THE BIRTH OF AN ULTRALUMINOUS X-RAY SOURCE IN M83

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ABSTRACT

A previously undetected ($L_X < 10^{36}$ erg s$^{-1}$) source in the strongly star-forming galaxy M83 entered an ultraluminous state between 2009 August and 2010 December. It was first seen with Chandra on 2010 December 23 at $L_X \approx 4 \times 10^{39}$ erg s$^{-1}$ and has remained ultraluminous through our most recent observations in 2011 December, with typical flux variation of a factor of two. The spectrum is well fitted by a combination of absorbed power-law and disk blackbody models. While the relative contributions of the models vary with time, we have seen no evidence for a canonical state transition. The luminosity and spectral properties are consistent with accretion powered by a black hole with $M_{BH} \approx 40–100 M_{\odot}$. In 2011 July we found a luminous, blue optical counterpart that had not been seen in deep Hubble Space Telescope observations obtained in 2009 August. These optical observations suggest that the donor star is a low-mass star undergoing Roche lobe overflow, and that the blue optical emission seen during the outburst is coming from an irradiated accretion disk. This source shows that ultraluminous X-ray sources (ULXs) with low-mass companions are an important component of the ULX population in star-forming galaxies and provides further evidence that the blue optical counterparts of some ULXs need not indicate a young, high-mass companion, but rather that they may indicate X-ray reprocessing.

Key words: accretion, accretion disks – black hole physics – galaxies: individual (M83) – X-rays: binaries

Online-only material: color figures

1. INTRODUCTION

Point-like X-ray sources with luminosities exceeding the Eddington limit of normal stellar-mass black holes ($L_X \gtrsim 3 \times 10^{39}$ erg s$^{-1}$, assuming isotropic emission) are commonly known as ultraluminous X-ray sources (ULXs). The most luminous class of non-nuclear sources in galaxies, they are widely believed to result from some extreme form of accreting X-ray binary containing a black hole. However, the nature of both the black holes that power the ULXs and the companion stars that fuel them remains enigmatic. Briefly, the principal competing models for the primaries are (1) intermediate (between normal stars and active galactic nucleus (AGN)) mass black holes ($10^5 M_{\odot} \lesssim M_{BH} \lesssim 10^4 M_{\odot}$) perhaps formed in the collapsed core of massive star clusters, many of which are present in M83 (Colbert & Mushotzky 1999); (2) “normal” stellar-mass black holes ($M_{BH} \lesssim 20 M_{\odot}$) that are accreting well above their Eddington limit (Begelman 2002) and/or that have beamed emission (e.g., King et al. 2001; Begelman et al. 2006); and (3) “heavy” stellar black holes ($M_{BH} \approx 30–70 M_{\odot}$)—perhaps formed from direct collapse of metal-poor, massive stars (Belczynski et al. 2010; Zampieri & Roberts 2009; Pakull & Mirioni 2002)—that are accreting near or just above their Eddington limit.

A number of lines of evidence suggest that most ULXs are associated with young, high-mass stellar populations—the extreme of the high-mass X-ray binary (HMXB) population. Statistically, ULXs are found mostly in star-forming spirals or irregular galaxies (Irwin et al. 2004; Swartz et al. 2004), and the number of ULXs per galaxy increases with the star formation rate (Colbert et al. 2004; Liu et al. 2006). The cumulative luminosity function for ULXs in star-forming galaxies is consistent with the extrapolation of that for HMXBs (Walton et al. 2011; Swartz et al. 2011). Within individual galaxies, ~75% of ULXs are found in thin spiral arms and dust lanes and tend to have high absorbing column densities (Liu et al. 2006). Theoretical considerations suggest that high-mass donors can maintain a ULX in a persistent high state for up to 10 Myr (Rappaport et al. 2005).

Yet there is mounting evidence for a second population of ULXs, a population that represents an extreme form of low-mass X-ray binaries (LMXBs). The cumulative luminosity function of ULXs in elliptical galaxies is consistent with the extrapolation of the luminosity function for LMXBs (Swartz et al. 2004; Walton et al. 2011), suggesting that those ULXs are extreme LMXBs. In spiral galaxies, the number of ULXs is not purely a function of the star formation rate, but is also a function of the total stellar mass, suggesting that 15%–25% of the total number of ULXs

Based on observations made with NASA's Chandra X-Ray Observatory, the NASA/ESA Hubble Space Telescope (HST), Swift, the 6.5 m Magellan Telescopes located at Las Campanas Observatory, and the Gemini Observatory. NASA’s Chandra X-Ray Observatory is operated by Smithsonian Astrophysical Observatory under contract NAS8-03060, and the data were obtained through program GO1-12115. The HST observations were obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy (AURA), Inc., under NASA contract NAS5-26555. The new HST observations were obtained through programs GO-12513 and GO-12683. Data in the HST archive from program GO-11360 were also used. The ground-based observations were obtained from the Magellan I Telescope at the Las Campanas Observatory and from the Gemini South Telescope of the Gemini Observatory, both awarded through NOAO, which is operated by Association of Universities for Research in Astronomy, Inc., for the National Science Foundation.

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are associated with the older stellar population (Colbert et al. 2004; Liu et al. 2006; Winter et al. 2006; Mushotzky 2006).

Point-like, blue optical counterparts have been identified for a number of ULXs (e.g., Ptak et al. 2006; Grisé et al. 2010), thus reinforcing the link with a young, high-mass stellar population. However, some ULX counterparts that were initially identified as massive, early-type stars on the basis of their blue colors (e.g., Kuntz et al. 2005) are now thought to be low-mass stellar donors and the blue colors due to optical emission from the accretion disk and/or reprocessed radiation from the X-ray source (e.g., Copperwheat et al. 2007). Indeed, Tao et al. (2011) have argued that the optical emission from the majority of ULX counterparts is dominated by X-ray reprocessing. However, there have been no unequivocal identifications of low-mass donors in such systems, because we have never had a chance to observe them in quiescence.

In this paper, we report the discovery of a ULX that recently erupted in the nearby (d = 4.6 ± 0.2 Mpc; Saha et al. 2006) grand-design spiral galaxy M83 (NGC 5236) and that we can confirm to be powered by a low-mass companion. The first exposures of a large *Chandra* project to study M83, taken on 2010 December 23 and 25, revealed an unexpected gift: a ULX—a non-nuclear source with a flux comparable to the total circumnuclear flux—that had not appeared in previous *Chandra* images from 2000–2001, nor in any other prior X-ray image of M83. The new source appeared ∼1′ east of the nucleus, well away from the spiral arms and from the many regions with active star formation. Since its discovery, we have monitored the source for a year with *Swift*, and with *Chandra* in our ongoing program observations. We have also obtained optical images of the field containing the ULX from the Gemini South telescope and from the Hubble Space Telescope (*HST*), and we find that a new unresolved source, not seen in previous *HST* observations of the same field, has appeared coincident with the ULX.

The remainder of this paper is organized as follows. In Section 2, we present the new *Chandra* and *Swift* data, along with a brief survey of archival X-ray data where the ULX was absent, and in Section 3 we give the results of spectroscopic and timing analyses. In Section 4, we describe the optical observations and results. In Section 5, we argue that the M83 ULX is powered by accretion from a low-mass companion that has recently expanded to overflow its Roche lobe, and that the present bright optical emission results from the reprocessing of X-rays in the accretion disk. We go on to discuss the probable geometry and black hole mass in some detail, and we close in Section 6 with a brief summary.

2. X-RAY OBSERVATIONS

The object was discovered using *Chandra*, whose spectacular angular resolution allowed the quick and definitive determination that no such source appeared in previous X-ray images. The source was discovered when its $L_{0.3–10} \sim 4 \times 10^{39}$ erg s$^{-1}$, a ULX by most definitions of that class. The *Chandra* spectrum is unequivocally that of a power-law-like source, but there are many classes of sources with similar spectra, so the nature of the source was not immediately clear. We turned to *Swift* to follow the short-term evolution of the source, and to archival data from other missions to determine what might have been there in the past.

2.1. Chandra Discovery

The recent *Chandra* data were obtained as part of a detailed study of M83 (Program 12620596; PI: Long). The data, totaling 729 ks, were obtained in 10 observations, each longer than 50 ks. The observations are clustered in 2010 December, 2011 March, and 2011 August, with a final observation in 2011 December (see Table 1). We used the back-illuminated S3 chip for maximum soft response, since most of the M83 disk fits within its $8' \times 8'$ field. We carried out the observations in the “very faint” mode for optimum background subtraction. We filtered and analyzed the data with standard imaging and spectroscopic tools, such as *dmcopy*, *dmextract*, and *specextract*, in the CIAO Version 4.3 (Fruscione et al. 2006) data analysis system.

