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New *Hubble Space Telescope* imaging of the counterparts to six ultraluminous X-ray sources

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ABSTRACT

We report the results of new *Hubble Space Telescope* imaging of the positions of six ultraluminous X-ray sources (ULXs). Using images in three Advanced Camera for Surveys (ACS) filters, we detect good candidate counterparts to four out of six ULXs, with one more possible detection, and observed magnitudes in the range $m \sim 22$–26 in the $F606W$ filter. The extinction-corrected colours and absolute magnitudes vary from source to source, even after correcting for additional extinction in the host galaxy, and only one counterpart is readily explained as an OB star. Nevertheless, these counterparts are decent candidates for future follow-up in pursuit of dynamical mass constraints on the likely black holes powering these sources.

Key words: black hole physics – X-rays: binaries – X-rays: galaxies.

1 INTRODUCTION

The ongoing controversy regarding the true nature of the so-called 'ultraluminous X-ray sources' (ULXs) stems from the simple fact that their extraordinary observed X-ray luminosities, at $>10^{39}$ erg s^{-1} in the 0.5–10 keV band alone, exceeds the Eddington limit for the stellar-mass black holes we observe in our own Galaxy. An obvious solution to this problem is that the black holes underlying ULXs are bigger, perhaps 2–3 orders of magnitude more massive [i.e. intermediate-mass black holes (IMBHs) with $M_{\rm BH} \sim 10^2$–10^4 M$_\odot$, e.g. Colbert & Mushotzky 1999]. The best supporting evidence for IMBHs derived from X-ray spectroscopy of luminous ULXs, that showed possible cool accretion disc spectral components, having temperatures consistent with discs around $\sim$1000 M$_\odot$ black holes (e.g. Miller, Fabian & Miller 2004). In some cases, this argument was supplemented by further evidence, for example the QPO detections from M82 X-1 (Strohmayer & Mushotzky 2003). However, there are strong arguments for the majority of ULXs possessing stellar-mass black holes, not least the high abundance of such objects in the most extreme star-forming environments (King 2004). Indeed, detailed re-evaluations of the X-ray spectra of ULXs have questioned whether the apparent cool accretion discs really do imply the presence of IMBHs (e.g. Goncalves & Soria 2006; Stobbart, Roberts & Wilms 2006). If ULXs do not contain the $\sim$1000 M$_\odot$ IMBHs suggested by cool discs, then the physical processes by which smaller black holes (stellar mass, or perhaps up to $\sim$100 M$_\odot$, cf. Stobbart et al. 2006) appear so luminous may include anisotropic radiation, relativistic beaming and/or truly super-Eddington emission (e.g. King et al. 2001; Begelman 2002; Körding, Falcke & Markoff 2002).

Multiwavelength follow-up – and, in particular, optical/ultraviolet (optical/UV) observations – can provide crucial diagnostics of the nature of ULXs. Probably the most important is the identification of an optical counterpart to the ULX. The study of such counterparts can reveal the type of the mass donor star, and subsequently lead to the single most important measurement for a ULX, namely constraining its mass function (and hence placing unambiguous limits on the black hole mass) by measuring a radial velocity curve. However, even initial identifications are not trivial in crowded galaxy fields at several Mpc distance. Fortunately, thanks to a combination of the sub-arcsec X-ray astrometry of *Chandra* and the very high spatial resolution and sensitivity in the optical/UV of the *Hubble Space Telescope* (*HST*), good identifications are now possible. Indeed, many recent studies have taken advantage of the excellent data from these missions to identify possible ULX counterparts (e.g. Goad et al. 2002; Liu, Bregman & Seitzer 2002, 2004; Kuntz et al. 2005; Soria et al. 2005; Ptak et al. 2006; Ramsey et al. 2006; Terashima, Inoue & Wilson 2006; Liu et al. 2007; Mucciarelli et al. 2007). Where such studies have focused on nearby ($d <$ 10 Mpc) spiral galaxies, individual counterparts with magnitudes $m_V \sim 22$–26 and blue colours have frequently been found, consistent with the interpretation of ULXs as high-mass X-ray binaries, where the mass donor star is a giant (or supergiant) O4–B8 star filling its Roche lobe. However, an alternative possibility is that the blue colours are due to reprocessed emission from an X-ray-illuminated accretion disc (Kaaret, Ward & Zezas 2004; Copperwheat et al. 2005; Rappaport, Podsiadlowski & Pfahl 2005). Indeed, Pakull, Grisé & Motch (2006) argue that the blue counterpart to NGC 1313 X-2 is dominated by accretion disc light (although see

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Table 1. Positions of the target ULXs as obtained from *Chandra* data, and the corresponding Galactic extinction.

