COMPACT OPTICAL COUNTERPARTS OF ULTRALUMINOUS X-RAY SOURCES

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ABSTRACT

Using archival \textit{Hubble Space Telescope} (HST) imaging data, we report the multiband photometric properties of 13 ultraluminous X-ray sources (ULXs) that have a unique compact optical counterpart. Both magnitude and color variation are detected at timescales of days to years. The optical color, variability, and X-ray to optical flux ratio indicate that the optical emission of most ULXs is dominated by X-ray reprocessing on the disk, similar to that of low-mass X-ray binaries. For most sources, the optical spectrum is a power law, $F_{\nu} \propto \nu^{\alpha}$ with $\alpha$ in the range 1.0–2.0 and the optically emitting region has a size on the order of $10^{12}$ cm. Exceptions are NGC 2403 X-1 and M83 II-82, which show optical spectra consistent with direct emission from a standard thin disk, M101 ULX-1 and M81 ULS1, which have X-ray to optical flux ratios more similar to high-mass X-ray binaries, and IC 342 X-1, in which the optical light may be dominated by the companion star. Inconsistent extinction between the optical counterpart of NGC 5204 X-1 and the nearby optical nebulae suggests that they may be unrelated.

Key words: accretion, accretion disks – black hole physics – galaxies: stellar content

1. INTRODUCTION

Ultraluminous X-ray sources (ULXs) are non-nuclear X-ray sources with luminosity above the Eddington limit of stellar mass black holes ($L_X > 3 \times 10^{39}$ erg s$^{-1}$) assuming isotropic emission. ULXs with fast variability or long-term chaotic flux variation may contain accreting black holes in an attached binary system. They could be powered by accretion onto either intermediate-mass black holes of $10^5$–$10^6 M_\odot$ at sub-Eddington rate (Colbert & Mushotzky 1999; Makishima et al. 2000; Kaaret et al. 2001) or normal or slightly massive stellar black holes of $\lesssim 100 M_\odot$ at super or near Eddington rate (Watarai et al. 2001; Begelman 2002).

In black hole binaries, the X-ray emission probes the deep potential at regions close to the event horizon, while the optical emission is important to constrain their masses, interaction with environment, and evolutionary history of the binary. Optical observations of ULXs have played a key role in unveiling the nature of these sources. Many bright ULXs are found to be spatially associated with an optical nebula (Pakull & Mirioni 2003). These nebulae are large, with an extent of tens to hundreds of pc, and expanding at a velocity in the order of $10^3$ km s$^{-1}$. Most of them are powered by strong shocks created by outflows from the binary hitting the surrounding medium, and in a few cases, extraordinary photoionization is required (Kaaret et al. 2004; Kaaret & Corbel 2009). The photoionized nebulae can be used as bolometers to extreme ultraviolet and soft X-ray photons, and suggest that the ULX luminosities are indeed high. Point-like optical objects as compact counterparts of ULXs have been identified for ten sources in the literature. The companion star, intrinsic emission from the disk at large radii, and disk irradiation may all contribute to the optical emission and even dominate at different wavelengths. Binary population synthesis indicates that the colors and magnitudes of the optical counterpart of ULXs can help distinguish between stellar mass and intermediate-mass black holes, and a sample of six sources favors the latter interpretation (Madhusudhan et al. 2008). The continuum component in the optical spectrum of NGC 5408 X-1 is consistent with that from a standard accretion disk with irradiation (Kaaret & Corbel 2009). However, this result is obtained from a ground-based telescope, so the nebular contribution cannot be directly resolved and has to be subtracted based on model prediction. Therefore, in most cases \textit{Hubble Space Telescope} (HST) observations are required for the study of the compact optical counterpart of ULXs, in particular for the continuum emission.

There are ten ULXs with a unique optical counterpart identified in the literature. We make three new identifications in this paper. Here, we analyze all available HST imaging data for these 13 ULXs, see Table 1, to investigate their multiband spectra and variation at long timescales. The observations and data analysis are described in Section 2, the results are discussed in Section 3, and the conclusions summarized in Section 4.

2. OBSERVATIONS AND DATA ANALYSIS

2.1. Sample

Up to beginning of analysis work for this paper, there have been ten ULXs with a unique optical counterpart identified: Holmberg II X-1 (Kaaret et al. 2004), Holmberg IX X-1 (Grisé et al. 2011), IC 342 X-1 (Feng & Kaaret 2008), M81 ULS1 (Liu et al. 2008), M81 X-6 (Liu et al. 2002), M101 ULX-1 (Kuntz et al. 2005), NGC 1313 X-2 (Ramsey et al. 2006; Pakull et al. 2006; Liu et al. 2007), NGC 5204 X-1 (Liu et al. 2004), NGC 5408 X-1 (Lang et al. 2007), and NGC 6946 ULX-1 (Kaaret et al. 2010). Moreover, Ptak et al. (2006) and Roberts et al. (2008) reported possible optical counterparts of another 50 ULXs. However, these sources appear to have more than one optical counterpart shown in the X-ray error circle. Here, using \textit{Chandra} and HST data up to date, we surveyed ULXs in these catalogs for possible means of improving the relative astrometry, which leads to the identification of a unique counterpart for another three sources, M83 IXO 82, NGC 2403 X-1, and NGC 4559 X-7.

The details about the astrometry correction have been described in Feng & Kaaret (2008). The relative astrometry between \textit{Chandra} and HST is improved by aligning objects (hereafter referred as reference objects) shown on both. For \textit{Chandra}, deepest observations with the Advanced CCD
Imaging Spectrometer are used. The X-ray positions are calculated using the wavdetect tool in CIAO from exposure-corrected images in the energy range of 0.3–8 keV. The HST images are first registered to the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006) source frame to achieve better absolute astrometry before searching for reference objects. For NGC 4559 X-7 and M83 IXO 82, there are one and two reference objects, respectively, identified for image alignment. The corrected X-ray error circle of the ULX after alignment, taking into account of all uncertainties, is around 0′′.6 corresponding to the absolute astrometry error of Chandra. The arrow points north and has a length of 1″. For NGC 4559 X-7 and M83 IXO 82, the dashed circle is the corrected X-ray position after alignment. For NGC 2403 X-1, the dashed circle is the mean position of the two Chandra observations. A unique optical counterpart is identified for each source. Lower panels: SEDs of the ULXs and nearby sources. The nearby sources are marked on the images in the upper panel. In all three cases, the SED of the ULX counterpart is consistent with a single power law, while the nearby stars show a turnover at short wavelengths.

As a whole, a list of the 13 ULXs in our sample with related information, such as the distance to their host galaxies, Galactic extinction along the line of sight, their environmental associations, and the references, is shown in Table 1.

### 2.2. Photometry

The HST data used in the paper are observations with either the Advanced Camera for Surveys (ACS) instrument or the
For Holmberg IX X-1, the nebular extinction is found to vary radius; for NGC 2403 X-1, it is the absolute astrometry error of and j9h803010, respectively, for the three targets. 2014 Chandra ULX. photometry is performed on drizzled images produced from Wide-Field Planetary Camera 2 (WFPC2). For ACS data, the optical source located at about 0′′ from the counterpart of the ULX. To minimize the contamination, we used a smaller aperture correction error into the results. For WFPC2 data, the optical spectrum of ULXs may be treated as the lower limit. A Galactic reddening law (Cardelli et al. 1989) is assumed for reddening correction. Except for the small handful of images in the near UV (F330W filter), the resultant magnitude varies very little, by 0.002 typically, if we choose a different reddening law for the excessive extinction above the Milky Way, like that for the Small Magellanic Clouds where the metallicity is significantly lower. We hence use the Galactic reddening law for all objects despite the fact that metal-poor environments have been suggested for a few of them (e.g., Mirioni 2002; Soria et al. 2005).