As shown in the upper right panel of Figure 1, the ULX appears ∼1′ east of the nucleus of M83. A count-weighted mean of the centroid positions over the first nine observations gives a position

$$R.A. \ (2000) = \ 13^h37^m05.135 \pm 0.014,$$

$$\text{decl.} \ (2000) = -29^\circ52'07.2 \pm 0.3$$

(90% confidence level). The rms scatter of the source positions derived from each *Chandra* observation is $\sigma \approx 0'.25$. We also determined a source position using only the five observations during 2011 March and April, in which the aim point was closest ($\sim 76'$) to the ULX, when the point-spread function (PSF) would be most narrow and symmetric, with a 90% encircled energy radius $\approx 0'.9$; we obtained the same result as from the total average, with a root-mean-square scatter $\sigma \approx 0'.15$. We confirmed the accuracy of the *Chandra* position further by using two sources in the S3 chip with both X-ray and radio detections: SN 1957D (located $\approx 2'.3$ northeast of the nucleus) and a background radio galaxy ($\approx 1'.8$ northeast of the nucleus). The mean X-ray positions of those two sources are within $\lesssim 0'.2$ of the radio positions, measured from our Australia Telescope Compact Array observations at 5 GHz; the radio positions have themselves an uncertainty of $\lesssim 0'.2$. We conclude that the mean *Chandra* coordinates can be offset by no more than $\approx 0'.3$ from the true position.

The two earlier observations of M83, taken with the *Chandra* ACIS-S in 2000 and 2001, do not show the presence of the ULX (see the upper left panel of Figure 1). Applying the Bayesian method of Kraft et al. (1991) to the number of detected counts in the source and background regions, we estimate the net count rate in 2000–2001 to be $<1.0 \times 10^{-4}$ counts s$^{-1}$ at the 90% confidence level. This corresponds to an emitted luminosity $\lesssim 1 \times 10^{36}$ erg s$^{-1}$ for any of the spectral parameter values found in the 2010--2011 series of observations. The newly erupted source had brightened by at least a factor of 3000.

2.2. Swift Monitoring

After the discovery of the ULX in the *Chandra* data, we monitored it with several series of short ($\approx 3$ ks) observations with the *Swift* X-Ray Telescope (XRT), to follow its short-term evolution.

The ULX is somewhat over 0.5′ outside the extended emission from the M83 bulge, in a region free of bright, strongly structured diffuse emission, but in a region where the diffuse emission is still significant, as can be seen in the lower right panel of Figure 1. Thus, we had to choose the background region for photometry from the *Swift* XRT, which has a pixel size of 2′/4, carefully. We set the source region to have a radius of 18′, which contains 70% of the encircled energy at 1 keV, and the background region to be an annulus stretching from 18′ to 35′, avoiding several nearby regions of enhanced diffuse emission.
### Table 1
M83 X-Ray Observations

| Epoch | Obsid | Instrument | Date          | Exposure (s) | Flux $^a$ (10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}) | $I_x$ (10^{37} \text{ erg s}^{-1}) |
|-------|-------|------------|---------------|--------------|-------------------------------------------------|----------------------------------|
| 1     | 0005605001 | XRT        | 2005 Jan 24   | 8592         | <1.75                                           | 490 ± 83                         |
| 2     | 0031905002 | XRT        | 2011 Jan 3    | 399          | 114 ± 33                                        | 290 ± 83                         |
| 3     | 0031905003 | XRT        | 2011 Jan 4    | 1620         | 96 ± 15                                         | 245 ± 39                         |
| 4     | 0031905004 | XRT        | 2011 Jan 7    | 2213         | 192 ± 25                                        | 489 ± 64                         |
| 5     | 0031905005 | XRT        | 2011 Jan 11   | 2140         | 139 ± 19                                        | 355 ± 48                         |
| 6     | 0031905006 | XRT        | 2011 Jan 23   | 2896         | 183 ± 17                                        | 465 ± 44                         |
| 7     | 0031905007 | XRT        | 2011 Feb 4    | 2938         | 113 ± 13                                        | 287 ± 35                         |
| 8     | 0031905008 | XRT        | 2011 Feb 16   | 2882         | 222 ± 18                                        | 566 ± 46                         |
| 9     | 0031905009 | XRT        | 2011 Feb 28   | 2863         | 163 ± 15                                        | 415 ± 39                         |
| 10$^b$| 0031905010 | XRT        | 2011 Mar 15   | 2285         | 187 ± 19                                        | 476 ± 48                         |
| 11$^b$| 0031905011 | XRT        | 2011 Mar 24   | 3258         | 201 ± 16                                        | 513 ± 40                         |
| 12    | 0031905012 | XRT        | 2011 Jun 25   | 3240         | 159 ± 15                                        | 404 ± 39                         |
| 13    | 0031905013 | XRT        | 2011 Jun 30   | 3146         | 147 ± 15                                        | 373 ± 38                         |
| 14$^d$| 0031905014 | XRT        | 2011 Jul 27   | 3588         | 94 ± 11                                         | 259 ± 27                         |
| 15    | 0031905015 | XRT        | 2011 Aug 24   | 951          | 155 ± 33                                        | 395 ± 84                         |
| 16$^e$| 0031905016 | XRT        | 2011 Aug 29   | 2706         | 106 ± 15                                        | 269 ± 39                         |
| 17    | 0031905017 | XRT        | 2001 Sep 4    | 4048         | 118 ± 12                                        | 300 ± 31                         |

| Epoch | Observations | Instrument | Date | Exposure (s) | Flux $^a$ (10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}) | $I_x$ (10^{37} \text{ erg s}^{-1}) |
|-------|--------------|------------|-------|--------------|-------------------------------------------------|----------------------------------|
| 793   | ACIS-S       | XRT        | 2000 Apr 29 | 50981        | <0.037                                           | >0.1                             |
| 2064  | ACIS-S       | XRT        | 2001 Sep 4 | 9842         | ...                                               | ...                              |
| 1A    | 12995        | ACIS-S     | 2010 Dec 23 | 59291        | 120–110                                          | 360–300                          |
| 1B    | 13202        | ACIS-S     | 2010 Dec 25 | 98780        | 130–120                                          | 440–320                          |
| 10A   | 12993        | ACIS-S     | 2011 Mar 15 | 49398        | 150–150                                          | 450–530                          |
| 10B   | 12994        | ACIS-S     | 2011 Mar 23 | 78963        | 160–150                                          | 530–410                          |
| 11A   | 12996        | ACIS-S     | 2011 Mar 29 | 53044        | 150–150                                          | 530–410                          |
| 11B   | 13248        | ACIS-S     | 2011 Apr 3  | 54329        | 150–150                                          | 500–400                          |
| 16$^e$| 14332        | ACIS-S     | 2011 Aug 29 | 52381        | 100–100                                          | 290–290                          |
| 18    | 12992        | ACIS-S     | 2011 Sep 5  | 66286        | 100–100                                          | 320–270                          |
| 19    | 14342        | ACIS-S     | 2011 Dec 28 | 67103        | 80–80                                            | 230–210                          |

| Epoch | Observations | Instrument | Date | Exposure (s) | Flux $^a$ (10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}) | $I_x$ (10^{37} \text{ erg s}^{-1}) |
|-------|--------------|------------|-------|--------------|-------------------------------------------------|----------------------------------|
| 0110910201 | MOS1       | HRI        | 1994 Jul 30  | 21168$^d$   | <0.895                                           | <2.28                            |
|       | MOS2       | HRI        | 1994 Jul 30  | 21670$^d$   | <0.879                                           | <2.23                            |
|       | PN         | HRI        | 1994 Jul 30  | 9668        | <0.728                                           | <1.85                            |
| 0503230101 | MOS1       | HRI        | 2008 Jan 16  | 15946       | not in FOV                                        |                                 |
|       | MOS2       | HRI        | 2008 Jan 16  | 16463$^d$   | <1.90                                             | <4.82                            |
|       | PN         | HRI        | 2008 Jan 16  | 9490        | not in FOV                                        |                                 |
| 0552080101 | MOS1       | HRI        | 2008 Aug 16  | 25413$^d$   | <1.50                                             | <3.82                            |
|       | MOS2       | HRI        | 2008 Aug 16  | 26619$^d$   | <1.65                                             | <4.19                            |
|       | PN         | HRI        | 2008 Aug 16  | 15706$^d$   | <0.988                                            | <2.51                            |

Notes.

$^a$ In 0.3–10.0 keV.

$^b$ The Swift exposure covered the first part of the Chandra exposure; the Swift exposure lasted from 12:17:32 to 22:05:56, while the Chandra exposure began at 12:21:40.

$^c$ The Swift exposure covered the end of the Chandra exposure; the Swift exposure lasted from 11:20:06 to 21:05:57, while the Chandra exposure ended at 22:18:33.

$^d$ 00:34:45 to 03:54:36; this exposure was coincident with the HST exposures in F336E, F438W, F814W. The HST exposure in F555W occurred shortly after the end of the Swift exposure.

$^e$ The Swift and Chandra exposures were not quite coincident; the Swift exposure lasted from 11:35:00 to 15:13:56, while the Chandra exposure began at 18:41:51.

$^f$ After soft proton flare cleaning.

$^g$ The limiting flux is taken from the 3σ limit given by Immler et al. (1999), who combined the two HRI observations for their analysis. The luminosity has been calculated from their flux using the Saha et al. (2006) distance.

