The optical counterpart of the ultraluminous X-ray source NGC 5204 X-1

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ABSTRACT

We use archival *HST*/WFPC2 *V*- and *I*-band images to show that the optical counterpart to the ultraluminous X-ray source NGC 5204 X-1, reported by Roberts et al., is composed of two sources separated by 0.5 arcsec. We have also identified a third source as a possible counterpart, which lies 0.8 arcsec from the nominal X-ray position. Point spread function fitting photometry yields *V*-band magnitudes of 20.3, 22.0 and 22.4 for the three sources. The $V - I$ band colours are 0.6, 0.1 and −0.2, respectively (i.e. the fainter sources are bluer). We find that all $V - I$ colours and luminosities are consistent with those expected for young stellar clusters (age <10 Myr).

Key words: accretion, accretion discs – black hole physics – galaxies: photometry – galaxies: star clusters – X-rays: binaries – X-rays: individual: NGC 5204 X-1.

1 INTRODUCTION

Einstein and *ROSAT* observations show that at high energies most nearby (spiral) galaxies are dominated by a relatively small number of discrete, compact, but highly luminous X-ray sources. These so-called ultraluminous X-ray sources (ULXs) have luminosities of $L_x \sim 10^{39}$–10^{41} erg s^{-1}, far in excess of the Eddington limit for spherical accretion on to a neutron star (Roberts & Warwick 2000).

Nearly 20 per cent of ULXs appear to be associated with supernova remnants (SNRs: Roberts et al. 2002), while the rest are thought to be powered by accretion on to a compact object. One possibility is that ULXs represent the missing class of intermediate-mass (10^2–10^5 M$_\odot$) black holes (Colbert & Mushotzky 1999). However, recent *Chandra* observations reveal a strong association between ULXs and active star-forming regions (Fabbiano, Zezas & Murray 2001; Lira et al. 2002), which are far too young to contain massive black holes (King et al. 2001). Subsequently, at least two alternative scenarios have been proposed. In the first, ULXs are stellar-mass black hole binaries undergoing a period of super-Eddington accretion (e.g. Watarai, Mizuno & Mineshige 2001; Begelman 2002). In the second, the apparent super-Eddington luminosities are due to the beamed X-ray emission from an otherwise normal intermediate/high-mass X-ray binary (King et al. 2001; Georganopoulos, Aharonian & Kirk 2002). While both scenarios tie in neatly with the observed association between ULXs and active star-forming regions (Long, Charles & Dubus 2002; Terashima & Wilson 2002; Zezas et al. 2002), the latter requires a significantly larger number of ULXs to be present.

Roberts et al. (2001) identified the first optical counterpart to a ULX, NGC 5204 X-1, based on its *Chandra* position and optical

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multifibre spectroscopy. The counterpart, located within 1 arcsec of the nominal *Chandra* position, displays a blue featureless continuum and is surrounded by an ionized bubble of gas with a diameter of some 360 pc (Pakull & Mirioni 2002). Here, we present archival *Hubble Space Telescope*/Wide Field Planetary Camera 2 (*HST*/WFPC2) *V*- and *I*-band images of this source, together with an improved analysis of the multifibre data. These data allow us to place more robust constraints on the nature of the counterpart, and thus obtain a deeper insight into the ULX phenomenon.

2 *HST*/WFPC2 IMAGES OF NGC 5204 X-1

We have obtained archival *HST*/WFPC2 *V*- and *I*-band (F606W and F814W) images of the dwarf magellanic-type galaxy NGC 5204 (Fig. 1, upper panel). These data (now public) were obtained as part of an ongoing *HST*/WFPC2 snapshot survey of nearby dwarf galaxies (Seitzer, Principal Investigator).

The *HST*/WFPC2 *V*- and *I*-band images (Fig. 1, lower panel) show that the optical counterpart can be resolved into at least two sources, here designated HST-1 and HST-2, separated by 0.47 arcsec. We also identify a third source designated HST-3, located 0.8 arcsec to the east of the nominal *Chandra* position. This source was not detected in the fibre data of Roberts et al. (2001), but because of its close proximity remains a possible counterpart to the ULX. The observed separations correspond to distances of 10−16 pc at the distance of NGC 5204 (4.8 Mpc).