A power-law spectrum is assumed to convert from the observed count rate or magnitude to the intrinsic flux or magnitude. We fit the intrinsic multiband spectrum after reddening correction with a power-law function, $F_\nu \propto \nu^\alpha$, where $\nu$ is the pivot frequency of the filter in Hz and $F_\nu$ is the flux in erg cm$^{-2}$ s$^{-1}$ Hz$^{-1}$. The same $\alpha$ is, in return, used for the assumed spectrum. A couple times of iterations are needed in the calculation until the fitted $\alpha$ is consistent with the input $\alpha$. Because we are only interested in the continuum component of the optical spectrum, data from narrow and medium bands are not used due to the possibility that the flux is dominated by emission lines. The optical spectrum of ULXs may be highly variable, thus only quasi-simultaneous observations executed within two days are used in the fits except for Holmberg II X-1, M81 ULS1, and NGC 5204 X-1, whose quasi-simultaneous observations only cover two bands, and spectra from different epochs are consistent with a single power law. A power-law relation is adequate to fit all spectra in the sample, except for a few sources where excessive flux in the F814W band is seen. We compared the properties of the ULX counterparts with nearby stars for the three newly identified sources, NGC 4559 X-7, M83 IXO 82, and NGC 2403 X-1, in Figure 1. The ULX counterparts differ from the nearby stars in that their spectral energy distributions (SEDs) are well fitted with a single power law, while those of the nearby stars show a roll over at short wavelengths, suggesting a blackbody-like spectrum with a moderate temperature. Also, the nearby stars are less luminous than the ULX counterpart. These trends are common to the whole sample. The dereddened magnitude in the observing band for the compact optical counterpart of each ULX from all observations is listed in the Appendix (Table 3).

2.3. Spectral Classification

Table 4 gives the absolute visual magnitudes and color indices for each quasi-simultaneous observation with at least three filters for each source, except for Holmberg II X-1, M81 ULS1, and NGC 5204 X-1, for which only two bands are available quasi-simultaneously and all their observations are listed. The most likely stellar spectral classification was inferred for each observation based on the magnitude and colors. For most sources, the classifications are not consistent with all the colors within one observation or the data from different observations suggest different spectral types for a given source. The exceptions are IC 342 X-1 and NGC 4559 X-7, which appear to be consistent with a fixed spectral type.

### Table 2

| Source           | Instrument | RA. (J2000.0) | Decl. (J2000.0) | $\Delta$ |
|------------------|------------|---------------|----------------|---------|
| NGC 4559 X-7     | Chandra    | 12 56 00.553  | +27 54 56.61   | 0.271   |
|                  | HST        | 12 56 00.554  | +27 54 56.67   | 0.052   |
| ULX              | Chandra    | 12 55 51.724  | +27 56 04.35   | 0.28    |
|                  | Corrected  | 12 55 51.725  | +27 56 04.41   |         |
| Counterpart HST  | 12 55 51.719 | +27 56 04.41  |               |         |
| M83 IXO 82       | Chandra    | 13 37 14.764  | −29 54 28.47   | 0.318   |
|                  | HST        | 13 37 14.761  | −29 54 28.26   |         |
| ULX              | Chandra    | 13 37 19.986  | −29 53 18.09   | 0.169   |
|                  | HST        | 13 37 19.979  | −29 53 17.68   |         |
| Counterpart HST  | 13 37 19.799 | −29 53 48.80  | 0.029          |
| NGC 2403 X-1     | Chandra    | 07 36 25.567  | +65 35 39.87   | 0.6     |
|                  | Mean       | 07 36 25.563  | +65 35 39.98   | 0.6     |
|                  | Corrected  | 07 36 25.562  | +65 35 39.93   | 0.42    |
| Counterpart HST  | 07 36 25.562 | +65 35 40.08  |               |         |

**Notes.** The Chandra observation used is 2686 for NGC 4559, 793 for M83, and 2014/4630 for NGC 2403. The HST data sets used are j92w02030, j9h811010, and j9h803010, respectively, for the three targets. $\Delta$ is the 90% statistical error radius; for NGC 2403 X-1, it is the absolute astrometry error of Chandra.

Wide-Field Planetary Camera 2 (WFPC2). For ACS data, the photometry is performed on drizzled images produced from standard pipeline calibration using the APPHOT package in IRAF with an aperture radius of 0′′.15–0′′.2. For Holmberg IX X-1, IC 342 X-1, and NGC 4559 X-7, each has a weak optical source located at about 0′′.2 from the counterpart of the ULX. To minimize the contamination, we used a smaller aperture with radius of 0′′.1–0′′.15 for photometry and added the aperture correction error into the results. For WFPC2 data, the photometry is performed on the c0f images using HSTPHOT 1.1, which outputs aperture-corrected VEGA magnitudes. As some sources are shown in crowded regions, the choice of background may slightly alter the derived net flux, which is particularly prominent for sources associated with an optical nebula that a flux difference up to 30% could arise whether or not the nebular emission is subtracted (e.g., Kaaret et al. 2010). Therefore, the uncertainty introduced by sky background subtraction is taken into account, estimated using various background regions or background estimate means.

The total extinction along the line of sight to the source is adopted in two ways. For those associated with an optical nebula and the extinction to the nebula has been measured from emission lines, the nebular extinction is adopted (see Table 1). Otherwise, we adopt Galactic extinction (Schlegel et al. 1998) for reddening correction. The extinction can also be estimated from the neutral hydrogen column density, which is derived via X-ray spectral fitting. For Holmberg II X-1, IC 342 X-1, M101 ULX-1, NGC 1313 X-2, NGC 5408 X-1, and NGC 6946 ULX-1, which reside in nebulae, the ratio of Galactic to nebular extinctions $(E_g/E_n)$ is 0.46, 0.69, 0.07, 0.65, 0.86, and 0.69, respectively, and the ratio of X-ray to nebular extinctions $(E_x/E_n)$ is 1.0, 1.42, 0.85, 3.0, 1.63, and 1.42, respectively. For Holmberg IX X-1, the nebular extinction is found to vary with position within the nebula from 0.09 to 0.26 (Grisé et al. 2011), and consequently causing $E_g/E_n$ to vary between 0.3 and 0.9, and $E_x/E_n$ between 1.3 and 3.9. It seems that $E_x$ often overestimate the total extinction. Plus, the X-ray column density usually varies dramatically, causing additional difficulty in deriving the extinction. Thus, we adopt Galactic extinction when the nebular extinction is unavailable, and this should be treated as the lower limit. A Galactic extinction law (Cardelli et al. 1989) is assumed for reddening correction. Except for the small handful of images in the near UV (F330W filter), the resultant magnitude varies very little, by 0.002 typically, if we choose a different reddening law for the excessive extinction above the Milky Way, like that for the Small Magellanic Clouds where the metallicity is significantly lower. We hence use the Galactic reddening law for all objects despite the fact that metal-poor environments have been suggested for a few of them (e.g., Mirioni 2002; Soria et al. 2005).

