The optical counterpart of the ultra-luminous 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 ultra-luminous x-ray source NGC 5204 X-1, reported by Roberts et al., is composed of two sources separated by 0.5″. We have also identified a third source as a possible counterpart, which lies 0.8″ from the nominal X-ray position. PSF 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: X-rays: NGC 5204 X-1, X-rays: binaries, galaxies: star clusters, galaxies: photometry, accretion, black hole physics

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 ultra-luminous 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 onto a neutron star (Roberts and Warwick 2000).

Nearly 20% of ULXs appear to be associated with supernova remnants (SNR, Roberts et al. 2002), while the rest are thought to be powered by accretion onto a compact object. One possibility is that ULXs represent the missing class of intermediate mass (10² – 10⁵ M\(_{\odot}\)) black holes (Colbert and Mushotzky 1999). However, recent Chandra observations reveal a strong association between ULXs and active star-forming regions (Fabbiano et al. 2001, Lira et al. 2002), that 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 et al. 2001, Begelman et al. 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 et al. 2002). While both scenarios tie in neatly with the observed association between ULXs and active star forming regions (Long et al. 2002, Terashima and 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 multi-fibre spectroscopy. The counterpart, located within 1" 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 and Mirioni 2002). Here, we present archival HST/WFPC2 V and I band images of this source, together with an improved analysis of the multi-fibre 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). This data (now public) was obtained as part of an ongoing HST/WFPC2 snapshot survey of nearby dwarf galaxies (Seitzer, PI). 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". We also identify a third source designated HST-3, located 0.8" to the east of the nominal Chandra position. This source was not detected in the fibre data of...
Figure 1. Upper panel - HST WFPC2 V (left-hand side) and I (right-hand side) band 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 \( \sim 0.47'' \). A third source (HST-3) is located 0.8'' east of the nominal Chandra position. The 1.0'' radius ring shows the formal error on the ULX position. North is up.

Roberts et al. but due to 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 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 HSTphot’s standard PSFs on the basis of the fit residuals. The chip positions, RA, DEC, V and I band magnitudes (referenced to a 0.5'' aperture), colours, and distances from the nominal Chandra position (\( \Delta \)), are quoted in Table 1 for each source.

Our HSTphot photometry reveals that all sources are blue (i.e. \( F_\lambda \) decreases with increasing \( \lambda \)), consistent with the finding of Roberts et al. 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'' 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-fit Chandra position for the ULX (determined using WAVDETECT; Freeman et al. 2002) – \( \alpha = 13\,29\,39.61, \delta = +58\,25\,05.7 \) – is located 0.34'' east of HST-1. The 1\( \sigma \) error associated with the Chandra reference frame is \( \pm 0.6'' \) (Aldcroft et al. 2000). However, errors of up to 1.0'' 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 or HST-3 can be ruled out.

3 COMPARISON WITH WHT/INTEGRAL MULTI-FIBRE SPECTROSCOPY

We have reanalysed the optical multi-fibre data on NGC 5204 X-1 from Roberts et al. (2001) with the aim of
improving the photometric 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 $\leq 1\%$) and contamination by the nightsky background. More importantly, we have also tried to correct for diffuse emission from within the host galaxy.

The reconstructed multi-fibre image of our source, shows that emission from the optical counterpart lies within a single central fibre and its surrounding nearest 6 neighbours. If we adopt the procedure followed by Roberts et al. and correct for nightsky background only, we derive a V-band magnitude of 20.3. This is 0.7 mag fainter than the magnitude quoted by Roberts et al. and 0.4 mag fainter than that derived 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.

### Table 1. HSTphot PSF fitting photometry

| Source | Chip no. | Chip position | RA X | RA Y | DEC | V | I | V−I | $\Delta$ |
|--------|---------|---------------|-----|------|-----|---|---|-----|---------|
| HST-1  | 2       | 273.75        | 13:29:38.57 | 20.3 | 19.7 | 0.6 |      | 0.34 |
| HST-2  | 2       | 273.37        | 13:29:38.51 | 22.0 | 21.9 | 0.1 |      | 0.82 |
| HST-3  | 2       | 274.44        | 13:29:38.71 | 22.4 | 22.6 | 0.2 |      | 0.80 |

![Figure 2](image.png)

**Figure 2.** The optical counterpart to NGC 5204 X-1 after removal of contaminating nightsky 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.