We have performed point spread function (PSF) fitting photometry on the *V*- and *I*-band images using HSTPHOT (Dolphin 2000). Unfortunately, only one image was available in each filter, hampering cosmic ray rejection. Given the difficulty of identifying real point sources, we decided against iterative adjustment of the standard PSFs of HSTPHOT on the basis of the fit residuals. The chip positions, RA, Dec., *V*- and *I*-band magnitudes (referenced to a
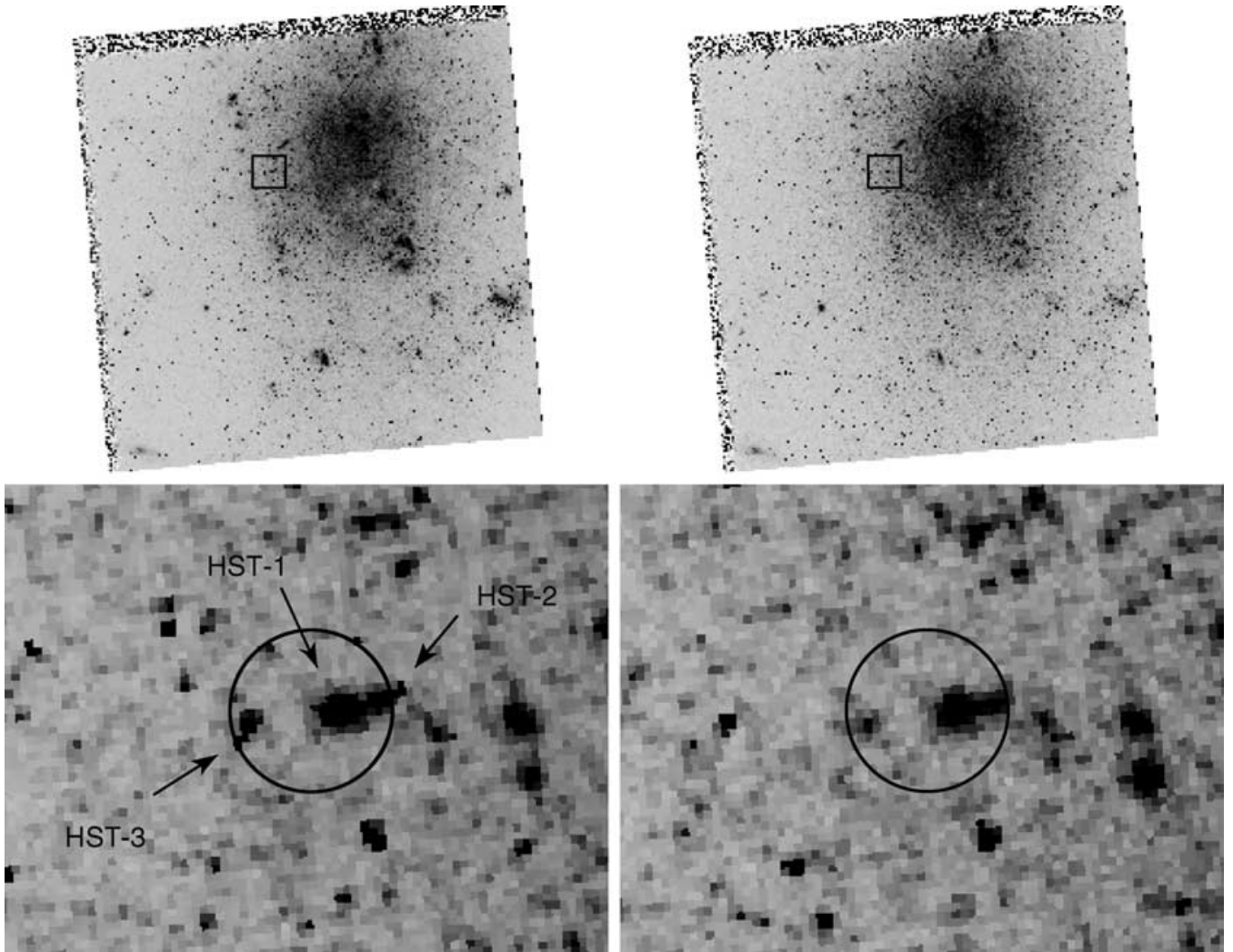
Figure 1. Upper panel: *HST* WFPC2 *V*-band (left-hand side) and *I*-band (right-hand side) images of NGC 5204 showing the location of the optical counterpart. Lower panel: enlarged *V*- and *I*-band images reveal that the optical counterpart is resolved into two components (HST-1 and HST-2) separated by ∼0.47 arcsec. A third source (HST-3) is located 0.8 arcsec east of the nominal *Chandra* position. The 1.0 arcsec radius ring shows the formal error on the ULX position. North is up.