$^h$ The angular resolution was insufficient to separate the ULX from the nuclear emission. However, it should be noted that while in the ULX state, our source has a flux comparable to that of the nucleus and thus would produce a roughly east–west elongation of the nuclear source. This elongation is not seen for this observation, suggesting that the source was not in an ultraluminous state.

$^i$ The limiting flux is taken from the analysis of Trinchieri et al. (1985), who combined the two HRI observations before analysis. We have used the smallest detected flux from a point-like source in that study for our limit. The luminosity has been calculated from their flux using the Saha et al. (2006) distance. Visual inspection of the images reveals no source at the location of the ULX in either image.
The background region contains the extended wings of the ULX, composing some 14% of the total source flux. Examination of the Chandra image for the source and background regions shows that both contain several faint point sources; none of these are readily detectable in the Swift image, suggesting that the error produced by not excluding them is on the order of the Poisson statistics of the background. We extracted counts from the source and background regions, solving the simultaneous equations to get the total source counts and the background counts per pixel. Since the exposures were relatively short, the background rate was somewhat uncertain, particularly in bands narrower than the full 0.3–10.0 keV range of the detector. In order to reduce this uncertainty, we determined the mean background rate over all the observations and recalculated the source rates. The difference among individual background rates was small, and the signal-to-noise ratio of the source counts was improved by using the time-averaged background. The resultant light curve is shown in Figure 2; the count rate varies from ≈0.03 to ≈0.07 counts s\(^{-1}\).

The (2.0–10.0 keV)/(0.3–2.0 keV) hardness ratios, shown in Figure 3, vary significantly among the observations, making the use of a single energy conversion factor inappropriate. Instead, we calculated the fluxes and hardness ratios expected as a function of power-law index, assuming an absorbed power law with \(N_{\text{H}} = 1.2 \times 10^{21} \text{ cm}^{-2}\), determined from the best-fitting parameters for the December and March Chandra data. Then, we used the measured count rates and hardness ratios to produce a flux for each Swift observation. The Swift light curve in flux units is shown in the right-hand panel of Figure 2. Even with 3 ks exposures, the total number of counts is insufficient for spectral fitting, and the variation in the hardness ratio argues against summing different observations. We obtained three Swift exposures that were nearly simultaneous with Chandra exposures. The fluxes calculated from the Swift count rates and hardness ratios are roughly consistent with those derived by fitting the Chandra spectra, after the latter were corrected for pileup.

The only earlier Swift XRT observation useful for this work was made in 2005. It provides an upper limit of \(F_{\text{X}}(0.3–10 \text{ keV}) < 1.7 \times 10^{-14} \text{ erg cm}^{-2} \text{ s}^{-1}\) \((L_{\text{X}}(0.3–10 \text{ keV}) < 4.5 \times 10^{37} \text{ erg s}^{-1})\), assuming an absorbed power law with \(N_{\text{H}} = 1.2 \times 10^{21} \text{ cm}^{-2}\) and \(\Gamma = 2.0\).

### 2.3. Previous X-Ray Observations from Other Missions

M83 has been a popular target in surveys of normal galaxies. As a result, there are sufficient data to determine whether the ULX in M83 has been bright in the past.
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Figure 2. Top: the Swift 0.3–10.0 keV count rate as a function of time. The open boxes are the Swift points labeled by their epoch. The filled diamonds are the Chandra powerlaw+diskbb spectral fits converted to Swift count rates. The dates of the Gemini and HST observations are also marked. Bottom: the flux as a function of time. The open boxes are the Swift count rates converted to fluxes as described in the text. The filled diamonds are the Chandra fluxes derived from the powerlaw+diskbb spectral fits.

**XMM-Newton.** Three observations of M83 are available in the public archive. The galaxy is well centered in the field of view of the first of these, from 2003, while in the following two, from 2008, the galaxy falls on a peripheral chip, so the ULX is not covered by all of the instruments in the last two observations. We measured upper limits to the EPIC count rates using a source region with $r < 18''$ and a background region with $18'' < r < 35''$; we converted count rates to fluxes assuming an absorbed power law with $N_H = 1.2 \times 10^{21}$ cm$^{-2}$ and $\Gamma = 2.0$. If we assume that the source was constant over all the XMM-Newton observations, the upper limit becomes $F_X(0.3–10.0 \text{ keV}) < 3.9 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ ($L_X(0.3–10.0 \text{ keV}) < 1.0 \times 10^{37}$ erg s$^{-1}$), while the best individual instrument/exposure result is for the PN in 2003 of $F_X(0.3–10.0 \text{ keV}) < 7.3 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$ ($L_X(0.3–10.0 \text{ keV}) < 1.8 \times 10^{37}$ erg s$^{-1}$).

**ROSAT.** There is one PSPC observation from 1993 and two HRI observations from 1993 and 1994 in the archive, each with exposure time $\approx 24$ ks (Immler et al. 1999). There is no obvious source at the location of the ULX in the HRI exposures; the detection limit for the combined HRI images from Trinchieri et al. (1985) as an extreme upper limit, we find that the flux is $F_X < 1.3 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ ($L_X < 3.3 \times 10^{38}$ erg s$^{-1}$).

**Summary.** M83 was observed to a depth that would have revealed a ULX, or even a moderately bright ($L_X > 10^{37}$ erg s$^{-1}$) X-ray binary in 1979, 1980, 1981, 1993, 1994, 2000, 2001, 2003, 2005, and 2008. The continuously high emission for at least 12 months, from late 2010 December through late 2011.

2.5 \times 10^{37}$ erg s$^{-1}$). The nucleus and the ULX are not resolved in the PSPC image. However, since in its ultraluminous state it is comparable to the nucleus in brightness, had the source been ultraluminous during the PSPC observation, one would expect the central source to have had an east–west elongation, which was not observed. Thus, we may be reasonably confident that the source was not ultraluminous during the PSPC observation. The same argument can be applied to the ASCA observation in 1994 February and the Einstein IPC observation in 1979 July.

**Einstein.** Besides the IPC observation from 1979, with an exposure time of 6 ks, there are two HRI observations from 1980 and 1981 with exposures of 25 and 20 ks, respectively (Trinchieri et al. 1985). Taking the dimmest detected source in the co-added HRI images from Trinchieri et al. (1985) as an extreme upper limit, we find that the flux is $F_X < 1.3 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$ ($L_X < 3.3 \times 10^{38}$ erg s$^{-1}$).

Summary. M83 was observed to a depth that would have revealed a ULX, or even a moderately bright ($L_X > 10^{37}$ erg s$^{-1}$) X-ray binary in 1979, 1980, 1981, 1993, 1994, 2000, 2001, 2003, 2005, and 2008. The continuously high emission for at least 12 months, from late 2010 December through late 2011.
December, suggests that if the source has repeated outbursts, they are relatively long. Thus, the non-detections over the last three decades suggest that this source is either new or has a long period between ultraluminous episodes.

3. X-RAY RESULTS

The Chandra data are magnificent, providing spectra with >10^4 counts, but have sparse temporal coverage. The Swift/XRT data provide a more complete light curve but can provide no more than a hardness ratio. The analysis of each informs and is informed by the other.

3.1. Temporal Variation

The Swift count rate light curve in Figure 2 shows that the count rate varied within a range of roughly a factor of two. The data hint at a flux decline since 2011 March, which is in agreement with the Chandra flux trend. However, given that the source showed flux variations of comparable amplitude during January and February, it may be too early to conclude that the outburst is near its end. The spectral shape, as tracked by the 2.0–10.0 keV/0.3–2.0 keV hardness ratio, is also strongly variable. The count rate versus hardness ratio plot in Figure 3 suggests two different regimes of behavior. In epochs 2–5, as defined in Table 1, the hardness ratio varied strongly while the count rate did not, staying within ~0.03–0.045 counts s^-1. In epochs 6–13 the hardness ratio did not vary significantly, while the count rate did. After epoch 13 the source returned to the mode seen in the earlier epochs. The broadband count rate and the hardness ratio are not well correlated and do not follow a characteristic track in the hardness–intensity diagram.

The broadband flux light curve derived from a combination of Swift and Chandra observations also fluctuates within a range of roughly a factor of two, between 1 and 2×10^{-12} erg cm^{-2} s^{-1}. We determined the Chandra fluxes from multicomponent spectral fits. We derived the Swift fluxes by assuming a power-law spectrum absorbed by a column of 1.2×10^{21} cm^{-2}, constraining the photon index from the hardness ratio, and normalizing the flux to obtain the measured 0.3–10.0 keV band count rate. The full range of flux was spanned by observations in epochs 2 and 3 (a day apart) and by epochs 1 and 2 (9 days apart) and 6 and 7 (11 days apart). There is a hint of greater variability in the observations before mid-February (epoch 8) than after; the clump of observations in March (epochs 9–11) shows little variation in count rate or flux. Unlike the count rate versus hardness ratio plot, the flux versus hardness ratio plot shows little structure, and the conversion from Swift count rates to fluxes adds scatter to the data.