Table 4 gives the absolute visual magnitudes and color indices for each quasi-simultaneous observation with at least three filters for each source, except for Holmberg II X-1, M81 ULS1, and NGC 5204 X-1, for which only two bands are available quasi-simultaneously and all their observations are listed. The most likely stellar spectral classification was inferred for each observation based on the magnitude and colors. For most sources, the classifications are not consistent with all the colors within one observation or the data from different observations suggest different spectral types for a given source. The exceptions are IC 342 X-1 and NGC 4559 X-7, which appear to be consistent with a fixed spectral type.
| ULX          | Data Set | Instrument and Filter | Exposure (s) | $m_{\text{filter}}$ | $m_V$ |
|--------------|----------|-----------------------|--------------|---------------------|-------|
| Holmberg II X-1 | j8ol03010 | ACS/WFC/F814W         | 600          | 21.450 ± 0.029      |       |
|              | j8ol03040 | ACS/WFC/F435W         | 252          | 21.461 ± 0.021      |       |
|              | j8ol03070 | ACS/WFC/F606W         | 248          | 21.521 ± 0.079      | 21.651 ± 0.100 |
|              | j8ol03030 | ACS/WFC/F555W         | 1160         | 21.885 ± 0.042      |       |
|              | j8ol03075 | ACS/WFC/F555W         | 240          | 21.960 ± 0.021      | 21.992 ± 0.021 |
| Holmberg IX X-1 | j8el28aaq | ACS/WFC/F555W         | 1160         | 21.868 ± 0.028      | 21.901 ± 0.028 |
|              | j9el28aaq | ACS/WFC/F435W         | 1080         | 21.942 ± 0.094      |       |
|              | j9el28aaq | ACS/WFC/F555W         | 1080         | 21.667 ± 0.089      | 21.640 ± 0.089 |
| IC 342 X-1   | j8el0090 | ACS/WFC/F814W         | 120          | 20.965 ± 0.050      |       |
|              | j9el0090 | ACS/WFC/F555W         | 1650         | 20.019 ± 0.312      |       |
|              | j9el0090 | ACS/WFC/F555W         | 120          | 21.460 ± 0.034      | 21.541 ± 0.044 |
|              | j9el0090 | ACS/WFC/F555W         | 120          | 21.648 ± 0.020      |       |
|              | j9el0090 | ACS/WFC/F555W         | 465          | 22.026 ± 0.024      |       |
|              | j9el0090 | ACS/WFC/F555W         | 470          | 21.699 ± 0.032      | 21.811 ± 0.041 |
| M81 ULS1     | j8ol2009 | ACS/WFC/F555W         | 500/500      | 20.369 ± 0.075      |       |
|              | j8ol2009 | ACS/WFC/F555W         | 120          | 21.460 ± 0.034      | 21.541 ± 0.044 |
|              | j8ol2009 | ACS/WFC/F555W         | 120          | 21.648 ± 0.020      |       |
|              | j8ol2009 | ACS/WFC/F555W         | 465          | 22.026 ± 0.024      |       |
|              | j8ol2009 | ACS/WFC/F555W         | 470          | 21.699 ± 0.032      | 21.811 ± 0.041 |
| M81 X-6      | j9ol0010 | ACS/WFC/F555W         | 300/600      | 23.880 ± 0.060      | 23.894 ± 0.060 |
|              | j9ol0010 | ACS/WFC/F555W         | 300/600      | 23.958 ± 0.107      |       |
|              | j9ol0010 | ACS/WFC/F555W         | 400/160/600  | 21.939 ± 0.142      |       |
|              | j9ol0010 | ACS/WFC/F555W         | 300/600      | 23.955 ± 0.109      |       |
|              | j9ol0010 | ACS/WFC/F555W         | 500/500/500  | 23.782 ± 0.060      | 23.791 ± 0.060 |
|              | j9ol0010 | ACS/WFC/F555W         | 500/500/500  | 23.737 ± 0.077      |       |
|              | j9ol0010 | ACS/WFC/F555W         | 1650         | 23.580 ± 0.099      |       |
|              | j9ol0010 | ACS/WFC/F555W         | 600/600      | 23.618 ± 0.074      |       |
|              | j9ol0010 | ACS/WFC/F555W         | 500/600      | 23.879 ± 0.076      | 23.872 ± 0.076 |
|              | j9ol0010 | ACS/WFC/F555W         | 120          | 23.722 ± 0.029      |       |
|              | j9ol0010 | ACS/WFC/F555W         | 120          | 23.664 ± 0.054      | 23.717 ± 0.068 |
|              | j9ol0010 | ACS/WFC/F555W         | 450          | 23.789 ± 0.053      | 23.829 ± 0.068 |
|              | j9ol0010 | ACS/WFC/F555W         | 400          | 23.781 ± 0.043      |       |
| M83 IXO82    | j9el0010 | ACS/WFC/F555W         | 1000         | 25.132 ± 0.107      |       |
|              | j9el0010 | ACS/WFC/F555W         | 1000         | 25.512 ± 0.080      |       |
|              | j9el0010 | ACS/WFC/F555W         | 1000         | 25.132 ± 0.107      |       |
|              | j9el0010 | ACS/WFC/F555W         | 2568         | 24.156 ± 0.263      |       |
| M101 ULX1    | j9el0010 | ACS/WFC/F555W         | 1200         | 22.895 ± 0.026      | 22.898 ± 0.026 |
|              | j9el0010 | ACS/WFC/F555W         | 1200         | 22.712 ± 0.041      |       |
|              | j9el0010 | ACS/WFC/F555W         | 1200         | 22.813 ± 0.070      |       |
|              | j9el0010 | ACS/WFC/F555W         | 1200         | 23.022 ± 0.032      | 23.040 ± 0.032 |
|              | j9el0010 | ACS/WFC/F555W         | 1200         | 23.044 ± 0.049      |       |
|              | j9el0010 | ACS/WFC/F555W         | 1200         | 23.120 ± 0.031      | 23.133 ± 0.031 |
|              | j9el0010 | ACS/WFC/F555W         | 1200         | 22.884 ± 0.068      |       |
|              | j9el0010 | ACS/WFC/F555W         | 1200         | 21.143 ± 0.058      |       |
|              | j9el0010 | ACS/WFC/F555W         | 1200         | 23.009 ± 0.009      | 23.027 ± 0.059 |
|              | j9el0010 | ACS/WFC/F555W         | 1200         | 23.108 ± 0.031      | 23.126 ± 0.031 |
|              | j9el0010 | ACS/WFC/F555W         | 1200         | 23.160 ± 0.032      | 23.178 ± 0.032 |
|              | j9el0010 | ACS/WFC/F555W         | 1200         | 23.192 ± 0.040      | 23.210 ± 0.040 |
|              | j9el0010 | ACS/WFC/F555W         | 1200         | 23.167 ± 0.028      | 23.185 ± 0.028 |
|              | j9el0010 | ACS/WFC/F555W         | 1200         | 23.222 ± 0.033      | 23.240 ± 0.033 |
|              | j9el0010 | ACS/WFC/F555W         | 1200         | 23.249 ± 0.031      | 23.267 ± 0.031 |
|              | j9el0010 | ACS/WFC/F555W         | 1200         | 23.252 ± 0.070      |       |
|              | j9el0010 | ACS/WFC/F555W         | 1200         | 23.256 ± 0.022      | 23.274 ± 0.022 |
Table 3 (Continued)

