pfahl, E. 2005, MNRAS, 356, 401

Rappaport, S. A., Verbunt, F., & Joss, P. C. 1983, ApJ, 275, 713

Shakura, N., & Sunyaev, R. 1973, A&A, 24, 337

Swartz, D. A., Ghosh, K. K., Tennant, A. F., & Wu, K. 2004, ApJS, 154, 519

Tanaka, Y., & Lewin, W. H. G. 1995, in X-Ray Binaries, ed. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge: Cambridge Univ. Press), 126

Terlevich, A. I., & Forbes, D. A. 2002, MNRAS, 330, 547

Thomas, D., Maraston, C., Bender, R., & de Oliveira, C. M. 2005, ApJ, 621, 673

Tonry, J. L., Dressler, A., Blakeslee, J. P., Ajhar, E. A., Fletcher, A. B., Luppino, G. A., Metzger, M. R., & Moore, C. B. 2001, ApJ, 546, 681

Trager, S. C., Faber, S. M., Worthey, G., & Gonzales, J. J. 2000, AJ, 120, 165

White, N. E., & Holt, S. S. 1982, ApJ, 257, 318

White, N. E., Nagase, F., & Parmar, A. N. 1995, in X-Ray Binaries, ed. W. H. G. Lewin, J. van Paradijs, & E. P. J. van den Heuvel (Cambridge: Cambridge Univ. Press), 1