Overall, the source variability during our first 12 months of observations is more similar to the variability seen in ULXs such as Holmberg II X-1 (Grisé et al. 2010) and Holmberg IX X-1 (Kaaret & Feng 2009) than to canonical state transitions, routinely seen in Galactic black hole binaries (Fender et al. 2004; McClintock & Remillard 2006).

We also investigated the intra-observational variability for each Chandra epoch. We extracted background-subtracted light curves with the CIAO task dmextract and analyzed them using the lsearch, efsearch, and powspec tasks in FTOOLS (Blackburn 1995). We computed the power spectrum from the shortest period not biased by the Chandra readout rate (~10 s) to the length of the shortest observation (~50 ks). We do not find significant features in the power spectral density over this 0.1–(2×10^{-5}) Hz band for any observation, nor do we see

![Figure 3](image-url)
any dips, eclipses, or flares. The $\chi^2$ probability of a constant light curve is $\approx 1$ for each epoch; the Kolmogorov–Smirnoff probability (Kolmogorov 1941) that the flux is constant is $\gtrsim 7\%$ for all observations except for that of 2011 September (when it is $\approx 4 \times 10^{-3}$). We can only place a $3\sigma$ upper limit of $\approx 45\%$ ($\approx 16\%$) to the rms fractional variation for 10 s (100 s) bins at any epoch. Overall, the short-term variability is unremarkable. Heil et al. (2009) have demonstrated that ULXs show a wide variety of short-term variability, including many that show no signs of variability.

### 3.2. X-Ray Spectroscopy

For each Chandra observation, we extracted source spectra from a circular region with a 4" radius and background spectra from an annular region between radii of 6" and 12"; we verified that the background region contains no other point sources and only a negligible amount of diffuse emission. We used the specextract script in CIAO Version 4.3 (Fruscione et al. 2006) to build response and area-corrected ancillary response files, and we fitted the spectra in XSPEC Version 12 (Arnaud 1996). Two fully representative examples of the Chandra spectra and the fits we carried out are shown in Figure 4.

We fitted the 0.3–10 keV spectrum from each of the Chandra observations with two XSPEC models commonly applied to the study of black hole X-ray binaries: an absorbed disk blackbody (diskbb) plus power-law model, and an absorbed thermal Comptonization (comptt) model (Titarchuk 1994). The diskbb plus power-law model in ULXs is typically a good but purely phenomenological test for the presence of a soft excess below 1 keV. Under certain assumptions, the soft excess emission may be attributed to the accretion disk and may be used to constrain the inner disk size. The comptt model is a suitable test for mild spectral curvature, in particular at the high energy end of the ACIS bandpass; a characteristic class of ULX spectra with a downturn around 5 keV is formally well fitted with Comptonization models at low plasma temperatures, $kT_e \approx 1.5–2$ keV (Stobbart et al. 2006; Roberts 2007; Gladstone et al. 2009).

The Galactic absorbing foreground column is $4 \times 10^{20}$ cm$^{-2}$ (Kalberla et al. 2005), while the column density due to M83 in this direction is $1.5 \times 10^{20}$ cm$^{-2}$ (using the naturally weighted map from Walter et al. 2008). Thus, other than any internal absorption, the emission should be only lightly absorbed by intervening components. As a result of these considerations, we assumed a fixed Galactic foreground absorption with a column density of $4 \times 10^{20}$ cm$^{-2}$ and a variable absorption from within M83 and the system itself. These column densities are roughly comparable to the optical extinction (see Section 4.2).

At the observed ACIS-S count rate $\approx 0.2$ counts s$^{-1}$ (Table 2 and 3), the source spectra are affected by pileup, meaning that there is a high probability that more than one photon falls in a single pixel (or adjacent pixels) between frame readouts. In general, one can correct for the spectral distortions caused by pileup either by removing pixels with a high pileup probability from the spectral extraction regions or by using convolution models during spectral fitting. We started with the latter technique and used the pileup convolution model of Davis (2001) within XSPEC. This model has two principal parameters that can be allowed to vary: the grade migration parameter, $\alpha$, and the fraction of the events in the source extraction region to which the pileup will be applied, $psffrac$. When we allowed both of these parameters to vary, we usually found that there were two separate regions of parameter space that fit the Chandra spectra. The two model fits implied very different pileup-corrected count rates and different ranges of the $\alpha$ and the $psffrac$ parameters but otherwise produced the same spectral shape and goodness of fit, as determined by $\chi^2$. To break the degeneracy and select the proper range for $\alpha$ and $psffrac$, we extracted another set of source spectra from annuli that excluded the piled-up central pixels. We then constrained the $\alpha$ and $psffrac$ parameters so that they would produce a spectral fit to the piled-up data that was consistent with the fits to the spectra extracted from the annuli. That this rather involved process produces the correct flux is supported by the several nearly simultaneous Swift observations for which the pileup-corrected Chandra fluxes are roughly consistent with their Swift counterparts.

We find that a diskbb component is significantly detected in five of the observations but not the other five (Table 2).
### Table 2

Best-fit power-law+diskbb Model Parameters

| Parameter | Value |
|-----------|-------|
| Date      |       |
| 12995     | Dec 23 |
| 13202     | Dec 25 |
| 12993     | Mar 15 |
| 13241     | Mar 23 |
| 12994     | Mar 26 |
| 12996     | Apr 3  |
| 13248     | Aug 29 |
| 14332     | Sep 4  |
| 12992     | Dec 28 |
| PSFfrac   | 0.60±0.26 |
| N_{H}(10^{20} \text{ cm}^{-2}) | 4.3±2.8 |
| $\Gamma$  | 1.98±0.22 |
| $N_E$(10^{-4} \text{ photons keV}^{-1} \text{ s}^{-1}) | 2.0±0.4 |
| $kT_{\text{disk}}(\text{keV})$ | 0.23±0.23 |
| K_{\text{disk}} | 1.1±0.1 |
| $\chi^2$/dof | 1.15 |
| $\chi^2$ | 0.009 |
| dof | 251 |

**Notes.**

- The complete spectral model fitted was pileup × tabls cgal × tabls i (power-law+diskbb). All uncertainties are for the 90% confidence interval.
- At 1 keV.
- $K_{\text{disk}} = (n_{\text{cgal}}/d(10\text{kpc}))^2 \times \cos \theta$, where $n_{\text{cgal}}$ is the apparent inner-disk radius and $\theta$ is the viewing angle.
- Before pileup correction.
- In 0.3–10 keV.
- After pileup correction.
- Fraction of unabsorbed X-ray luminosity in the disk component.

### Table 3

Best-fit comptt Model Parameters

| Parameter | Value |
|-----------|-------|
| Date      |       |
| 12995     | Dec 23 |
| 13202     | Dec 25 |
| 12993     | Mar 15 |
| 13241     | Mar 23 |
| 12994     | Mar 26 |
| 12996     | Apr 3  |
| 13248     | Aug 29 |
| 14332     | Sep 4  |
| 12992     | Dec 28 |
| PSFfrac   | 0.59±0.17 |
| N_{H}(10^{20} \text{ cm}^{-2}) | <1.6 |
| $kT_{\text{disk}}(\text{keV})$ | 0.11±0.02 |
| $K_{\text{disk}}$ | 1.9±2.2 |
| $\chi^2$/dof | 1.10 |
| $\chi^2$ | 0.95 |
| dof | 232 |

**Notes.**

- The complete spectral model fitted was pileup × tabls cgal × tabls i (comptt). All uncertainties are for the 90% confidence interval.
- Seed photon temperature.
- Plasma temperature.
- Scattering optical depth.
- Normalization in 10^{-4} XSPEC units (Titarchuk 1994).
- Uncertainty does not converge as the temperature is unconstrained.
- Before pileup correction.
- In 0.3–10 keV.
- After pileup correction.
- Unabsorbed luminosity.
Although a cool disk blackbody component produces a marginal improvement in the $\chi^2$ for two of those four observations, the $F$-test shows that it is not statistically significant ($F$-test probability $P = 0.654$ for the 2010 December 23 observation, $P = 0.203$ for 2011 September 4). For the 2011 December 28 observation the disk blackbody produces a significant improvement in the fit ($F$-test probability $P = 0.011$) although the disk blackbody component itself is only marginally detected (see Table 2). We see no evidence for a disk blackbody component in the remaining two observations. A soft excess is detected significantly in the 2011 April 3 observation ($F$-test probability $P = 1.1 \times 10^{-3}$), but at very low temperatures ($kT < 0.16 \text{ keV}$) in an energy range where the ACIS-S3 sensitivity is low and most of the emitted flux is absorbed. Thus, we can neither determine whether that soft excess is a diskbb component nor reliably constrain its characteristic temperature and emission radius.

The absence of a diskbb component in some observations cannot be due simply to shorter exposure times. Had such a component always been as strong as during the 2011 March observations, when it accounted for almost half of the emitted X-ray flux, it would have been easily detected at every other epoch. It is implausible that an accretion disk would form, in an energy range where the ACIS-S3 sensitivity is low and most of the emitted flux is absorbed. Thus, we can neither determine whether that soft excess is a diskbb component nor reliably constrain its characteristic temperature and emission radius.