| ULX       | Date        | Data Set   | Instrument and Filter | Exposure (s) | $m_{\text{FILTER}}$ | $m_{\text{V}}$ |
|-----------|-------------|------------|-----------------------|--------------|----------------------|--------------|
| NGC 1313 X-2 |            |            |                       |              |                      |              |
| 1994 May 10 | u2780b02t   | WFPC2/WF4/F814W | 1200                  | 23.316 ± 0.053 |                      |              |
| 1995 Mar 22 | u2780d01t   | WFPC2/WF4/F555W | 1200                  | 23.237 ± 0.034 | 23.255 ± 0.034      |              |
| 1995 Apr 17 | u2ms030[1][2] | ACS/WFC/F814W   | 500/500               | 23.208 ± 0.039 | 23.226 ± 0.039      |              |
| 2002 Nov 15 | j8d01031    | ACS/WFC/F555W   | 720                   | 23.315 ± 0.047 |                      |              |
| 2002 Nov 15 | j8d01021    | ACS/WFC/F555W   | 720                   | 23.261 ± 0.030 | 23.283 ± 0.030      |              |
| 2006 Dec 23 | j9o401020   | ACS/WFC/F555W   | 1330                  | 23.177 ± 0.014 | 23.199 ± 0.014      |              |
| 2006 Dec 23 | j9o401010   | ACS/WFC/F814W   | 724                   | 23.146 ± 0.033 |                      |              |
| 2006 Dec 24 | j9o402020   | ACS/WFC/F555W   | 1330                  | 23.167 ± 0.015 | 23.190 ± 0.015      |              |
| 2006 Dec 24 | j9o402010   | ACS/WFC/F814W   | 724                   | 23.116 ± 0.029 |                      |              |
| 2006 Dec 25 | j9o403020   | ACS/WFC/F555W   | 1330                  | 23.205 ± 0.015 | 23.227 ± 0.015      |              |
| 2006 Dec 25 | j9o403010   | ACS/WFC/F814W   | 724                   | 23.144 ± 0.027 |                      |              |
| 2006 Dec 26 | j9o404020   | ACS/WFC/F555W   | 1330                  | 23.181 ± 0.014 | 23.204 ± 0.014      |              |
| 2006 Dec 26 | j9o404010   | ACS/WFC/F814W   | 724                   | 23.183 ± 0.032 |                      |              |
| 2006 Dec 28 | j9o405020   | ACS/WFC/F555W   | 1330                  | 23.156 ± 0.015 | 23.178 ± 0.015      |              |
| 2006 Dec 28 | j9o405010   | ACS/WFC/F814W   | 724                   | 23.227 ± 0.030 |                      |              |
| 2006 Dec 30 | j9o406020   | ACS/WFC/F555W   | 1330                  | 23.201 ± 0.016 | 23.224 ± 0.016      |              |
| 2006 Dec 30 | j9o406010   | ACS/WFC/F555W   | 724                   | 23.119 ± 0.030 |                      |              |
| 2007 Jan 1  | j9o407020   | ACS/WFC/F555W   | 1330                  | 23.243 ± 0.015 | 23.266 ± 0.015      |              |
| 2007 Jan 1  | j9o407010   | ACS/WFC/F814W   | 724                   | 23.216 ± 0.030 |                      |              |
| 2007 Jan 4  | j9o408020   | ACS/WFC/F555W   | 1330                  | 23.249 ± 0.016 | 23.272 ± 0.016      |              |
| 2007 Jan 4  | j9o408010   | ACS/WFC/F814W   | 724                   | 23.221 ± 0.030 |                      |              |
| 2007 Jan 7  | j9o409020   | ACS/WFC/F555W   | 1330                  | 23.311 ± 0.017 | 23.334 ± 0.017      |              |
| 2007 Jan 7  | j9o409010   | ACS/WFC/F814W   | 724                   | 23.177 ± 0.031 |                      |              |
| 2007 Jan 11 | j9o410020   | ACS/WFC/F555W   | 1330                  | 23.179 ± 0.016 | 23.202 ± 0.016      |              |
| 2007 Jan 11 | j9o410010   | ACS/WFC/F814W   | 724                   | 23.069 ± 0.028 |                      |              |
| 2007 Jan 17 | j9o411020   | ACS/WFC/F555W   | 1330                  | 23.009 ± 0.012 | 23.031 ± 0.012      |              |
| 2007 Jan 17 | j9o411010   | ACS/WFC/F814W   | 724                   | 22.928 ± 0.025 |                      |              |
| 2007 Jan 21 | j9o412020   | ACS/WFC/F555W   | 1330                  | 23.081 ± 0.014 | 23.104 ± 0.014      |              |
| 2007 Jan 21 | j9o412010   | ACS/WFC/F814W   | 724                   | 23.054 ± 0.031 |                      |              |
| 2008 May 5  | uao3640[3][4]m | WFPC2/WF3/F555W | 500/500               | 22.642 ± 0.024 | 22.660 ± 0.024      |              |
| 2008 May 5  | uao3640[1][2]m | WFPC2/WF3/F814W | 350                   | 22.616 ± 0.048 |                      |              |
As a further check, we compared stellar models for the candidate classifications to all of the available data for each source and calculated the $\chi^2$ deviation of the (non-simultaneous) data from the stellar model normalized to the average $V$ magnitude. For NGC 1313 X-2 and M101 ULX-1, where there are a large number of observations available, we chose a subset of the data. The $\chi^2$ and degrees of freedom (dof) are reported in the table. In most cases, the fit to the stellar model is strongly excluded by the data. The exceptions are IC 342 X-1 and NGC 6946 X-1. IC 342 X-1 appears consistent with an F5I star both from the spectral fit and the colors noted above. NGC 6946 X-1 has a low $\chi^2$ because of the large uncertainty in its reddening correction. The $\chi^2$ of NGC 4559 X-7, which has a consistent spectral classification based on colors, is dominated by variability.

### 2.4. Distribution of Spectral Parameters

Diagrams of $M_V$ versus $\alpha$ and $M_V$ versus $(B-V)_0$ are shown in Figure 2 and the distribution of the optical colors is shown in Figure 3. A value for $\alpha$ is computed only when the spectrum has at least three bands, except for Holmberg II X-1, M81 ULS1, and NGC 5204 X-1, whose quasi-simultaneous spectra have only two points. The absolute magnitude $M_V$ is found in a wide range, from $-7$ to $-3$, for all sources. The spectral index $\alpha$ also appears in a wide range from $-0.6$ to around 2.0, but seems to have a distribution peaked between 1 and 2. The $\alpha$ of NGC 6946

### Table 3

(Continued)

| ULX          | Date       | Data Set | Instrument and Filter | Exposure (s) | $m_{\text{filter}}$ | $m_V$  |
|--------------|------------|----------|-----------------------|--------------|---------------------|-------|
| NGC 2403 X-1 | 2005 Oct 17 | j9h803020 | ACS/WFC/F606W        | 1248         | 24.564 ± 0.064     |       |
| NGC 4559 X-7 | 2001 May 25 | u6eh0509[9]abc[1]f | WFPC2/PC1/F814W | 500/500/500/500 | 23.139 ± 0.038     |       |
| NGC 5204 X-1 | 2001 May 28 | u6723901r  | WFPC2/PC1/F606W        | 600         | 22.492 ± 0.044     | 22.393 ± 0.089 |
| NGC 5408 X-1 | 2000 Jul 4  | u6724101r  | WFPC2/PC1/F606W        | 600         | 22.175 ± 0.020     | 22.161 ± 0.041 |
| NGC 6946 ULX-1| 1996 Jan 27| u33d1005    | WFPC2/PC1/F555W        | 400         | 21.268 ± 0.115     | 21.275 ± 0.115 |
|              | 1996 Jan 27| u33d1006[7][1]f | WFPC2/PC1/F439W        | 400/400     | 21.239 ± 0.184     |       |
|              | 2001 Jun 8  | u6eh0201[5]6[7][8]jr | WFPC2/PC1/F439W        | 500/500/500/500 | 20.905 ± 0.130     |       |
|              | 2001 Jun 8  | u6eh0201[1]2[3][4]jr | WFPC2/PC1/F555W        | 500/500/500/500 | 21.238 ± 0.122     | 21.267 ± 0.122 |
|              | 2004 Jul 29 | j8mxds8xxq   | ACS/WFC/F814W          | 120         | 21.450 ± 0.072     |       |

**Notes.** $m_{\text{filter}}$ is the magnitude quoted in the filter bandpass. $m_V$ is the magnitude in Johnson V, translated from F555W or F606W. All magnitudes are in Vega zero-point corrected for extinction.
Figure 2. Absolute visual magnitude $M_V$ vs. the spectral power-law index $\alpha$ (top) or vs. ($B - V$)$_0$ (bottom). The dotted lines at $\alpha = 1/3$ and $\alpha = 2$ are, respectively, the values expected for the intrinsic emission from a steady thin disk and for the Rayleigh–Jeans tail of a blackbody. Different points with the same color are from different observations of the same source. Sources for which the reddening was derived from an associated nebula are shown as triangles, while circles denote sources for which only Galactic reddening was assumed. The sources are (1) Holmberg II X-1, (2) Holmberg IX X-1, (3) IC 342 X-1, (4) M81 ULX1, (5) M81 X-6, (6) M83 IXO 82, (7) M101 ULX-1, (8) NGC 1313 X-2, (9) NGC 2403 X-1, (10) NGC 4559 X-7, (11) NGC 5204 X-1, (12) NGC 5408 X-1, and (13) NGC 6946 ULX-1.