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 GHz with the VLA (Wong et al. 2002), shows the source to be radio faint ($< 8 \mu$J), 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 type B5-B6 (Zombeck 1990). The absolute magnitudes of the three sources are $M_v = -8.1$ (HST-1), $M_v = -6.4$ (HST-2), and $M_v = -6.0$ (HST-3), which at the bare minimum requires $\sim 1$ F supergiants, $\sim 2$ A2 supergiants, and $\sim 3$ 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 Figure 4 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 powerlaw with slope 2.35 between the low- and high-mass cut-offs and 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 $20.4 \pm 0.1$. This is 0.7 mag fainter than the magnitude quoted by Roberts et al. and 0.4 mag fainter than that derived 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.
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 and Charlot (BC, dotted line), the solar metallicity model of Bruzual and 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 co-eval, then Fig 4 shows that the observed V–I band colours are broadly consistent with young stellar clusters with ages between $10^{6.6} - 10^{7.3}$ yrs. 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 $10^{6.6} - 10^{6.9}$ yrs. This timescale is much shorter than the formation timescale of a low mass x-ray binary, $\sim 10^{5} - 10^{6}$ yrs, but is consistent with the formation timescale of an intermediate/high mass x-ray binary, $\sim 10^{7}$ yrs (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 to be between several hundred (HST-3) and a few thousand stars (HST-1). We note that the upper limit to our source “sizes” (a few pcs at the distance of NGC 5204) are consistent with cluster sizes determined for nearby starburst galaxies (2-3 pcs, 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 ultra-luminous x-ray source NGC 5204 X-1, can be resolved into two sources separated by 0.47". We have also identified a third possible counterpart 0.8" east of the nominal Chandra position. All three sources appear blue (i.e. $F_\lambda$ decreases with increasing $\lambda$), 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 co-eval, 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.

REFERENCES
Aldcroft, T.L., Karovska, M., Cresciolito-Ditmat, M.L., Cameron, R.A. & Markovitch, M.L. 2000, Proc. SPIE, 4012, 650. Belgelman, M. 2002, ApJL 568, L97.
Bruzual, A. G. and Charlot, S. 1993, ApJ 405, 538.
Colbert, E.J.M. and Mushotzky R.F. 1999, ApJ, 519, 89.
Dolphins, A. 2000, PASP 112, 1383.
Fabbiano, G., Zezas, A., Murray, S. 2001, ApJ 554, 1035.
Freeman, P. E., Kashyap, V., Rosner, R., Lamb, D. Q. 2002, ApJS 138, 185.
Georganopolous, M., Aharonian, F.A. and Kirk, J.G. 2002, A&A Letts 388, L25.
Grindlay, J.E. Heinke, C.O., Edmunds, P.D., Murray, S.S. and Cool, A.M. 2001, ApJL 563, L53
King, A., Davies, M.B., Ward, M.J., Fabbiano, G., Elvis, M. 2001, ApJL 552, L109.
Leitherer et al. 1999, ApJS 123, 3.
Lira, P., Ward, M.J., Zezas, A., Alonso-Herrero, A. Ueno, S. 2002, MNRAS, 330, 259.
Long, K.S., Charles, P.A. and Dubus, G. 2002, ApJ 569, 204.
Meurer, G. R., Heckman, T. M., Leitherer, C., Kinney, A., Robert, C., Garnett, D.R. 1995, AJ, 110, 2665.
Pakull, M.W. and Mirioni, L. Proceedings of the Symposium on “New Visions of the Universe in the XMM-Newton and Chandra Era”, 26-30 November 2001, ESTEC, The Netherlands, ESA SP-488 August 2002, Eds. F. Jansen and TBD.
Roberts, T.P., and Warwick, R.S. 2000, MNRAS 315, 98.
Roberts, T.P., Goad, M.R., Ward, M.J., Warwick, R.S., O'Brien, P.T., Lira, P., and Hands, A.D.P. MNRAS 2001, 325, L7.
Roberts, T.P., Goad, M.R., Ward, M.J. Warwick, R.S., and Lira, P., Proceedings of the Symposium on “New Visions of the Universe in the XMM-Newton and Chandra Era”, 26-30 November 2001, ESTEC, The Netherlands, ESA SP-488 August 2002, Eds. F. Jansen and TBD.
Salpeter, E.E. 1955, ApJ 121, 161.
Terashima, Y. and Wilson, A., Proceedings of the Symposium on “New Visions of the Universe in the XMM-Newton and Chandra Era”, 26-30 November 2001, ESTEC, The Netherlands, ESA SP-488 August 2002, Eds. F. Jansen and TBD.
Watarai, K. Mizuno, T. and Mineshige, S. 2001, ApJL 549, L77.
Wong, D.et al. 2002, Proc. Symposium ‘New Visions of the X-ray Universe in the XMM-Newton and Chandra Era’, ESA SP-488, Eds. F. Jansen & TBD.
Wu, H., Xue, S.J., Xia, X.Y. Deng, Z.G. and Mao, S. 2002, ApJ in press.
Zezas A., Fabbiano, G. Rots, A.H., Murray, S.S. 2002, ApJ in press.
Zombeck, M.V. 1990, Handbook of Space, Astronomy and Astrophysics. Cambridge University Press, Cambridge.