As the observations from 2011 March are those where the diskbb component is most prominent, they give us the best direct view of the inner disk and allow us to use those observations to constrain the disk parameters. The characteristic peak temperatures at those epochs are $\approx 3–0.4 \text{ keV}$, corresponding to a characteristic inner radius $r_{in}/(\cos \theta)^{1/2} \approx 700–1000 \text{ km}$. If $r_{in}$ corresponds to the innermost stable circular orbit of a face-on Schwarzschild black hole, this value would suggest a black hole mass $\approx 80–100 \text{ M}_\odot$, or higher for a fast-spinning black hole. On the other hand, the classical Eddington-luminosity argument provides a lower limit of $\approx 40 \text{ M}_\odot$ for the black hole mass for the same data, $L_X(3.0–10.0 \text{ keV}) \approx 5 \times 10^{39} \text{ erg s}^{-1}$. These two estimates stand in apparent contrast to one another. However, we have no reason to assume that we are seeing disk emission from near the innermost stable circular orbit. If the inner part of the disk is covered by an optically thick scattering region, the thermal component should come from a larger radius. This is likely to be the case if the mass accretion rate is supercritical, that is, above the threshold at which a radiatively efficient, geometrically thin disk cannot survive. At such accretion rates (which may be the defining characteristic of ULXs), the inner region may be shrouded by a mass-loaded, optically thick outflow, and thus the observed temperature of the soft thermal component would be the temperature at the photosphere of such outflow, while the fitted inner-disk radius would be the radius at which the disk begins to be covered or replaced by the outflow (e.g., King & Pounds 2003; Poutanen et al. 2007; Soria 2007; Gladstone et al. 2009).

It has been suggested (Gladstone et al. 2009) that a ULX with lower diskbb temperature ($kT_{in} \lesssim 0.2 \text{ keV}$) and relatively weak soft thermal component compared to the hard power-law component will have a stronger outflow and greater mass loading, and thus a lower electron temperature in the wind-dominated. Comptonizing inner region (“warm corona” at $kT_e \approx 2 \text{ keV}$), which results in a spectral break at energies $\sim 5 \text{ keV}$.

In our case, the power-law component is dominant or comparable to the diskbb emission at all epochs. The strong power-law component suggests that the inner disk may indeed remain partly shrouded even in the 2011 March observations, and hence the characteristic masses and sizes based on $r_{in}$ must be taken as upper limits. Fitting the spectra with the compTT model helps us investigate this issue. For all observations, the compTT model provides statistically equivalent fits to the diskbb plus power-law model. For all except the 2010 December 23 observation, we can place only a lower limit (typically, $T_e \gtrsim 2 \text{ keV}$) to the best-fitting electron temperature in the scattering region; this is another way of saying that the power-law-like portion of the spectrum extends beyond the upper limit of the ACIS energy band, without a sharp downturn at least up to $\approx 7 \text{ keV}$. To test for the presence of a high-energy spectral break, we fitted the 2.0–10 keV portion of the spectrum with both power-law and broken power-law models, after fixing the pileup model parameters. We find (Table 4) that a broken power-law model does not improve the fit in any of the Chandra observations. The lack of a break in the power law suggests either that this ULX was not in a slim-disk/optically thick warm-corona state (Roberts 2007; Gladstone et al. 2009) or that its characteristic coronal temperature was higher than typically found in that variety of ULXs. We conclude that the accretion rate was only moderately supercritical, perhaps not high enough to launch a massive outflow, and that the spectral appearance of this ULX is closer to the “very high state” of Galactic black hole transients than to the most extreme examples of warm-corona/outflow sources described in Gladstone et al. (2009).

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With only a few exceptions, both the $\text{powerlaw+diskbb}$ fits and the $\text{compTT}$ fits indicate that the source has very little internal absorption. The diskbb fits suggest intrinsic absorbing column densities $\sim$ a few times $10^{20} \text{ cm}^{-2}$, somewhat larger than the local H$_\alpha$ column, $1.5 \times 10^{20} \text{ cm}^{-2}$; the compTT fits suggest values consistent with no M83 absorption at all.

Finally, we searched for emission lines, either from the ULX itself (e.g., Fe K lines) or from spatially unresolved, X-ray ionized gas in its surroundings. We combined the spectra and their respective response files from all the 2010–2011 Chandra observations to increase the signal-to-noise ratio of any possible features. We do not find any significant lines or edges. A narrow 6.4 keV emission line could be added to the local best-fitting continuum but can have an equivalent width no greater than $\sim 12 \text{ eV}$ (90% confidence level). Non-detection of either broad or narrow fluorescent Fe lines is not a surprising feature for a ULX (e.g., Goad et al. 2006), although such lines have been detected in the peculiar case of a ULX in M82 (Strickland & Heckman 2007; Dewangan et al. 2006). In general, Fe lines from stellar-mass black holes are weaker than those from AGNs (Ross & Fabian 2007), because iron in the inner region of the accretion disk is more highly ionized, and the blurring of the line profile due to Compton scattering is more severe.

This is the case in particular when the power-law-like X-ray emission from a scattering corona is comparable to or stronger than the direct thermal emission from the accretion disk—as is the case for most ULXs above 1 keV. If the inner region of the disk is covered or replaced by an optically thick scattering corona (Roberts 2007), we do not expect to see any reflection features. Caballero-García & Fabian (2010) proposed that ULX spectra with a steepening around $\approx 5–7 \text{ keV}$ are dominated by a reflection component with a relativistically broadened Fe line;
however, this interpretation remains somewhat controversial as it requires ad hoc parameters. In any case, the continuum spectrum of the ULX in M83 does not have such high-energy steepening, either.

In conclusion, had we not had previous observations of M83, it was recorded with high confidence by HST and ground-based observatories.

4. OPTICAL COUNTERPART

Optical counterparts of persistent ULXs are typically faint, usually with a B-type star-like appearance at extragalactic distances. When significantly detected, optical variability is only a fraction of a magnitude (e.g., Zampieri et al. 2012) and its physical interpretation is unclear. But in this case, given the proximity of M83 and the dramatic change in the X-ray flux, we have a unique opportunity to investigate and understand the corresponding changes in the optical and UV fluxes. The change was, as expected, below the detectability of the Swift UVOT, but

1. Broken power-law models with the constraint that $\Gamma_2 > \Gamma_1$ do not provide any improvement to the $\chi^2$ value.

4.1. Ground-based Observations

As part of a previously planned Gemini program, we were able to image the section of M83 containing the ULX from the 8.2 m Gemini South telescope on 2011 April 8 (UT) (Program 2011A-0436, PI: Winkler). We used the Gemini Multi-Object Spectrograph (GMOS) in its imaging mode, which has a field 5.5′ square and 0′.0728 pixels. We binned the image 2 × 2 for an effective pixel size of 0′.146, appropriate for the seeing of ≈0′.7 at the time of our observations. Four filters were used: u′, g′, r′, and i′, with individual exposures of 600, 100, 150, and 200 s, respectively, and with four dithered exposures through each filter. We processed the image data using standard IRAF9 and Gemini reduction procedures for overscan and bias subtraction, flat-fielding, aligning, and stacking. Flux calibration was done using observations of the spectrophotometric standard LTT 4316 (see Hamuy et al. 1992) taken immediately after the M83 images. All observations were at airmass < 1.1.

A blue stellar object, faint but clearly visible, is present at the position of the ULX in the stacked images in the u′, g′, r′ bands, and possibly in i′ as well (Figure 5, central panel). Even though the source is located in an interarm region well

9 IRAF is distributed by the National Optical Astronomy Observatories, which are operated by AURA, Inc., under cooperative agreement with the National Science Foundation.
within the innermost spiral arm of M83, the background from the galaxy is complex enough to make accurate photometry of a faint object difficult.

We had previously taken images of M83 with the IMACS instrument on the 6.5 m Magellan I telescope in 2009 April as part of a program to inventory supernova remnants and other nebulae in M83 (Program 2009A-0446, PI: Winkler). These images were taken through narrowband filters and so are not directly comparable to the 2011 Gemini images, but they nevertheless show fainter stars than the 2011 images because of long exposures and exceptional seeing, ≲0.′4. No object at the ULX position is visible in these 2009 images with an upper limit $m_{5150} \gtrsim 25$ mag. Although the bands are far from identical, we can use the Magellan images (after PSF matching and scaling) to subtract much of the stellar contribution in the Gemini images near the ULX, to produce a background that is far more uniform and thus more amenable to aperture photometry. Figure 5 shows both a Gemini and a Magellan image of the region, together with a difference image that clearly shows the ULX counterpart. From the $u'$ and $g'$ images we subtracted the sum of [O iii] plus a 200 Å wide continuum band centered at 5200 Å; from the $r'$ image we subtracted one in a 150 Å wide continuum band centered at 6800 Å. We used these difference images for conventional aperture photometry of the ULX counterpart to obtain the Gemini AB magnitudes given in Table 5. The uncertainties quoted include any due to possible residuals from imperfectly subtracted stars and diffuse background.