ULX-1, NGC 5204 X-1, and Holmberg IX X-1 is consistent with 2.0, which is the slope of the Rayleigh–Jeans tail of a blackbody spectrum. The $\alpha$ of most sources is less than 2.0, consistent with the fact that no thermal emission can produce a spectrum with $\alpha > 2$. It is worth noting that the derived $\alpha$ is sensitive to the extinction that is assumed; higher extinction leads to larger $\alpha$. Here, many sources are assumed to have Galactic extinction, which may be lower than the total extinction by 30% or so (see the $E_g/E_n$ ratios above). Taking this factor into account, it is likely that the peak of $\alpha$ distribution is slightly larger and close to two. The $\alpha$ expected for the intrinsic emission from a steady thin disk is 1/3, which, however, is inconsistent with most sources except NGC 2403 X-1.

2.5. Long-term Variation

$F555W$ and $F606W$ are the two filters used most often in our sample. Magnitudes in Johnson $V$ were calculated from these two bands to examine variability (see Table 3). The observed range in the $V$ band, $V_{\text{max}} - V_{\text{min}}$, was calculated for each source and is shown in Table 5.

For M101 ULX-1 and NGC 1313 X-2, multiple quasi-simultaneous observations in two bands are available, allowing us to investigate long-term variability. Not only the magnitude, but also the color index, varies significantly; see light curves of ($F555W - F814W$)$_0$ for M101 ULX-1 and of ($F450W - F555W$)$_0$ for NGC 1313 X-2 in Figure 4. For M101, we plotted ACS data from 2006 December 23 to 2007 January 21. For NGC 1313 X-2, all WFPC2 data are plotted. We have checked light curves obtained using different sky background subtractions and they show the same variation pattern, suggesting that the variability does not arise from the background. For each ULX, a nearby comparison object was chosen to examine instrumental effects. For M101 ULX-1, fitting with a constant results in $\chi^2$/dof of 2.6 and 0.6, respectively, for the ULX and the comparison object. For NGC 1313 X-2, the color seems to be constant during the first three quarters of the total observing window, but exhibits large variation in the last six observations. Fitting with a constant for the last six colors, the $\chi^2$/dof is 3.6 and 0.8, respectively, for the ULX and the comparison object.

Change of the intrinsic emission or the extinction along the line of sight could both give rise to the observed color variation. Assuming constant intrinsic emission, the change of extinction can be directly derived from the change of observed magnitude in each band. However, for each source the inferred extinctions
at the two bands do not agree with each other. Therefore, pure extinction variation can be ruled out as the nature of the observed variability, and variation of the intrinsic optical emission is required. The irregular nature of the variability indicates that it cannot be completely caused by a periodic phenomenon, such as ellipsoidal variations. Changes in X-ray illumination, perhaps due to changes in the mass accretion rate, could cause the observed variability. Indeed, for NGC 1313 X-2, as previously shown by Impriombato et al. (2011), the variability is higher in the B band ($F_{B}$) than in the V band ($F_{V}$), suggesting that the variability arises from X-ray irradiation. Unfortunately, there were no suitable contemporaneous X-ray observations that would allow us to study the correlation between X-ray and optical variability.

### 2.6. X-Ray to Optical Flux Ratio

The X-ray to optical flux ratio, defined following Maccacaro et al. (1982) as $\log(f_X/f_V) = \log f_X + m_V/2.5 + 5.37$, where $f_X$ is the X-ray flux in erg cm$^{-2}$ s$^{-1}$ and $m_V$ is the visual magnitude, is calculated for each source. This value can be used to distinguish active galactic nuclei (AGNs), BL Lac objects, clusters of galaxies, normal galaxies, normal stars, and X-ray binaries (Stocke et al. 1991). Another form of the X-ray to optical flux ratio as $\xi = B_0 + 2.5 \log F_X$ has been proposed to distinguish between low-mass X-ray binaries (LMXBs) and high-mass X-ray binaries (HMXBs), where $B_0$ is the dereddened $B$ magnitude and $F_X$ is the X-ray flux in $\mu$Jy (van Paradijs & McClintock 1995).

Due to the highly variable nature of these sources, simultaneous X-ray and optical observations may be needed to calculate the flux ratio. Holmberg IX X-1 and NGC 1313 X-2 are the only two sources in our sample for which simultaneous X-ray and optical observations are available. For the Chandra observation of Holmberg IX X-1 on 2004 February 7, the pileup effect is manageable; its X-ray flux is derived by fitting the spectrum with a power-law model subject to absorption and pileup. For the Chandra observation of NGC 1313 X-2 on 2004 February 22, the source is placed on the chip with a large offset, such that the pileup is negligible; an absorbed power-law model is used to fit the spectrum.

M101 ULX-1 and M81 ULX1 are the two most variable X-ray sources in our sample. The typical X-ray luminosity of M101 ULX-1 is about $2 \times 10^{37}$ erg s$^{-1}$ in the low state in 0.3–7 keV (Kong et al. 2004), or a bolometric luminosity of $3 \times 10^{39}$ erg s$^{-1}$ in the high state (Mukai et al. 2005). For M81 ULX1, the $0.3–8$ keV flux is $9.3 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ in the low state and $5.3 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ in the high state (Liu 2008). The optical flux does not appear to vary as much as in the X-ray band. We thus calculate two sets of $\log(f_X/f_V)$ and $\xi$ using the high- and low-state X-ray fluxes, respectively. As M81 ULX1 and M101 ULX-1 are very soft and radiate most of their fluxes below 2 keV, the 2–10 keV flux calculated from models in the literature may be inaccurate as model parameters were mainly obtained by fitting the spectrum in the low energy band. Therefore, we measured Chandra count rates in the 2–7 keV band and converted these to fluxes in the 2–10 keV band. This conversion was done using the power-law index (but not normalization) of the best-fit models from