ULX	*Chandra* data[a]	RA[b]	Dec.[b]	$\sigma_{\rm cent}$[c]	$\sigma_{\rm astr}$[d]	$N_{\rm H,X}$[e]		d[f]	$E(B-V)$[g]
IC 342 X-1	600254	03 45 55.590	+68 04 55.52	0.02	0.55	~3	(1,2)	3.9	0.561
IC 342 X-2	600273 (H)	03 46 15.745	+68 11 12.59	0.10	0.61	~10	(2)	3.9	0.558
NGC 2403 X-1	600274 (H)	07 36 25.525	+65 35 39.97	0.05	0.65	~3	(3)	4.2	0.037
NGC 4485 X-1	600381	12 30 30.487	+41 41 42.24	0.02	0.54	~3	(4)	7.8	0.022
NGC 5055 X-2	700387	13 15 19.578	+42 03 01.92	0.05	0.59	~1	(5)	7.2	0.018
M83 IXO 82	600477 (H)	13 37 19.801	−29 53 48.72	0.02	0.55	~1	(3)	4.7	0.063

Notes: [a]*Chandra* observation sequence number. An appended '(H)' indicates that the observation was with the HRC-I detector; otherwise observations were taken with the ACIS-S. [b]Right ascension (RA) and declination (Dec.) (epoch J2000) in hexagesimal format. [c]Error on position of the centroid of the X-ray source, in arcsec. [d]Error on the astrometric precision of the X-ray source position in arcsec. [e]Absorption column towards the ULX, external to our own Galaxy, measured by X-ray spectroscopy (10^{21} cm^{-2}). Measurements from (1) Roberts et al. (2004); (2) Bauer, Brandt & Lehmer (2003); (3) Stobbart et al. (2006); (4) Roberts et al. (2002); (5) analysis of the *Chandra* data, using standard reduction and analysis techniques, and an absorbed power-law continuum model (giving $\Gamma \sim 2.5$). [f]Distance to host galaxy in Mpc, from papers quoted in the previous column. [g]Line-of-sight foreground Galactic extinction for each ULX counterpart, inferred from Schlegel, Finkbeiner & Davis (1998).

Table 2. *HST* observations of the ULX locations, and characteristics of the candidate counterparts.