0.5-arcsec aperture), colours and distances from the nominal *Chandra* position (Δ) are quoted in Table 1 for each source.

Our HSTPHOT photometry reveals that all sources are blue (i.e. F_λ decreases with increasing λ), consistent with the finding of Roberts et al. (2001) for a single unresolved source. However, the two fainter sources are significantly bluer than HST-1. The combined magnitudes of HST-1 and HST-2 are 20.1 in *V* and 19.6 in *I*, with a $V - I$ colour of 0.5. These magnitudes are referenced to a 0.5-arcsec aperture, becoming 20.0 and 19.5 when corrected to infinite aperture. We do not include HST-3 in the combined magnitude estimate, as it does not fall within the same fibre in the data of Roberts et al.

The best-fitting *Chandra* position for the ULX (determined using WAVDETECT: Freeman et al. 2002) – $\alpha = 13^h 29^m 38.61$, $\delta =$

$+58°25'05.\!\!''7$ – is located 0.34 arcsec east of HST-1. The 1σ error associated with the *Chandra* reference frame is ±0.6 arcsec (Aldcroft et al. 2000). However, errors of up to 1.0 arcsec are not uncommon when linking the *Chandra* and *HST* reference frames (see e.g. Grindlay et al. 2001). Thus, while HST-1 is the preferred location for the optical counterpart, neither HST-2 nor HST-3 can be ruled out.

3 COMPARISON WITH WHT/INTEGRAL MULTIFIBRE SPECTROSCOPY

We have reanalysed the optical multifibre data on NGC 5204 X-1 from Roberts et al. (2001) with the aim of improving the photometric

Table 1. HSTPHOT PSF fitting photometry.

Source	Chip no.	Chip position		RA	Dec.	*V*	*I*	$V - I$	Δ
		X	*Y*	h m s	° ′ ″				(arcsec)
HST-1	2	273.75	343.96	13 29 38.57	58 25 05.78	20.3	19.7	0.6	0.34
HST-2	2	273.37	348.66	13 29 38.51	58 25 05.86	22.0	21.9	0.1	0.82
HST-3	2	274.44	332.56	13 29 38.71	58 25 05.62	22.4	22.6	−0.2	0.80

accuracy of their spectrum. This allows a direct comparison of their results with our new results from HSTPHOT. Our new analysis takes better account of fibre throughput corrections (using an improved throughput image, with repeatability errors of <0.1 per cent) and contamination by the night sky background. More importantly, we have also tried to correct for diffuse emission from within the host galaxy.

The reconstructed multifibre image of our source shows that emission from the optical counterpart lies within a single central fibre and its surrounding nearest six neighbours. If we adopt the procedure followed by Roberts et al. (2001) and correct for night sky background only, we derive a V-band magnitude of 19.9. This is 0.2 mag fainter than found by Roberts et al.; this difference is due partly to our improved throughput correction and partly to the use of a median (instead of a mean) night sky background.