### Table 4

| ULX            | Date        | $M_V$ | $U - B$ | $B - V$ | $V - I$ | $V - R$ | Sp.          | $\chi^2$/dof |
|----------------|-------------|-------|---------|---------|---------|---------|--------------|--------------|
| Holmberg II X-1| 2006 Dec 30 | −6.00 | ...     | ...     | −0.02   | ...     | B6–B7 Ib–Iab | B0 I, 112.4/8; B0.5 I, 70.6/8; |
|                | 2007 Oct 3  | −5.93 | ...     | −0.24   | ...     | ...     | B0–B1 Ib    | B5 I, 73.5/8  |
|                | 2007 Oct 7  | −5.94 | ...     | −0.18   | ...     | ...     | B1–B2 Ib    |              |
|                | 2007 Oct 9  | −5.94 | ...     | −0.27   | ...     | ...     | O9–B0 Ib    |              |
| Holmberg IX X-1| 2004 Feb 7  | −5.88 | −1.33   | −0.42   | −0.04 a| ...     | O5V, O6III  | O3 V, 232.3/4; O5 V, 253.3/4 |
| IC 342 X-1     | 2005 Sep 2  | −5.94 | >−0.77  | 0.37    | ...     | ...     | F5 Ib–Iab   | F5 I, 10.7/5  |
|                | 2005 Dec 18 | −5.95 | ...     | 0.30    | 0.60/0.38| ...     | F5 Ib–Iab   |              |
| M81 ULS1       | 2006 Mar 21 | −6.26 | ...     | 0.11    | ...     | ...     | A5–A7 Iab   | F2 I, 424.1/6; F5 I, 418.3/6; |
|                | 2006 Mar 27 | −5.99 | ...     | 0.22    | ...     | ...     | F2–Iab      | F8 I, 786.3/6; G0 I, 1505.1/6 |
| M81 X-6        | 1995 Jan 31 | −3.91 | −1.51 a| 0.06    | −0.05   | −0.06   | B5–A3 II    | B2 II, 78.6/14; B5 II, 61.6/14 |
|                | 2001 Jun 4  | −4.01 | ...     | −0.13   | 0.07 a  | ...     | B7–B8 II    |              |
| M83 IXO 82     | 2006 Feb 25 | −3.11 | −0.96 a| 0.26    | ...     | ...     | A2–F2 II, B1 V| F0 II, 16.2/2; F2 II, 11.5/2; |
|                | 2006 Oct 17 | −2.90 | −1.01   | 0.07 a  | ...     | ...     | B0–B2 V     | B1 I, 21.7/2  |
| M101 ULX-1     | 1994 Mar 22 | −6.39 | ...     | −0.11   | 0.20 a  | ...     | B5 Iab, A3 Iab| O5 I, 412.8/9; O8 I, 334.2/9; |
|                | 1994 Apr 8  | −6.15 | −1.20   | −0.28   | 0.10 a  | ...     | O5 III, O8 II| B5 I, 320.1/9 |
|                | 2002 Nov 15 | −6.00 | ...     | −0.31   | −0.01 a| ...     | O5 III, O8–O9 II, B7 Ib |              |
| NGC 1313 X-2   | 2003 Nov 22 | −4.61 | −1.14   | −0.26   | −0.09 a| ...     | O9V, B0–B1 III| O9 V, 76.4/3; B0 III, 62.7/3; B1 I, 153.1/3 |
| NGC 2403 X-1   | 2005 Oct 17 | −2.90 | −1.01   | 0.07 a  | ...     | ...     | B0–B2 V     | B0 V, 33.6/2; B1 V, 28.5/2; |
| NGC 4559 X-7   | 2001 May 25 | −6.98 | ...     | −0.17   | −0.11  | ...     | B2–B5 Ia    | B5 I, 26.0/6  |
| NGC 5204 X-1   | 2005 Mar 8  | −7.10 | ...     | −0.12   | −0.06   | ...     | B3–B5 Ia    |              |
| NGC 5204 X-1   | 2001 May 27 | −5.77 | ...     | −0.52   | ...     | ...     | O5V         | O9 III, 33.8/9; B0 I, 25.7/9; |
| NGC 6946 ULX-1 | 1996 Jan 27 | −7.26 | ...     | −0.07   | ...     | ...     | B6–B7 Ia    | O5 I, 8.3/5; O8 I, 7.3/5; |
| NGC 6946 ULX-1 | 2001 Jun 8  | −7.27 | ...     | −0.42 a| −0.21   | ...     | B2 Ia       | B0 I, 4.3/5; B5 I, 6.0/5 |

Note. a Color that does not agree with the best-fit spectral type.

### Table 4

Absolute Visual Magnitudes, Colors, and spectral classifications of the ULXs in the Sample
Figure 4. Color variation of M101 ULX-1 and NGC 1313 X-2 (plus) and comparison objects (diamond). For the comparison object of M101 ULX-1, its flux on MJD 54096 was affected by cosmic rays and thus not plotted.

Figure 5. Distributions of the X-ray to optical flux ratio, defined as log($f_X/f_V$) or $\xi$, for ULXs in the sample, LMXBs, and HMXBs. M81 ULS1 is not detected in 2–10 keV in the low state, and thus the left arrow indicates its upper limit.

the literature and response matrices calculated at the source position. M81 ULS1 is not detected in the 2–10 keV band in the low state and we thus adopted an upper limit on the flux calculated from the measured upper limit on the count rate.

For other sources, their X-ray flux variability is usually less than a factor of ten or even five, which does not affect the X-ray to optical flux ratio significantly. We thus adopted a typical model for each source from the literature\(^3\) and calculated the flux given the above energy bands. The X-ray fluxes and the X-ray to optical flux ratios are listed in Table 5.

The distribution of log($f_X/f_V$) and $\xi$ of ULXs in the sample are plotted in Figure 5. The $\xi$ distributions of LMXBs and HMXBs from van Paradijs & McClintock (1995) are displayed for comparison. We note that the three of the 13 LMXBs and three of the seven HMXBs in the comparison sample are black hole candidates. For HMXBs, different types are separately indicated as in the reference. $\xi$ of most ULXs in the sample is consistent with that of LMXBs and is statistically higher than the distribution of HMXBs. The X-ray to optical ratios of M101 ULX-1 and M81 ULS1 at the low state are significantly lower than those of other ULXs. At the low state, their log($f_X/f_V$) is around zero, consistent with that of AGN, and their $\xi$ is lower than that of LMXBs, but similar to HMXBs.

3. DISCUSSION

We have analyzed the largest sample to date of HST observations of ULXs with a unique compact optical counterpart, including three new identifications and ten counterparts identified in the literature. For each source, we measured the broadband optical SED, its variation, and the X-ray to optical flux ratio. In the following, we discuss constraints on the nature of ULXs and their optical emission derived from our results.

3.1. Origin of the Optical Emission

X-ray variability rules out that ULXs are clusters of galaxies, normal galaxies, or normal stars. The log($f_X/f_V$) distribution of ULX in our sample, peaked around three, suggests that most of them are X-ray binaries instead of AGNs or BL Lac objects, whose log($f_X/f_V$) ranges from $-1$ to 1.2 or 0.3 to 1.7, respectively (Stocke et al. 1991).

Optical light from an X-ray binary can arise from the companion star, direct emission from the accretion disk, reprocessing of X-rays from the inner disk in the outer disk, or some combination of the above. If the optical light is dominated by the companion star, then the optical colors in all observations should be consistent with a single spectral type and the optical variability

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\(^3\) Holmberg II X-1, IC 342 X-1, and NGC 5204 X-1 (Feng & Kaaret 2009); M81 X-6 (Mizuno el al. 2001) M83 X0 82 (Stobbart et al. 2006); NGC 1313 X-2 (Feng & Kaaret 2007); NGC 2403 X-1 (Feng & Kaaret 2005); NGC 4559 X-7 (Stobbart et al. 2006); NGC 5408 X-1 (Kaaret & Feng 2009); NGC 6946 ULX-1 (Kajava & Poutanen 2009).
should be low. The only variable stars with colors and magnitudes similar to those of most ULX counterparts are β-Cepheid and PV Telescopii stars; such star have variabilities of 0.1 mag or less (Stankov & Handler 2005; Jeffery 2008); even heated companion stars, which would vary in an ellipsoidal pattern, are ruled out due to the irregular variation of most ULXs. If the optical light is dominated by direct emission from a multi-color disk blackbody (MCD), then the optical SED should have a \( \nu^{1/3} \) form consistent with extrapolation of the X-ray spectrum and there should be significant optical variability. If the optical light is dominated by reprocessing of X-ray in the outer accretion disk, then the optical SED should have a roughly power-law form with an index between about \(-1\) and \(2\) (Gierliński et al. 2009) and, again, there should be significant optical variability, correlated with the X-ray variability. Also, the X-ray to optical flux ratio should be similar to those observed from LMXBs, in which the optical light is usually dominated by reprocessing of X-ray in the outer accretion disk when in active states. If the companion and disk produce comparable optical fluxes, then the variability would be reduced relative to that expected from a disk alone and the SED would be a combination of a roughly power-law and a blackbody form. The observed \( \xi \), variability, stellar spectrum fitting, and spectral index are used as evaluation criteria for different models in Table 6. These properties favor the irradiated disk model for most sources.

The distributions of \( \xi \), \((B - V)_{0}\), and \((U - B)_{0}\) of ULXs in the sample appear to be similar to LMXBs, see Figures 3 and 5. This does not mean that ULXs actually contain low-mass companions, but suggests that the optical spectra of ULXs are dominated by emission from the disk instead of the companion star. The fact that the whole optical SED of most ULXs cannot be matched with a single spectral type, see Table 4, is further evidence that the optical emission is not dominated by the companion stars.