ULX	Filter	Observation date	Exposure (s)	Mag (pivot)[a]	Vega mag[b]	M_V[c]	$U-B$[d]	$B-V$[d]
	F330W	2005 September 02 03:14:42	2900	>25.2	$U > 22.4$			
IC 342 X-1	*F435W*	2005 September 02 01:19:59	1248	25.21 ± 0.07	$B = 22.98 \pm 0.07$	−5.57 (−7.30)	> −0.6 (> −1.1)	0.60 (0.16)
	F606W	2005 September 02 01:47:02	1248	23.91 ± 0.05	$V = 22.38 \pm 0.06$			
	F330W	2005 September 02 06:31:42	2900	–	–			
IC 342 X-2	*F435W*	2005 September 02 04:31:39	1248	26.71 ± 0.26	$B \approx 24.5$	–	–	–
	F606W	2005 September 02 04:58:42	1248	–	–			
	F330W	2005 October 17 04:22:04	2912	24.82 ± 0.14	$U = 23.87 \pm 0.14$			
NGC 2403 X-1	*F435W*	2005 October 17 02:23:25	1248	24.74 ± 0.11	$B = 24.74 \pm 0.11$	−3.42 (−5.14)	−0.87 (−1.20)	0.04 (−0.42)
	F606W	2005 October 17 02:50:28	1248	24.90 ± 0.11	$V = 24.70 \pm 0.11$			
	F330W	2005 November 19 12:42:30	2652	22.20 ± 0.04	$U = 21.31 \pm 0.04$			
NGC 4485 X-1	*F435W*	2005 November 19 07:56:30	1116	21.73 ± 0.03	$B = 21.78 \pm 0.03$	−7.56 (−9.28)	−0.47 (−0.82)	−0.12 (−0.59)
	F606W	2005 November 19 09:18:42	1116	22.02 ± 0.03	$V = 21.90 \pm 0.04$			
	F330W	2006 January 29 20:13:18	2652	24.15 ± 0.06	$U = 23.35 \pm 0.06$			
NGC 5055 X-2	*F435W*	2006 January 22 02:41:42	1116	24.71 ± 0.04	$B = 24.79 \pm 0.04$	−4.64 (−5.35)	−1.44 (−1.46)	0.14 (0.14)
	F606W	2006 January 22 04:15:29	1116	24.85 ± 0.03	$V = 24.65 \pm 0.04$			
	F330W	2006 February 25 19:43:52	2568	>25.0	$U > 24.7$			
M83 IXO 82	*F435W*	2006 February 25 17:46:39	1000	25.79 ± 0.13	$B = 25.66 \pm 0.13$	−3.00 (−3.57)	> −1.0 (> −1.1)	0.30 (0.15)
	F606W	2006 February 25 18:09:34	1000	25.57 ± 0.16	$V = 25.36 \pm 0.17$			

Notes: [a]Magnitude of the counterpart at the pivot wavelength of the ACS filter. The uncertainty in the measurement is calculated by seeding the image with fake stars of the same magnitude. The two limits are calculated by seeding the images with fake stars covering a range of input magnitudes. [b]*UBV* magnitudes in the Vega magnitude system. These are extinction corrected for material in our own Galaxy, then directly photometered from the ACS filters as discussed in the text. The error includes an additional (relatively small) uncertainty from the calculated error in the slope of the power-law continuum used to photometer the data. We use a ν^{-1} spectrum to provide the magnitude for the possible IC 342 X-2 counterpart, but quote no limits on non-detections as we cannot obtain a proxy for the spectral shape of this source from the one data point. [c]Absolute magnitude of the counterpart at the distance of its host galaxy (also foreground extinction corrected). Figures in parentheses include a further correction for the excess column to the ULX measured by X-ray spectroscopy (see the text). [d]Foreground extinction-corrected counterpart colours, again shown with a further possible extinction correction in parentheses.

Liu et al. 2007, for counter arguments). Optical spectroscopy shows a variation in the centroid of the He II λ4686 emission line from the disc, which might indicate that an IMBH is ruled out for this source, though further observations are required to distinguish whether this is a true radial velocity variation.

Here, we present the results of a programme to produce a deep, homogeneous set of imaging data for six nearby ULXs, designed to provide possible targets for future radial velocity studies. We selected ULXs from the *ROSAT* catalogues of Roberts & Warwick (2000) and Colbert & Ptak (2002) based on the following criteria: (i) distance $d < 8$ Mpc, to potentially resolve spatial scales below ~2 pc using *HST* Advanced Camera for Surveys (ACS) data; (ii) the ULX is located away from the centre of the host galaxy, to avoid inherently dense stellar environments where individual identifications are unlikely and (iii) no *HST* imaging data at the position of the ULXs existed at the time of sample selection. In addition, the selection of *ROSAT* ULXs (i.e. ULXs detected at relatively soft X-ray energies, ⩽2 keV) ensures a relatively low extinction in the host galaxies. The six target ULXs are listed in Tables 1 and 2, and we discuss the identification of optical counterparts to these objects in the following sections.

2 DATA REDUCTION

Our target ULXs were observed by *HST* between 2005 September and 2006 February (programme number 10579; see Table 2 for details). A standard set of observations was obtained for each source, concentrated primarily in the blue in order to match the colours of known ULX counterparts. Hence, we obtained a single orbit (four exposures) of imaging in the *F*330*W* filter using the ACS high-resolution camera (HRC), and half an orbit (two exposures apiece) in each of the *F*435*W* and *F*606*W* filters using the ACS Wide Field Camera (WFC). The data were reduced to provide cleaned and stacked images in each filter via the standard multidrizzle software, with PIXFRAC set to one since the data were not well dithered.