As noted above, we have also tried to account for diffuse emission from the host galaxy, which shows a clear west–east gradient (see Fig. 1). We do this by taking a median of the local background continuum over 18 fibres arranged in a hexagonal ring ∼3 arcsec from the source. This avoids including source flux in the background fibres. As in Roberts et al. (2001), the resultant spectrum (Fig. 2) is blue and featureless at the resolution of our instrument (6 Å per two-pixel resolution element). However, removal of local galaxy contributions results in a cleaner, fainter and marginally bluer spectrum. The measured flux near 5500 Å translates to a V-band magnitude of 20.4 ± 0.1. This is 0.7 mag fainter than the magnitude quoted by Roberts et al. and 0.4 mag fainter than that derived
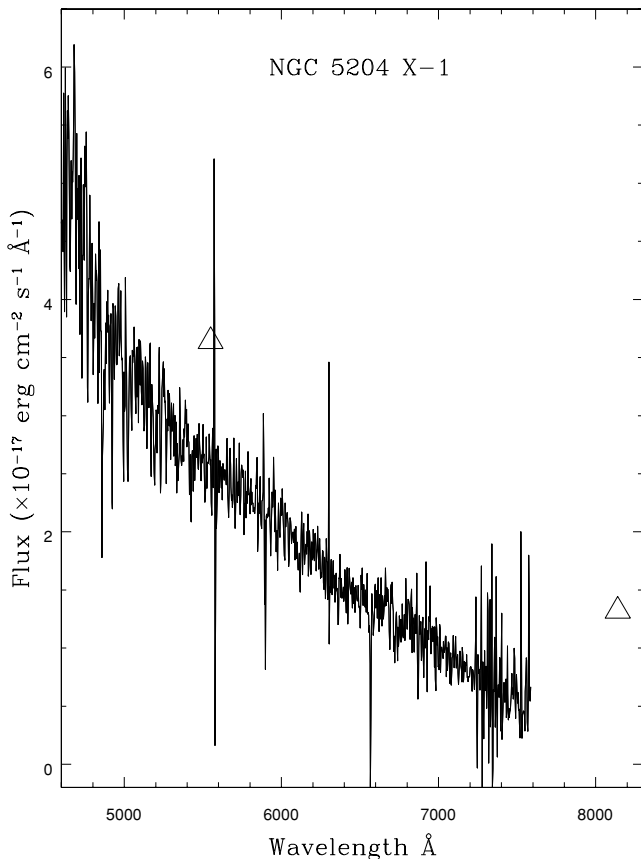

Figure 2. The optical counterpart to NGC 5204 X-1 after removal of contaminating night sky and host galaxy emission. The open triangles represent the derived V- and I-band fluxes for the combined sources as estimated from the *HST*/WFPC2 images.

from the *HST*/WFPC2 V-band image. The discrepancy between the WHT V-band flux estimate and that determined directly from the *HST*/WFPC2 V-band image most likely results from the intermittent presence of high cloud during some of the ground-based observations. This gives an indication of the accuracy of the absolute spectral flux calibration of the fibre data.

4 THE NATURE OF THE ULX AND ITS COUNTERPART

Roberts et al. (2001) found that the optical counterpart to NGC 5204 X-1 was unlikely to be a Galactic foreground object, but could not rule out the possibility that it was a background BL Lac. This was because the derived X-ray to optical slope, $\alpha_{ox} \approx 1.0$, lies well within the parameter range occupied by BL Lacs. However, a recent measurement of the radio flux at 8.3 GHz with the Very Large Array (Wong 2002) shows the source to be radio-faint (<84 μJy), yielding an upper limit to $\alpha_{ro} < 0.08$. This places the source well outside the parameter space occupied by BL Lacs and confirms the status of NGC 5204 X-1 as a bona fide ULX.

4.1 ULXs in young star clusters?

The *HST*/WFPC2 colours show that our composite WHT spectrum, which is dominated by the brighter and significantly redder source, must flatten towards longer wavelengths. Based on the colours alone, HST-1 has an apparent spectral type F2–F5, HST-2 is type A2, and HST-3 is type B5–B6 (Zombeck 1990). The absolute magnitudes of the three sources are $M_v = -8.1$ (HST-1), -6.4 (HST-2) and -6.0 (HST-3), which at the bare minimum requires ∼1–2 F supergiants, ∼2–3 A2 supergiants and ∼2–3 B5 supergiants respectively. However, a much more likely scenario is that the colours are representative of young stellar clusters. Indeed, there is increasing evidence to support such an idea. Zezas et al. (2002) find several instances of ULX/young stellar cluster coincidences in the Antennae galaxies. Further, based on its location and colour, one of the two optical counterparts to the known ULXs in NGC 4565 has been associated with a globular cluster located in the outer bulge of this galaxy (Wu et al. 2002).

In Fig. 3 we show $V - I$ colours as a function of age for three stellar cluster models. Each model assumes a single instantaneous burst of star formation. The adopted stellar initial mass function (IMF) is here represented by a power law with slope 2.35 between the low- and high-mass cut-offs and approximates the classical Salpeter IMF (Salpeter 1955), appropriate for most observations of star-forming regions. Two of the models are from the STARBURST99 models of Leitherer et al. (1999). For comparison, we also show the solar-metallicity model of Bruzual & Charlot (1993), which highlights the effect of adopting a smaller lower mass cut-off.