Some sources show significant optical variability: M101 ULX-1, M81 ULS1, NGC 1313 X-2, and NGC 5204 X-1. Notably, both sources for which there are more than ten observations, M101 ULX-1 and NGC 1313 X-2, show significant variability. The non-detection of optical variability in the other sources may be due to the limited number of observations available. Further, these two sources also show color variations that cannot be explained as solely due to changes in extinction, there must be intrinsic changes in the optical spectra. The detected optical variability is 0.2 mag or larger. The only variable stars with colors and magnitudes similar to those of the ULX counterparts are β-Cepheid and PV Telescopii stars. However, such stars have variabilities of 0.1 mag or less (Stankov & Handler 2005; Jeffery 2008). Thus, the variability is inconsistent with a scenario in which the companion star dominates the optical light. The variability is consistent with the assertion that the optical light from ULXs is dominated by emission from the disk.

The optical spectral index \( \alpha \), see Figure 2, for most of the ULXs in our sample lies in the range \( \alpha = -1 \) to 2. Irradiated disks can produce optical spectra with such slopes (Gierliński et al. 2009). A spectrum with \( \alpha = 2 \) corresponds to the Rayleigh–Jeans tail of thermal emission and would be produced if all of the optically emitting regions have temperatures above \(\sim 2 \times 10^4 \) K corresponding to the shortest wavelength of the observed optical photons. Spectral indices between \(-1\) and 2 suggest that there are optically emitting regions of the disk with temperatures down to \(\sim 6000 \) K. Variations in the optical brightness and spectral slope of the reprocessed emission could be produced by variations in the X-ray flux from of the central
object, the disk radius, or the fraction of flux intercepted by the outer disk.

A B0 Ib supergiant companion has been suggested for NGC 5204 X-1 based on UV spectroscopy (Liu et al. 2004). We re-examined the data but found that the Si iv 1299 Å line that was used for the classification lies close to the strong geocoronal O iv 1304 Å line, and is thus suspicious. A background spectrum also shows a similar absorption feature. Plus, characteristic absorption lines such as C iv and Si iv seen in typical B0 Ib spectra do not appear in the spectrum of NGC 5204 X-1. In the current study, the source displays remarkable variation in color or spectral index, see source 11 in Figure 2, that could not be produced if the optical emission is dominated by light from the companion star. Also, the X-ray to optical flux ratio is consistent with that for an LMXB. We therefore argue that the optical/UV emission of NGC 5204 X-1 is dominated by the accretion disk and not by a supergiant companion star.

3.2. Size of the Optically Emitting Region

If the optical light is due to thermal emission, then the size of the emitting region can be estimated from the flux density measured at a particular frequency using Planck’s law if the temperature and distance to the source are known. Assuming a simple blackbody model for the optical emission, the measurements for Holmberg IX X-1 suggest an emitting region size of \( \sim 3 \times 10^{12} \text{ cm} \) for a distance of 3.6 Mpc and a blackbody temperature of \( T = 2 \times 10^4 \text{ K} \). The size estimate decreases by a factor of \( \sim 5 \) if the assumed temperature is increased by a factor of ten to \( T = 2 \times 10^5 \text{ K} \). The size depends more sensitively on temperature for lower temperatures; it increases by a factor of two if the temperature is decreased to \( T = 1 \times 10^4 \text{ K} \) and a factor of nine for \( T = 5000 \text{ K} \). Temperatures lower than 5000 K appear to be excluded by the optical spectral shape for most of the sources.

It is possible to check if the size of the emitting region is consistent with a picture in which the optical emission is due to reprocessing. Assuming a fraction \( \eta \) of the X-ray luminosity \( L_X \) is reprocessed, then \( \eta = \sigma T^4 A/L_X \) where \( T \) and \( A \) are the temperature and area, respectively, of the reprocessing region and \( \sigma \) is the Stefan–Boltzmann constant. Inserting \( T = 2 \times 10^4 \text{ K}, A = 1 \times 10^{24} \text{ cm}^2, \) and \( L_X = 1 \times 10^{40} \text{ erg s}^{-1} \), we find \( \eta \sim 0.001 \). This is similar to values found for the Galactic black hole X-ray binary XTE J1817−330 when in soft spectral states similar to those usually observed from ULXs (Gierliński et al. 2009). Thus, again, the properties of the optical emission appear to be consistent with reprocessing.

The Milky Way black hole binary with the longest orbital period, GRS 1915+105, has a separation of \( 8 \times 10^{12} \text{ cm} \) and an outer disk radius of \( 5 \times 10^{12} \text{ cm} \), comparable to the values discussed here. The 60 day X-ray periodicity seen from M82 X-1 (Kaaret & Feng 2007) is longer than that of GRS 1915+105, suggesting a larger orbital separation. The binary separation of M82 X-1 is estimated to be a few times \( 10^{13} \text{ cm} \) (Feng & Kaaret 2010). In general, large accretion disks, of order \( 10^{12} \text{ cm}, \) would require long orbital periods. Following Frank et al. (2002), the disk outer radius should be smaller than the circularization radius, \( R_c \), for matter flowing through the Lagrangian point toward the black hole. The orbital period is related to \( R_c \) as

\[
\left( \frac{P}{\text{day}} \right) = \left( \frac{R_c}{2.9 \times 10^{11} \text{ cm}} \right)^{3/2} f^{-3/2} \left( \frac{M_X}{M_\odot} \right)^{-1/2},
\]

where \( M_X \) is the mass of the accretor and \( f = (1 + q)^{1/3}[0.5 - 0.227 \log q]^4 \) is a function of the mass ratio \( q = M_c/M_X \), and \( M_c \) is the companion mass. Requiring \( R > 10^{12} \text{ cm}, \) for \( M_X = 10 M_\odot \) and \( q = 0.1 \), we find that \( P > 11 \text{ days} \). This would be a \( 1 M_\odot \) companion. The period is longer if the companion is heavier, e.g., \( P > 26 \text{ days} \) for \( q = 0.5 \). Shorter periods would be possible for more massive black holes.

3.3. Comparison with Binary Synthesis Models

The \( M_V \) versus \( (B - V)_0 \) diagram can be compared directly with that obtained from binary population synthesis, in which

| ULX      | Stellar Spectrum | Spectral Index | Variability | Models       |
|----------|------------------|----------------|-------------|--------------|
| Holmberg II X-1 | M                | B              | R           | +            |
| Holmberg IX X-1  | M                | B              | R           | +            |
| IC 342 X-1       | N                | G              | R           | ++       |
| M81 ULS1         | V                | B              | R           | +            |
| M81 X-6          | M                | B              | R           | +            |
| M83 3XO 82       |         |                |             |              |
| M101 ULX-1       | V                | B              | R           | ++       |
| NGC 1313 X-2     | V                | B              | R           | ++       |
| NGC 2404 X-1     | V                | B              | D           | 0          |
| NGC 4559 X-7     | M                | B              | R           | +            |
| NGC 5204 X-1     | V                | B              | R           | ++       |
| NGC 5408 X-1     | H                | N              | R           |              |
| NGC 6946 ULX-1   | H                | N              | G           | ++       |