### 4.2. Hubble Observations

Images with better angular resolution and higher sensitivity for the M83 field containing the ULX were taken in 2009 August with the newly installed WFC3 instrument on HST as part of the Early Release Science program (Dopita et al. 2010). Within the error circle of the ULX position, there are no blue sources; the only objects are a few very faint red stars. Following the discovery of the ULX counterpart in the Gemini images, we requested and were awarded two orbits of Director’s Discretionary HST time for a second-epoch WFC3 observation, which was carried out on 2011 July 27 (Program 12683, PI: Winkler). The data were processed with the standard WFC3 pipeline, including drizzling of the three dithered frames taken through each of the four filters. The ULX counterpart is readily apparent in the 2011 WFC3 images through the F336W ($U$), F438W ($B$), and F555W ($V$) filters. Alignment and subtraction of the 2009 $I$ image renders the counterpart easily visible on the 2011 F814W ($I$) image as well. The world coordinate systems associated with the WFC3 images at both epochs have been updated to agree with that which we determined for the Magellan images, which in turn was based on several hundred astrometric stars. The position of the ULX counterpart is

|R.A. (2000.) = 13°37′05″127, decl. (2000.) = −29°52′06″92.|

We estimate the absolute uncertainty in the coordinates to be, at worst, 0.′1, and the registration of all the images relative to one another is better than 10 mas. The difference between the optical and X-ray coordinates is 0′.28, which is well within the combined uncertainty of the X-ray and optical positions. WFC3 images from both the 2009 and the 2011 epochs are shown for a small region directly around the ULX position in Figure 6.

We have carried out photometry of the ULX counterpart and neighboring stars in the WFC3 images using DAOPHOT, consistently taking an aperture with a radius of 2 pixels (0′.08) and using standard encircled-energy corrections to account for the missing flux. In the 2009 images, there are a number of very faint red stars quite near the position of the ULX counterpart, though it is not clear if one of them is actually the donor star in quiescence. After updating the world coordinate systems of both images so they are accurately registered, we carried out photometry of the 2009 images using the identical positions and

### Table 5

| Date       | Telescope | Instrument | Exposure (s) | Band        | Filter          | Magnitude* | $A$(V)* | Unabsorbed Flux (Jy)* |
|------------|-----------|------------|--------------|-------------|-----------------|------------|---------|----------------------|
| 2009 Apr 26| Magellan I| IMACS      | 7 × 600      | [O III]     | 5007 50         | m5150 = 28.1 ± 0.8 | 0.48     | 3.2 × 10^-8          |
| 2009 Apr 26| Magellan I| IMACS      | 7 × 200      | Green contin | 5316 161        | m5150 = 27.5 ± 0.6 | 0.40     | 5.4 × 10^-8          |
| 2009 Apr 26| Magellan I| IMACS      | 7 × 200      | Red continuum | 6815 216        | m5150 = 26.4 ± 0.3 | 0.30     | 1.3 × 10^-7          |
| 2009 Aug 9 | HST       | WFC3       | 3 × 630      | U (F336W)   | 3355 111        | m5150 = 24.4 ± 0.3 | 0.18     | 7.7 × 10^-7          |
| 2009 Aug 9 | HST       | WFC3       | 3 × 640      | B (F438W)   | 4326 168        | m5150 = 23.4 ± 0.3 | 0.47     | 2.4 × 10^-6          |
| 2009 Aug 9 | HST       | WFC3       | 3 × 401      | V (F555W)   | 5308 1562       | m5150 = 23.8 ± 0.2 | 0.35     | 1.6 × 10^-6          |
| 2009 Aug 9 | HST       | WFC3       | 3 × 401      | I (F814W)   | 8030 1536       | m5150 = 23.8 ± 0.3 | 0.25     | 1.4 × 10^-6          |
| 2011 Apr 8 | Gemini-S  | GMOS       | 4 × 600      | u'          | 3650 490        | m5150 = 23.1 ± 0.8 | 0.48     | 2.0 × 10^-6          |
| 2011 Apr 8 | Gemini-S  | GMOS       | 4 × 100      | g'          | 4780 1540       | m5150 = 23.7 ± 0.04 | 0.20     | 1.7 × 10^-6          |
| 2011 Apr 8 | Gemini-S  | GMOS       | 4 × 150      | r'          | 6340 1440       | m5150 = 23.8 ± 0.3 | 0.25     | 1.4 × 10^-6          |
| 2011 Jul 27| HST       | WFC3       | 3 × 608      | U (F336W)   | 3355 111        | m5150 = 23.8 ± 0.04 | 0.48     | 2.0 × 10^-6          |
| 2011 Jul 27| HST       | WFC3       | 3 × 330      | B (F438W)   | 4326 168        | m5150 = 23.7 ± 0.04 | 0.40     | 1.7 × 10^-6          |
| 2011 Jul 27| HST       | WFC3       | 3 × 245      | V (F555W)   | 5308 1562       | m5150 = 23.7 ± 0.05 | 0.30     | 1.6 × 10^-6          |
| 2011 Jul 27| HST       | WFC3       | 3 × 487      | I (F814W)   | 8030 1536       | m5150 = 23.8 ± 0.06 | 0.18     | 1.7 × 10^-6          |

Notes.

*a* All magnitudes are observed AB magnitudes at the central wavelength. For WFC3, these use the nominal WFC3 zero points given at http://www.stsci.edu/hst/wfc3/phot_zp_lbn.

*b* Assuming $A_V = 0.30$ and using reddening corrections from Romaniello et al. (2002) for the HST filters and from Cardelli et al. (1989) at the central wavelengths for the Gemini filters.

*c* Values obtained from the 2009 HST observations correspond to the excess flux at the location of the ULX and are upper limits to the flux of the pre-outburst donor star.
apertures as in 2011 to obtain the limits given in Table 5. While we used standard procedures for the 2011 July observations, we used “forced photometry” at the position of the ULX for the 2009 July data. We did see an excess at the position of the ULX, used “forced photometry” at the position of the ULX for the 2011 July observations, we used standard procedures for the 2011 July observations, we represent upper limits to the flux from the counterpart. there was no specific counterpart at this position, the values represent upper limits to the flux from the counterpart.

As part of an ongoing analysis of the HST data for M83, H. Kim (2011, private communication) provided photometry and reddening estimates for stars surrounding the ULX position. She determined a mean total extinction of $A_V = 0.30 \pm 0.34$. This value indicates modest but variable extinction, consistent with the appearance of the HST imagery. We adopt this mean value for the ULX in correcting the values in Table 5 to obtain intrinsic fluxes. From the WFC3 data we find that the counterpart’s absolute magnitude is $M_V = -4.85$, as well as a total optical luminosity of $L(3300–9000 \, \text{Å}) \approx 2 \times 10^{37} \text{erg s}^{-1}$ at the time of the 2011 July observation. In quiescence, the counterpart was no brighter than $M_V \approx -2.1$, and therefore the optical counterpart has brightened optically by a factor of at least 10.

Comparison between the AB magnitudes obtained on April 8 from Gemini and those obtained on July 27 (from HST (Table 5) indicates no evidence for optical variability over this period. Further monitoring of the optical source would be valuable, either in tight coordination with X-ray observations or especially if the X-ray object starts to fade significantly.

5. DISCUSSION

We have discovered a bright new source in the low-extinction interarm region of M83. Although it is well within the D$_{25}$ radius, it is still worth considering whether the source could be a background AGN. Using a standard definition of the X-ray/optical flux ratio

$$\log \left( \frac{f_X}{f_R} \right) = \log f_X + 5.5 + m_R/2.5$$

(Hornschemeier et al. 2001), where $f_X$ is the 0.3–10 keV flux and $m_R$ is the Cousins magnitude, we find for this source, with $m_R \approx 24$, $\log f_X \approx -12$ and $\log (f_X/f_R) \approx 3.5$. This is typical of stellar-mass systems, while AGNs have typical $-1 \lesssim \log (f_X/f_R) \lesssim 1$ (Bauer et al. 2004; Laird et al. 2009). Furthermore, AGNs at this flux level are relatively rare (only $\approx 0.1 \deg^{-2}$; Cappelluti et al. 2009) and nearly always have identified optical counterparts. Finally, we are not aware of any AGN that has been observed to vary in X-rays by the factor of at least 3000, as seen for the X-ray source in M83. Thus, it is highly improbable that the source is a background AGN. There are no known historical supernovae in this region, so it is unlikely that the sudden X-ray/optical increase is due to a previously undetected remnant beginning to interact with the circumstellar medium.