If each of our sources represents a stellar cluster, and the clusters are coeval, then Fig. 3 shows that the observed $V - I$ band colours are broadly consistent with young stellar clusters with ages between $10^{6.6}$ and $10^{7.3}$ yr. Furthermore, assuming that the clusters have the same metallicities, then the low-metallicity model is inconsistent with the $V - I$ colour of HST-1, and the age constraint is tightened to between $10^{6.6}$ and $10^{6.9}$ yr. This time-scale is much shorter than the formation time-scale of a low-mass X-ray binary, ∼10^8–10^9 yr, but is consistent with the formation time-scale of an intermediate/high-mass X-ray binary, ∼10^7 yr (King et al. 2001).

By comparing the absolute V-band magnitudes with the V-band magnitudes predicted by the nuclear STARBURST99 models of Leitherer et al. (1999), we estimate the number of cluster members
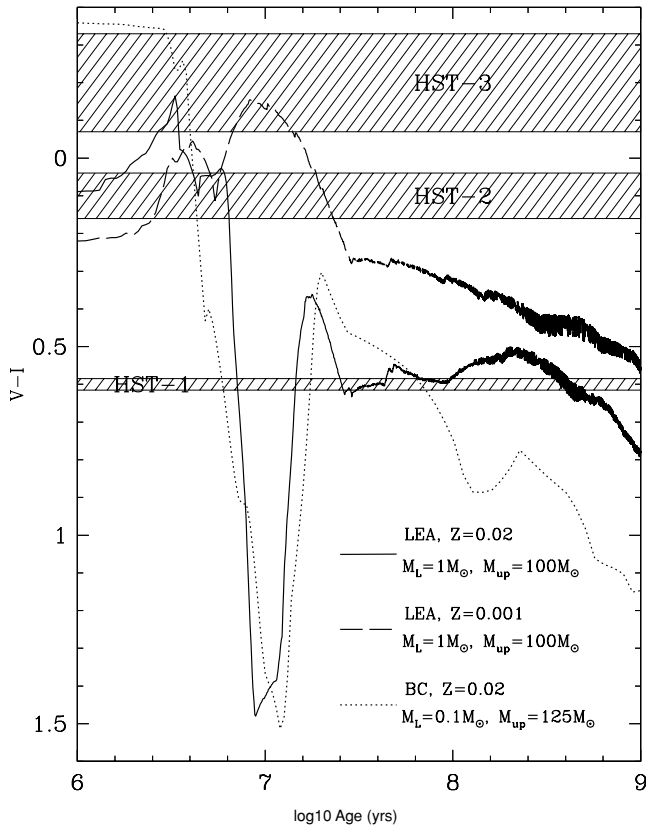
Figure 3. $V - I$ colours as a function of age for an instantaneous burst of star formation (see text for details). Individual models represent STARBURST99 models of Leitherer et al. (LEA) with solar metallicity (solid line) and 1/20th-solar metallicity (dashed line), and the 1993 solar-metallicity model of Bruzual & Charlot (BC, dotted line). The hatched regions indicate the $V - I$ colours of our three sources.

to be between several hundred (HST-3) and a few thousand stars (HST-1). We note that the upper limits to our source 'sizes' (a few parsecs at the distance of NGC 5204) are consistent with cluster sizes determined for nearby starburst galaxies (2–3 pc, see Meurer et al. 1995).

5　CONCLUSIONS

We have used archival *HST*/WFPC2 *V*- and *I*-band images to show that the previously reported optical counterpart to the ultraluminous X-ray source NGC 5204 X-1 can be resolved into two sources separated by 0.47 arcsec. We have also identified a third possible counterpart 0.8 arcsec east of the nominal *Chandra* position. All three sources appear blue (i.e. F_λ decreases with increasing λ), with the fainter sources being significantly bluer. PSF fitting photometry with HSTPHOT yields source magnitudes of 20.3, 22.0 and 22.4 in *V*. Assuming that all three sources are coeval, the

$V - I$ band colours suggest that NGC 5204 X-1 lies within a young (<10 Myr) stellar cluster. This is consistent with the idea that ULXs are intermediate/high-mass X-ray binaries.

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