Notes. \( \xi \): those sources whose \( \xi \) is larger than 18 are marked as L; otherwise, they are marked as H. Variability: \( V, M, \) and \( N \) are used for those sources whose \( V_{\text{max}} - V_{\text{min}} \geq 4 \) error, 4 error > \( V_{\text{max}} - V_{\text{min}} \geq 2 \) error, and \( V_{\text{max}} - V_{\text{min}} < \) error, respectively. Stellar spectrum: using \( \chi^2/\text{dof} \) in Table 4 to calculate the probability \( P \) that a random variable \( \chi^2 \) is less than equal to observed \( \chi^2 \). The stellar spectrum fitting is bad (B) if \( P > 99\% \); otherwise, it is good (G). Spectral index: D is used if \( \alpha \) is consistent with 1/3 within errors; otherwise, R is used. Star: ++ if stellar spectrum fitting is good and variability is H, - if stellar spectrum fitting is bad or variability is V. Irradiated disk: ++ if \( \xi = L \) and spectral index = R and variability = V, + if \( \xi = L \) and spectral index = R and variability \( \neq V \) or \( \xi = H \) and spectral index = R and variability = V, 0 if \( \xi = L \) and spectral index \( \neq R \) and variability \( \neq V \) or \( \xi = H \) and spectral index = R and variability \( \neq V \). Direct disk: + if spectral index = D, - if spectral index = R. The rate of how strongly the model is recommended should be based on the decreasing from ++ to -.
they assume the optical spectrum comprised of emission from both a steady thin disk and the companion (Madhusudhan et al. 2008). Based on their models, the most likely color of ULXs is about \((B - V)_0 = -0.3\) to \(-0.2\) independent of the mass of the accretor. However, ULXs with an intermediate-mass black hole are brighter than those with a super-Eddington stellar mass black hole of the same luminosity, with the most probable \(M_V \approx -6\) for the former and \(M_V \approx -4\) for the latter. Our results are consistent with their model that most ULXs have a \((B - V)_0\) color about \(-0.3\) to \(-0.2\). The concentration of most sources at \(M_V \approx -6\) would suggest that most ULXs in our sample contain intermediate-mass black holes. However, we note that this result is model dependent. Other binary evolution models with different assumptions, i.e., that some mass is lost from the system rather than all mass being accreted (Patruno & Zampieri 2010), could lead to different conclusions.

3.4. NGC 2403 X-1 and M83 IXO 82: Intrinsic Disk Emission?

NGC 2403 X-1 has an optical spectral index consistent with that expected, \(\alpha = 1/3\), for the intrinsic emission of a standard MCD. Assuming \(\alpha = 1/3\), its optical spectrum can be written as \(F_\nu = 6 \times 10^{-35} (\nu/1\text{ Hz})^{1/3} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1}\). A face-on standard disk at 3.2 Mpc with an inner temperature \(kT_{\text{in}} = 1\) keV and a bolometric luminosity \(L_{\text{bol}} = 3 \times 10^{40} \text{ erg s}^{-1}\), or with \(kT_{\text{in}} = 0.1\) keV and \(L_{\text{bol}} = 10^{39} \text{ erg s}^{-1}\), can produce an optical tail consistent with the observed spectrum. The measured X-ray luminosity for the source ranges from 3 to 9 \(\times 10^{39} \text{ erg s}^{-1}\) (Feng & Kaaret 2009), which is in the required range. Thus, the optical emission for this source may be dominated by intrinsic emission from an accretion disk. However, simultaneous X-ray and optical/UV observations are needed to test this hypothesis.

The optical spectrum of M83 IXO 82 could be consistent with the \(\alpha = 1/3\) expected for intrinsic emission of a standard MCD if our assumed reddening is incorrect. We calculated the reddening assuming only Galactic absorption of \(E(B-V) = 0.066\). Additional intrinsic absorption of \(E(B-V) = 0.111\) would make \(\alpha\) consistent with \(1/3\). This source shows an absolute visual magnitude, \(M_V \sim -3\), and an X-ray luminosity, \(L_X \sim 2 \times 10^{39} \text{ erg s}^{-1}\) (Feng & Kaaret 2005), similar to that of NGC 2403 X-1. Thus, this source is also a good candidate to have optical emission dominated by intrinsic emission from an accretion disk.

3.5. M101 ULX-1 and M81 ULS1

M101 ULX-1 and M81 ULS1 are exceptional cases owing to their strong X-ray variability and deviation from the main population in the X-ray to optical flux ratio distributions. Especially when in the low state, their X-ray to optical flux ratios are consistent with that of AGNs. However, detection of variability on timescales of \(10^3\) s from both sources (Mukai et al. 2005; Liu 2008), more rapid than the X-ray variability seen from AGNs, makes an AGN identification unlikely. The X-ray to optical flux ratio of the two sources is consistent with that of HMXBs. Many Galactic HXMBs, especially with a neutron star accretor, are transient sources with huge variability due to uneven wind-fed accretion in an elliptical orbit. The high luminosity and moderate absorption column density of these ULXs suggest that they are Roche-lobe overflow systems, where circular orbits are often presumed. However, the large long-term variability of these two systems may suggest eccentric orbits.

The optical spectral properties of the two sources are different. The SED of M101 ULX-1 at three epochs is shown in Figure 6.

There is variability at every waveband where there are multiple observations and the variations are stronger at long wavelengths. The variability could be explained in a disk irradiation as due to changes in the outer disk radius. If the blue wing of the spectrum is due to companion light, then a very hot star would be required. We note that Liu (2009) fitted the same data using the sum of a Wolf–Rayet star, an irradiated disk described by an \(\alpha = -1\) spectrum, and an additional hot component ascribed to the X-ray heated side of the companion. We note that more complex irradiated disk models (Gierliński et al. 2009) can produce the extra hot component needed by Liu (2009) in the inner regions of the disk without need of an additional physical surface.

In contrast, the optical spectrum of M81 ULS1 is significantly shallower. At least for one observation, the spectrum could be consistent with \(\alpha = 1/3\), as expected for intrinsic emission of a standard MCD if there is additional reddening beyond the Galactic value assumed in our analysis. We note that Liu et al. (2008) modeled the blue part of the optical spectrum as being due to direct disk emission. However, this modeling was based on simultaneous fitting of HST observations obtained over a period of four years. Given the highly variable nature of the source, it is important to better constrain the spectral behavior with simultaneous observations extending into the UV.

3.6. IC 342 X-1: A Single Blackbody?

The spectrum from IC 342 X-1 on 2005 December can be equally well fitted by a power-law spectrum with \(\alpha = -0.62 \pm 0.18\), or a blackbody spectrum with a temperature of \(7100 \pm 400\) K, see Figure 7. However, the spectrum from 2005 September shows a cutoff in the F330W band, inconsistent with the power law. Fitting to the combined data favors the blackbody model.

Such blackbody emission could arise from a companion star. There is no evidence of optical variability and a spectral classification of F5 Ib or F8 Ib fits all the data available at both observation epochs. If the reddening is less than the nebular value we have assumed, then the star would be a later spectral type, i.e., F8-G0 Ib (Feng & Kaaret 2008). Such blackbody emission could also arise from irradiation in a very large disk. For IC 342 X-1, the blackbody fitting suggests a surface area of \(6 \times 10^{26} \text{ cm}^2\), or a reflector radius of \(10^{13} \text{ cm}\), which is about an order of magnitude larger than the value inferred for the majority
The dotted line indicates a power-law model fitted to the short wavelength (Pakull & Mirioni 2002) with a measured nebular extinction to distinguish between these two possibilities. New observations with multiple bands at several epochs could test for optical variability and low X-ray to optical flux ratios. These systems may have eccentric orbits.

4. CONCLUSIONS

1. The dominant component of optical emission in most ULXs is produced via X-ray irradiation of the outer accretion disk, similar to the case of LMXBs.
2. As a corollary, one cannot use broadband optical colors to infer the companion spectral type.
3. Large optical emitting regions are required, suggesting relatively large orbital separations and long orbital periods.
4. The optical spectrum and X-ray luminosity of NGC 2403 X-1 are consistent with both arising from intrinsic emission from a standard accretion disk. M83 1XO 82 is a somewhat weaker candidate for intrinsic disk emission extending into the optical.
5. M101 ULX-1 and M81 ULS1 are unique in high X-ray variability and low X-ray to optical flux ratios. These systems may have eccentric orbits.
6. IC 342 X-1 has a spectrum quite different from that of most ULXs and the optical emission may be dominated by an F5 or somewhat later supergiant companion star.
7. NGC 5204 X-1 seems not to be physically related to the nearby optical nebulae due to inconsistent extinction.

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