Our discovery of a transient ULX in an interarm region of M83 suggests that the ULX population is more diverse than often assumed. Most ULXs in nearby galaxies are variable sources but have been persistently active throughout the years since their original discovery (typically, with ROSAT in the 1990s). Instead, this source was not detected by Einstein, ROSAT, XMM-Newton, or in previous Chandra observations. A flux increase of $>3000$ between the 2000–2001 and the 2010–2011 Chandra observations is very unusual for a ULX, but it resembles typical behavior of Galactic black hole transients. Its current bright state has lasted at least 12 months, but likely less than two years (based on the faintness of its optical counterpart in the 2009 August HST observations). This is longer than most Galactic black hole transients (typically, a few weeks; McClintock & Remillard 2006) but is not unprecedented. For example, the 1996–1997 outburst of GRO J1655−40 lasted for 15 months (Soria et al. 2000), and GRS 1915+105 has remained bright since 1992 (Castro-Tirado 2011)

The other defining characteristic of this ULX is that it is located far from any star-forming region, and it must have a low-mass, evolved donor star (mass $< 4 M_\odot$), since no OB counterparts were detected at the ULX position before the start of the outburst (see Section 5.2). Irwin et al. (2003, 2004) argued that ULX candidates in the old stellar populations of elliptical galaxies were mostly due to background AGN contamination. In spiral galaxies with mixed populations, ULXs with low-mass counterparts had been identified only in a statistical sense (Swartz et al. 2004; Walton et al. 2011). However, our secure identification of this ULX with its optical counterpart confirms the existence of two different classes of ULXs. More specifically, this source is a ULX powered by accretion from a low-mass donor in an older environment within a galaxy with active star formation. This suggests that a classification of ULXs based on the global properties of their host galaxies is incomplete, as it may miss or underestimate a population

![Figure 6. HST WFC3 true-color images of the region around the ULX. In all panels, the colors are: blue, for the F438W filter; green, for F555W; and red, for F814W. North is up and east to the left. Left: image from 2011 July, during the X-ray luminous state; the ULX counterpart appears distinctly blue. The field size is 10′′ square. This panel can be compared to the ground-based images in the previous figure. The dashed box shows the region covered by the next two panels. Middle: a 2′5 × 2′5 detail of the 2011 July image. Right: image from 2009 August, at the same scale as the previous panel. The bright blue “star” is not present; there are many faint red stars near the ULX position in the 2009 image, but none are exactly coincident.](image-url)
of older, transient ULXs with short active phases, particularly at the lower reaches of the “ultraluminous” luminosity range. The presence of older ULXs in star-forming galaxies has long been proposed by Mushotzky (2006). Further evidence for the existence of ULXs with low-mass donors in old stellar populations comes from two transient sources that are only a factor of two less luminous than the new ULX in M83: one in NGC 5128 (Sivakoff et al. 2008) and one in M31 (Kaur et al. 2012).

5.1. The Nature of the Accretor

Beginning with Shakura & Sunyaev (1973), a number of steady-state mechanisms have been proposed to allow large super-Eddington accretion rates that lead to much milder super-Eddington luminosities. Galactic black hole binaries, however, with a few exceptions (Jonker & Nelemans 2004), stubbornly remain below the Eddington limit. While it is accepted that ULXs are powered by accreting black holes, the main unsolved issue is whether they contain a different (more massive) kind of black hole than typical Galactic sources, or are simply in a different accretion state (e.g., at a super-Eddington accretion rate). We found that the 0.3–10 keV spectrum of this source is typical of ULXs: dominated by a power law with a photon index $\approx 2$ (intermediate between the soft and hard state of Galactic black holes), with an additional soft thermal component at $kT \approx 0.3$ keV (cooler than typical accretion disks of Galactic black holes). The characteristic inner-disk radius implied by the thermal component is $\approx 1000$ km: this corresponds to a Schwarzschild black hole mass $\approx 100 M_\odot$ if we are directly seeing the disk all the way to the innermost stable circular orbit, or $< 100 M_\odot$ if the inner disk is hidden by a Comptonizing region. The latter scenario is more likely, given the dominant power-law component. In fact, in some Chandra observations the thermal component disappears altogether, which suggests that a larger fraction of the disk emission is Comptonized at such times.

A strict application of the Eddington limit requires a black hole mass $\gtrsim 40 M_\odot$; however, luminosities up to $\sim 3$ times Eddington (implying correspondingly lower black hole masses) can be produced in standard accretion scenarios. For example, analytical solutions of standard accretion models show that the true emitted luminosity is $\sim (1 + \log M)$ for $M > 1$ (Poutanen et al. 2007). Recent radiation-magnetohydrodynamic simulations confirm that the isotropic luminosity can reach $\sim L_{\text{edd}}$ during supercritical accretion (Ohsuga & Mineshige 2011). In addition, mild geometrical beaming can further increase the apparent luminosity by a factor of two for a standard disk seen face-on and by a factor of 10 for supercritical accretion flows (Ohsuga & Mineshige 2011). Observationally, several neutron star X-ray binaries have reached luminosities of a few times Eddington in their flaring state (Bąucińska-Church et al. 2010; Barnard et al. 2003; Homan et al. 2007). Thus, calculated black hole masses may be overestimated by a factor of $\lesssim 3$.

It is still an unsolved theoretical problem whether black holes can form from standard stellar evolution at high metallicity (Belczynski et al. 2010; Heger et al. 2003), as metal lines make mass loss more efficient, decreasing the pre-collapse stellar mass drastically. As pointed out in Heger et al. (2003), there are very large uncertainties on exactly what mass/metallicities can actually produce a black hole. It has been argued (Pakull & Mirioni 2002; Mapelli et al. 2009; Zampieri & Roberts 2009) that ULX formation either requires a low-metallicity environment or is enhanced by a low-metallicity environment (Prestwich et al. 2011). This source demonstrates that low metallicity need not always be the case, since the environment in the inner disk of M83 where the ULX is located can hardly be characterized as a low-metallicity one. Accurate measurements of abundances in regions with relatively high metallicity are notoriously difficult, but recent estimates based on deep spectra of H II regions within the D25 radius give oxygen abundances for a radius of 1.0 from the nucleus to be $12 + \log(O/H) = 8.73 \pm 0.01$ (Bresolin et al. 2009), compared to the solar value of 8.69 (Asplund et al. 2005) and the local ISM value of 8.69 (Snow & Witt 1996). A different method applied to the H II regions of M83 produces for the same radius $12 + \log(O/H) = 8.59 \pm 0.01$ (Pilyugin et al. 2006) compared to their local ISM reference value of 8.50. While there is some disagreement about the absolute oxygen abundance, it is clear that the relative oxygen abundance for this region is slightly higher than solar. In such an environment, even an older population is unlikely to have a low metallicity, unless the ULX is from a disrupted dwarf galaxy. This object suggests that black holes with masses $\gtrsim 40 M_\odot$ can be found in environments where the local abundance is solar to somewhat supersolar, whereas models suggest that at these abundances only black holes with $\lesssim 15 M_\odot$ are produced (Belczynski et al. 2010). Reducing abundances to LMC values can produce black holes $\lesssim 30 M_\odot$, so finding a $\gtrsim 40 M_\odot$ black hole in a region with solar abundances, even accounting for enrichment since its stellar formation, is rather unusual and difficult to understand.

5.2. The Nature of the Optical Counterpart

The optical colors of the system in outburst are not consistent with a simple blackbody-like spectrum; the flux density, as shown in Figure 7, decreases from the near-UV to the visible band but increases again toward the $I$ band. This behavior...
suggests the presence of at least two components: one peaking in the UV (implying a characteristic blackbody temperature \( \gtrsim 20,000 \, \text{K} \) and a characteristic effective radius \( \lesssim 20 \, R_\odot \)) and one in the IR (implying a characteristic blackbody temperature \( \lesssim 4000 \, \text{K} \) and a characteristic effective radius \( \gtrsim 100 \, R_\odot \)). There are (at least) two ways to interpret this situation. One possibility is that the IR emission is dominated by the large outer disk, and the UV excess is the hot spot or the irradiated surface of the donor star. An alternative is that the UV peak is the Rayleigh–Jeans tail of the emission from a cool stellar component. In the latter case the disk must be truncated or at least shaded is the Wien tail of the emission from an irradiated disk and the \( j \)-band excess is the Wien tail of the emission from a cool stellar component. In the latter case the disk must be truncated or at least shaded is the Wien tail of the emission from a cool stellar component.

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transient, where the optical colors and luminosity in outburst suggest an orbital period \( P \approx 360 \)–830 days. Since the donor star is filling its Roche lobe, \( P_h \rho^{1/2} \approx 10.5 \) for mass ratios \( 0.01 \lesssim q \lesssim 1 \) (Eggleton 1983), where \( \rho \) is the average stellar density in g cm\(^{-3}\)). Thus, we obtain \( 3 \times 10^{-7} \lesssim (\rho/g \text{ cm}^{-3}) \lesssim 1.5 \times 10^{-6} \). These are typical densities of red giants or AGB stars (Salasnich et al. 2000; Bertelli et al. 2008, 2009), consistent with our interpretation of the system. As a comparison, our independent estimate of a mass \( \approx 3 \, M_\odot \) and radius \( \approx 150 \, R_\odot \) for the red star apparently associated with the ULX implies a mean density \( \rho \approx 10^{-6} \, g \text{ cm}^{-3} \), in agreement with the expectations if that is the true donor star.