In five of the six cases, we obtained X-ray positions from archival *Chandra* data. In the sixth case (M83 IXO 82), we were awarded a new *Chandra* high-resolution camera for imaging (HRC-I) observation to obtain an accurate position, as the ULX lay outside the field of view of previous *Chandra* observations of that galaxy. Archival data from both the HRC-I and ACIS (either -S or -I) were considered, and that with the best combination of exposure length and proximity of the ULX to an on-axis position selected. These data sets are listed in Table 1. The astrometry of the archival data was initially corrected for known aspect offsets,[1] before the data were reprocessed using CIAO version 3.3.0.1 and the *Chandra* calibration data base version 3.2.1. Broad-band (0.5–8 keV) images were extracted from the reprocessed event files, and searched for sources using the WAVDETECT algorithm. We list the derived ULX positions and centroiding errors ($\sigma_{\rm cent}$) in Table 1.

3 IDENTIFICATION AND CHARACTERIZATION OF THE POSSIBLE NEW COUNTERPARTS

The key step in identifying optical counterparts to our target ULXs is registering the relative astrometries of the *HST* and *Chandra* data. Ideally, this would be done by finding a number of *HST* counterparts to *Chandra* X-ray sources; however, there were insufficient matches present in our data. Instead we aligned our ACS images to 2MASS (which typically had the largest number of sources in an ACS field), or, in the case of NGC 4485 where only two 2MASS sources fell within the ACS field, we performed relative astrometry using observations of NGC 4485 obtained at the Isaac Newton Telescope on 2001 January 4. We then took advantage of the small intrinsic errors in *Chandra* astrometry (90 per cent confidence region of 0.5 arcsec on the absolute position accuracy, after known aspect errors are removed, for both the HRC-I and ACIS-S[2]) and overlaid error regions on the corrected *HST* images with radii that were a combination (in quadrature) of this *Chandra* uncertainty and the residual uncertainty in the *HST* astrometry after correction to 2MASS. The resulting error regions – typically ∼0.6 arcsec radius – are shown in Table 1.

The locations of the ULXs are shown in Fig. 1. In several cases, a relatively bright counterpart is clear. In other cases, multiple counterparts are present, or (in the case of IC 342 X-2) a counterpart is indiscernible. We take the view that the most likely counterpart to the ULX is the brightest source within the error circle or, in the case of multiple sources, that with the bluest colours. We tabulate the observed and inferred characteristics of these candidates in Table 2. The magnitudes of the counterparts were derived using the following procedure. First, magnitudes were derived at the pivot wavelength of each ACS filter using a small (0.1 arcsec) aperture, with zero-points taken from Sirianni et al. (2005), and additional aperture corrections calculated using SYNPHOT. This is shown as Mag (pivot) in Table 2. These magnitudes were then corrected for reddening within our own Galaxy using the value of $E(B-V)$ in Table 1 and the filter specific extinction ratios given by Sirianni et al. (2005) for an O5 V star. Finally, each filter magnitude was photometered into the appropriate tabulated *UBV* magnitude (Vega mag in Table 2, with *F*330*W* converting to *U*, etc.) using a power-law continuum slope derived from the relative extinction-corrected magnitudes in the ACS filters as a proxy for the spectral shape. In the few cases where we saw no counterpart, we seeded the appropriate images with fake stars in order to infer a detection limit at the position of the ULX. These limits are also shown in Table 2.

The extinction-corrected and photometered magnitudes were converted to absolute magnitudes using the distances to the host galaxies in Table 1, and also used in the calculation of the counterpart colours $U-B$ and $B-V$. However, these values do not allow for any extinction within the host galaxy of the ULX. As the absorption column imprinted on the X-ray spectra of the ULXs appears a good measure of the column through the host to the ULX position in most cases (Winter, Mushotzky & Reynolds 2007), we use the values in Table 1 to infer an additional, host galaxy *V*-band extinction by considering a column of $10^{21}\ {\rm cm^{-2}}$ to correspond to $A_V = 0.56$ magnitudes of extinction (Predehl & Schmitt 1995). This additional extinction was also applied to the ACS magnitudes, before photometering by the method described above. The results of applying this second correction are shown in parentheses for the absolute magnitudes and colours of the counterparts in Table 2.