The size of the accretion disk remains uncertain. Using our lowest estimate for \( M_{\text{BH}} \approx 4 \, M_\odot \) and our upper estimate for the \( M_{\text{star}} \approx 4 \, M_\odot \), the radius of the primary’s Roche lobe is at least a few hundred \( R_\odot \). The maximum size of an accretion disk is \( 80\% \) of the size of the primary’s Roche lobe (Paczynski 1977; Whitehurst 1988), which corresponds to a characteristic size \( \approx 10^{13} \) cm for this ULX. On the other hand, we have argued that the optical colors and luminosity in outburst suggest an irradiated disk size \( \approx 10^{12} \) cm. One possibility is that the disk is truncated at that radius, in which case the whole disk would be kept ionized by the X-ray illumination. Alternatively, the outer part of the disk may be shielded from irradiation and therefore much colder, neutral, and not a significant contributor to the optical/IR emission; the temperature of a non-irradiated standard disk (Shakura & Sunyaev 1973) at \( R \approx 10^{13} \) cm would be only \( \approx 600 \) K, for the disk parameters fitted to the X-ray emission. We do not have enough information to choose between the two scenarios. Whether the outer disk is mostly ionized or neutral has implications for the transient behavior.

5.4. Transient Behavior

Most Galactic black holes with a low-mass donor star are transient, while most of those with an OB donor are persistent X-ray emitters (albeit with flux and spectral variability). We suggest that the same may be true for ULXs. A few other examples of ULX transients are two sources in NGC 1365 (Soria et al. 2009), one in M31 (Kaur et al. 2012), two in M101 (Kuntz et al. 2005), one in NGC 3628 (Strickland et al. 2001), and one in M82 (Feng & Kaaret 2007). The transient behavior in accreting stellar-mass black holes has been attributed to thermal/viscous disk instabilities (Mineshige & Wheeler 1989; Osaki 1996; Lasota 2001) and/or to mass transfer instabilities (Hameury et al. 1986, 1987, 1988; Vialet & Hameury 2008).

Mass transfer instabilities operate when the evolved donor star is nearly but not entirely filling its Roche lobe, providing only a low accretion rate and thus producing a low-luminosity “quiescent” state. The resulting X-ray photons penetrate a few Thompson optical depths below the photosphere of the donor star, causing the convective envelope to expand slowly until the star makes full contact with its Roche lobe. This contact dramatically enhances both the mass transfer rate through the L1 point and the X-ray luminosity of the system, which is generally seen as an “outburst” state. However, as a larger accretion disk is formed, it eventually shades the L1 region from X-ray irradiation, decreasing or stopping mass transfer. The parameter space for the mass transfer instability in ULXs is largely unexplored. A necessary condition is that the irradiating X-ray flux at the surface of the donor star be stronger than its intrinsic flux. This is not the case for ULXs with massive donors, but it is true for this source and probably for other ULXs with low-mass donors.

In the disk instability model, the disk follows a limit cycle between a hot (higher viscosity) and a cold (lower viscosity) state. The difference between the two states is due to the sudden jump in opacity when the temperature reaches \( \approx 6500 \) K and hydrogen becomes mostly ionized (Cannizzo et al. 1988). The instability can be suppressed if the whole disk is kept ionized by X-ray irradiation (Burderi et al. 1998; King & Ritter 1998; Janiuk & Czerny 2011). For the observed luminosity of the M83 ULX at the peak of the outburst, the outer disk can be kept ionized by irradiation up to a radius \( R_{\text{ir}} \approx 10^{13} \times (f_{\text{ir}}/10^{-2})^{1/2} \) cm, where \( f_{\text{ir}} \) is the fraction of X-ray flux reprocessed by the disk. From the inferred size of the binary system, the accretion disk can extend beyond this instability boundary if the outer radius reaches the tidal truncation radius (Paczynski 1977; Whitehurst 1988). On the other hand, the observed optical colors suggest that the outer disk of the ULX has a temperature \( \approx 20,000 \) K and hence is truncated well inside the tidal radius. Thus, we cannot tell whether the disk instability operates on the ULX in M83 and will be responsible for ultimately bringing the outburst to a close.

If the outburst does end soon, and the X-ray luminosity declines to below \( 10^{39} \) erg s\(^{-1}\), we will have a great opportunity to monitor its spectral behavior in the luminosity range typical of Galactic black holes. Determining whether or not a ULX behaves like an ordinary stellar-mass black hole (e.g., similar state transitions and evolution in the hardness–intensity diagram) when its luminosity drops will tell us whether it is powered by an intrinsically different type of black hole, or by an ordinary stellar-mass black hole at an extremely high accretion rate, not usually reached by Galactic black holes.

6. SUMMARY

We have discovered a new ULX in M83 using Chandra and have characterized the X-ray properties of the source in a series of Chandra and Swift observations extending through 2011 December. We have also detected the optical counterpart to the source using the Gemini South Telescope and HST. The ULX is located in an interarm region and well away from sites of active star formation. Its observed properties and our interpretation of them can be summarized as follows:

1. At its discovery in 2010 December, the luminosity was \( L_X(0.3–10\text{keV}) \approx 4 \times 10^{39} \) erg s\(^{-1}\). The source has remained bright; its luminosity has varied by a factor of two, and it has only recently dropped to \( \approx 2 \times 10^{39} \) erg s\(^{-1}\). There is no previous evidence for the existence of this X-ray source in observations extending back to 1979; the X-ray flux has increased by at least a factor of 3000.
2. Although there is significant variation between observations, the X-ray light curves of individual observations show no signs of short-term variability, nor are there signs of orbital modulations or eclipses.
3. The X-ray spectra can be well fitted by a disk blackbody plus power-law model, or by an absorbed Comptonized spectrum, typical of most ULXs. The strength of the disk blackbody component varies on timescales of days. We attribute this to the fraction of inner disk photons upscattered in a variable Comptonizing region, rather than to a change in the disk.
4. In those X-ray spectra where a disk is evident, the disk luminosity and temperature suggest an inner accretion disk radius of about 1000 km, corresponding to a Schwarzschild black hole with mass $M_{\text{BH}} \approx 100 M_\odot$. The black hole mass could be less if the inner disk is hidden by a Comptonizing region. In order to strictly obey the Eddington limit, the black hole must have a mass $M_{\text{BH}} \gtrsim 40 M_\odot$. However, if we allow the possibility of accretion luminosities up to three times the Eddington limit at supercritical accretion rates, the X-ray data are still consistent with an ordinary stellar-mass black hole.

5. A blue optical counterpart with $M_V \approx -4.85$ has appeared since 2009 August, presumably at the same time as the ULX. The only stars near this site prior to the appearance of the ULX are faint and red, so they must belong to an older population. The donor star is not an OB star and is likely to be a red giant or AGB star with $M \lesssim 4 M_\odot$ and age $\gtrsim 500$ Myr. We note, however, that had the system been observed only in its luminous state, the donor could easily have been mistakenly interpreted as an OB star, consistent with most other ULXs with uniquely identified optical counterparts. Some of these other ULXs may well have low-mass donor stars as well.

6. During the X-ray outburst, the SED of the optical counterpart is dominated by a blue component, with $M_V \approx -4.85$ mag, which we interpret as the Rayleigh–Jeans tail of the emission from the outer disk, heated by the X-ray photons. In addition, there is a faint red component that may arise from the surface of the donor star, although we cannot exclude the possibility that it stems from other unrelated stars in the vicinity.

7. The M83 ULX system provides clear evidence that not all ULXs involve an OB donor and a young stellar population, confirming the suggestion from statistical studies that there are two classes of ULXs.

8. The existence of a ULX in the inner disk of M83 suggests that it is possible to produce black holes also in systems with at least solar metallicity.

The ULX in M83 has provided significant insight into the diversity of the ULX population and provides us with an unequivocal example of a ULX with a low-mass donor. Continued monitoring of this source will bring greater depth of understanding to this source and this class of sources. Determining the length of the current outburst will constrain the extent to which sources like this contribute to the persistent ULX population, and the length of the decline may constrain the size of the accretion disk. It is still actively debated whether ULXs are a state reached by ordinary stellar-mass black holes at extremely high (super-Eddington) accretion rates or are powered by a different (more massive) type of accreting black hole. Almost all Galactic black hole transients pass through a high/soft state (dominated by thermal disk emission) after the peak of their outburst and before returning to quiescence; they remain in that state for several weeks. If this ULX does the same, the luminosity at which the state changes will help us understand and quantify the relation between stellar-mass black holes and ULXs. If, instead, this ULX continues to behave like a ULX even when its luminosity goes below $\approx 10^{39}$ erg s$^{-1}$, then it is likely that there are intrinsic physical differences between the black holes in ULXs and the ordinary stellar-mass black holes. Clearly, this is an interesting object that will continue to illuminate our ignorance about ULXs.

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Note added in proof. After our article was submitted, Middleton et al. (2012) published an X-ray/optical study of the transient ULX in M31, discovered in 2009 December. Its peak X-ray luminosity of $\approx 5 \times 10^{39}$ erg s$^{-1}$, its optically bright accretion disk in outburst, and the lack of a massive stellar counterpart in quiescence place this transient in the same class as the M83 ULX. However, it is important to know that the transient in M31 declined on an e-folding timescale of $\approx 40$ days, while the ULX in M83 has been at nearly the same luminosity for over a year.

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