4 THE COUNTERPARTS

Our observations detect four likely counterparts to ULXs, plus two more possible. Three of these likely counterparts are previously unreported; the counterpart to IC 342 X-1 was been reported twice before. It was described as 'candidate 1' (of two possible counterparts) by Grisé, Pakull & Motch (2006) based on ground-based imaging, and latterly identified as the unique counterpart 'Star A' in a separate *HST* programme by Feng & Kaaret (2008). Although their observations took place three months after ours, Feng & Kaaret's Star A has identical *B* and *V* magnitudes to our detection (within the quoted errors), suggesting it displays little intrinsic variability. From their characterization of Star A, they derive a classification as an F8 to a G0 Ib supergiant, although they choose to omit any corrections to their characterization based on extinction intrinsic to IC 342. Candidate 1 of Grisé et al. (2006) also displays a similar magnitude after extinction correction ($m_V \sim 22.3$).

The likely counterparts are all luminous point-like sources, with absolute magnitudes in the range $M_V \sim -3.4$ to -7.6, or perhaps even higher ($M_V \sim -5.1$ to -9.3) if we take into account possible additional extinction in the host galaxies of the ULXs.[3] The inferred $U-B$ colours of these ULXs are very blue, in the range -1.4 to -0.5, or -1.5 to -0.8 accounting for the putative host galaxy reddening. The $B-V$ colour ranges from -0.1 to 0.6 (-0.6 to 0.2 with host galaxy reddening).

Of the two possible counterpart detections, IC 342 X-2 is very marginal, with a minimal detection in the *F*435*W* filter image alone.

[1] See http://cxc.harvard.edu/cal/ASPECT/fix_offset.

[2] See http://cxc.harvard.edu/cal/ASPECT/celmon/.

[3] These columns are approximations based on values taken from a range of models for the X-ray spectra of the ULXs. As the variance in measured column between models can be factors of at least ∼2, the uncertainties on the quoted values are large, though we note that this correction will always work in the sense of increasing the intrinsic brightness of the counterpart.

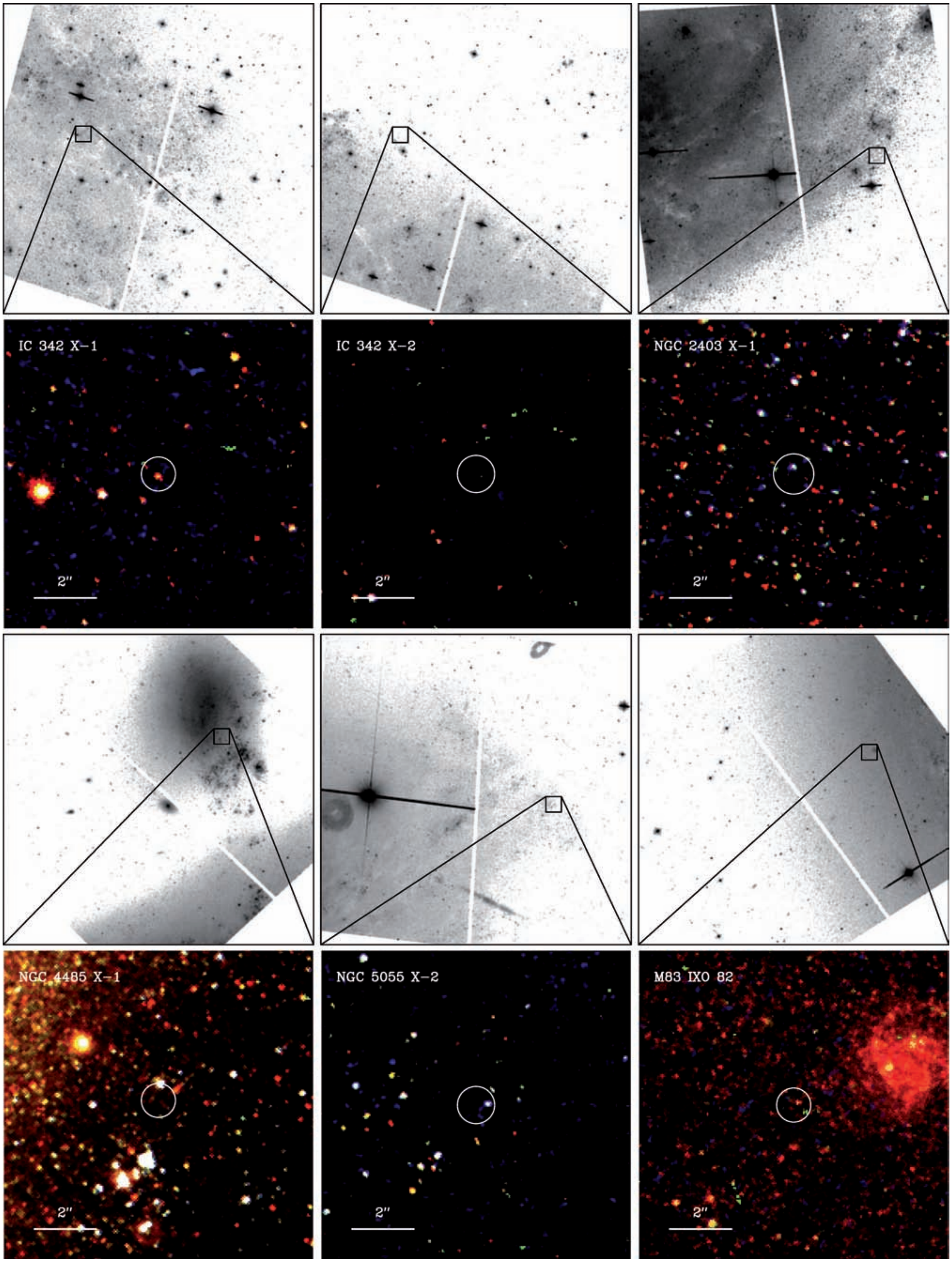

Figure 1. *HST* ACS images of ULX locations. North is up in each image. For each of the six targets, we show a wide-ACS/WFC *F*606*W* view of the ULX environment, with a true-colour blow-up of the immediate vicinity of the ULX beneath it (blue = *F*330*W*, green = *F*435*W* and red = *F*606*W*). The error circles are as per Table 1.

This is perhaps not surprising, given the high foreground Galactic extinction to IC 342, and the even higher X-ray column, which may result in >5 mag of extinction in the *V* band alone. In this regard, the detection in the *F*435*W* filter but not the *F*606*W* is very suspicious, and increases the chances of this being a spurious detection. M83 IXO 82, on the other hand, probably is a real detection. The question here is whether it is the correct one. It is suspiciously close (at ∼5 arcsec distance) from the centre of a galaxy lying behind a spiral arm of M83, which does raise the question of whether this *Chandra* HRC data set has an unusually bad aspect solution, and the X-ray source is, in fact, located within the background galaxy (probably an active galactic nuclei). However, to argue against this, the colours of the counterpart are somewhat similar to IC 342 X-1, and (though it is fainter than IC 342 X-1 by ∼2.5 mag) it is only ∼1.5 mag intrinsically fainter then NGC 2403 X-1. Clearly, future work should attempt to clarify the astrometry for this field and confirm the likely nature of this X-ray source.

Previous observations have also revealed blue counterparts to ULXs, that have generally been identified as O or B stars. In order to clarify whether we are viewing similar objects, we referred to the work of Wegner (2006) to provide us with typical M_V measurements for such stars, and Martins & Plez (2006) and Knyazeva & Kharitonov (1998) for typical colours. These colours for OB stars cover ranges of $U - B \sim -1.2 \rightarrow -0.6$ and $B - V \sim -0.3 \rightarrow -0.1$. Hence, taking only the Galactic extinction-corrected magnitudes into consideration, the four good candidate counterparts, in general, appear too red to be OB stars. This situation is, however, mostly remedied when we take into account possible extinction in the host galaxy – in most cases, the colours (particularly the $U - B$ colour) become sufficiently blue to originate in OB stars. However, the inherent uncertainty in this additional correction is large (see footnote 3), so it is perhaps sensible to simply conclude that the Galactic extinction-corrected magnitudes provide an upper (reddened) limit on the colours, which are intrinsically bluer than this value. Indeed, if some fraction of the additional X-ray absorption is local to the ULX accretion disc, or if the intense X-ray emission of the ULX can deplete the dust content of its local environment, it is quite plausible that the extinction to the optical counterpart within the host galaxy could be lower than estimated. Evidence supporting this is provided by Grisé et al. (2006), who infer $E(B - V) = 0.26$ within IC 342 from the Hα/Hβ ratio (albeit from the bubble nebula surrounding this ULX) – this is somewhat smaller than the value $E(B - V) = 0.53$ within IC 342 derived from the X-ray absorption.

Supposing that the true counterpart colours lie between the tabulated colours and magnitudes, (i.e. with and without additional host galaxy extinction), we can speculate on the nature of the counterparts. The colours and magnitude of the counterpart to NGC 2403 X-1 suggest it could plausibly be an O star or an early B giant/B supergiant. NGC 4485 X-1 is somewhat trickier to classify – it is relatively blue in $B - V$ but red in $U - B$ compared to other candidates. Given its high absolute magnitude perhaps the most likely explanation is that this object is a young, compact stellar cluster that has lost its youngest and hottest OB stars (perhaps similar to HST-1 identified by Goad et al. 2002 as a possible counterpart to NGC 5204 X-1, though this was later ruled out by Liu et al. 2004). The counterpart to NGC 5055 X-2 is an oddball – its absolute magnitude is bright enough for an OB giant/supergiant, but its $U - B$ colour is too blue, whereas its $B - V$ colour is too red. It is unclear what is causing this unusual colour, though domination of the optical light by the accretion disc can be ruled out, as this will produce a spectrum redder than an O star. We speculate that this blueness could be caused by emission lines and/or non-stellar processes, and may possibly even be attributable to variability in the accretion disc. However, this cannot be confirmed without repeated spectroscopic observations. Finally, the $B - V$ colour of the counterpart to IC 342 X-1 is quite red, even after correction, apparently ruling out an OB star unless substantial additional local extinction (not seen in X-rays) is present. In fact, its red colour and magnitude are more reminiscent of a F-type supergiant, probably earlier in type (F0–F5 supergiant) than suggested in Feng & Kaaret (2008) after accounting for the additional column within IC 342. Again, this source would benefit from further deep spectroscopic follow-up to clarify its nature.

Unlike previous studies, it appears that few of our counterparts can be easily associated with individual OB stars. This may be a result of detecting fainter targets than previously observed (and hence poorer data quality), a situation that could be improved with future, deeper observations. Indeed, a combination of deeper observations and the new generation of models for the optical emission of ULXs, such as those of Copperwheat et al. (2007), Patruno & Zampieri (2008) and Madhusudhan et al. (2008), should reveal more of the nature of ULXs. So far, the work of both Copperwheat et al. and Patruno & Zampieri has suggested that the currently known counterparts of ULXs are older and less massive than initially suggested (due to the modifying effects of, for example, the illumination of the donor star by the ULX on the optical emission of these systems). All authors agree that the presence of an IMBH will increase the optical luminosity of the systems, and indeed Madhusudhan et al. claim that the colours of current ULX counterparts appear more consistent with their models incorporating the presence of an IMBH.

However, the most important observations remain those that could constrain the mass of a ULX dynamically. Rather encouragingly, recent work by Orosz et al. (2007), Prestwich et al. (2007) and Silverman & Filippenko (2008) shows that this can be done for massive stellar donors in X-ray binary systems out to distances ∼1 Mpc. To perform similar observations – particularly based on the He II λ 4686 line used by Prestwich et al. (2007) and Silverman & Filippenko (2008) – on the slightly more distant ULX counterparts may therefore only be a small step away. The counterparts revealed by this study are promising candidates for such observations, albeit technically challenging ones for the immediate future due to their relatively faint magnitudes. Such studies should be pursued regardless, as the prize – a dynamical mass constraint on the black hole in an ULX – is the single most important measurement to be made in this field.

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