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The identification of an optical counterpart to the super-Eddington X-ray source NGC 5204 X-1

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ABSTRACT

We report the identification of a possible optical counterpart to the super-Eddington X-ray source NGC 5204 X-1. New *Chandra* data show that the X-ray source is point-like, with a luminosity of 5.2×10^{39} erg s^{-1} (0.5–8 keV). It displays medium- and long-term X-ray variability in observations spanning a period of 20 yr. The accurate *Chandra* position allows us to identify a blue optical continuum source ($m_v = 19.7$) at the position of NGC 5204 X-1, using newly obtained optical data from the INTEGRAL instrument on the William Herschel Telescope. The X-ray and optical source properties are consistent with the scenario in which we are observing the beamed X-ray emission of a high-mass X-ray binary in NGC 5204, composed of an O star with either a black hole or neutron star companion.

Key words: galaxies: individual: NGC 5204 – galaxies: stellar content – X-rays: galaxies.

1 INTRODUCTION

Einstein imaging observations were the first to reveal that the X-ray emission of many spiral galaxies is dominated by a small number of luminous ($L_X \sim 10^{38–40}$ erg s^{-1}) discrete X-ray sources located outside the nucleus of the galaxy (Fabbiano 1989, and references therein). *ROSAT* and *ASCA* observations have since confirmed the presence of one or more luminous extra-nuclear sources in many individual nearby galaxies, for example Dwingeloo 1 (Reynolds et al. 1997), Holmberg II (Zezas, Georgantopoulos & Ward 1999), NGC 5194 (Marston et al. 1995) and NGC 4321 (Immler, Pietsch & Aschenbach 1998). Early results from the *Chandra* observatory have extended this theme, most notably with the resolution of a high-luminosity ($L_X \sim 10^{40–41}$ erg s^{-1}), variable X-ray source located just off-nucleus in the nearby starburst galaxy M82 (Kaaret et al. 2001; Matsumoto et al. 2001). In a recent survey using archival *ROSAT* High Resolution Imager (HRI) observations, Roberts & Warwick (2000, hereafter RW2000) catalogued 29 sources with $L_X > 10^{39}$ erg s^{-1} in the 0.1–2.4 keV *ROSAT* band in a variety of nearby galaxies. Each of these sources is at least as luminous as a 10-$M_\odot$ black hole accreting at close to its Eddington limit; however, the nature of these super-Eddington sources (SES[1]) remains unclear. Known candidates for explaining the SES phenomena include recent supernovae/very young supernova remnants (SNRs), accretion on to a compact object, or unresolved complexes of X-ray sources.

Supernovae exploding into a dense circumstellar medium can produce very X-ray-luminous nebulae in their early stages (e.g. SN 1988Z with $L_X \sim 10^{41}$ erg s^{-1} : Fabian & Terlevich 1996), and indeed several of the RW2000 SES sample can be identified with recent supernovae, for example SN 1979C ≡ NGC 4321 X-4 (Immler et al. 1998) and SN 1986J ≡ NGC 891 X-3 (Bregman & Pildis 1992).

Alternatively, accretion processes may power much of the SES population. Evidence in favour of accretion comes from an *ASCA* study of several SES (Makishima et al. 2000), in which the spectra are shown to be well fitted by multicolour disc blackbody (MCD) emission from an optically thick standard accretion disc around a black hole. The unusually high temperatures required to fit these systems suggest that SES are analogous to the Galactic micro-quasars GRO 1655−40 and GRS 1915+105, and may be powered by accretion on to rapidly rotating high stellar mass (a few tens of $M_\odot$) black holes. In a similar vein, Colbert & Mushotzky (1999) suggested that some SES observed to be marginally offset from galactic nuclei (on scales of several hundred parsecs) in *ROSAT* HRI observations are not a type of low-luminosity AGN, but in fact constitute a new class of 'intermediate-mass' accreting black holes having masses of 10^2–$10^4\,M_\odot$. The key to recognizing SES as accreting systems is, of course, via significant variability; indeed, some systems are already known to display short-term variability over time-scales of ∼1000 s (IC 342 X-1, Okada et al. 1998; Holmberg II source, Zezas et al. 1999). Also, recent *ASCA* studies have demonstrated that long-term variability is present in several

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[1] A note on taxonomy: we refer to the class of $L_X > 10^{39}$ erg s^{-1} extra-nuclear sources as SESs throughout this Letter. This class of object is alternatively referred to as super-luminous X-ray sources (SLS), intermediate-luminosity X-ray objects (IXOs) or ultra-luminous compact X-ray sources (ULXs) in the literature, although the last acronym refers in particular to objects suspected to be powered by accretion.

SES, and is accompanied by transitions in the X-ray spectra of the objects between 'hard' and 'soft' states (Mizuno, Kubota & Makishima 2001; Kubota et al. 2001).

Unfortunately, X-ray data from the pre-*Chandra* era are severely spatially limited and so moderately compact complexes of X-ray-emitting sources (e.g. a cluster of low-mass X-ray binaries, each radiating at close to its Eddington luminosity, or a giant H II region containing one or more X-ray binaries plus a diffuse component) could not be spatially distinguished from bona fide individual examples of the SES phenomenon. This problem can now be addressed with the order-of-magnitude improvement in spatial resolution offered by *Chandra*.

A key to understanding the nature of the SES would be an identification with a known class of object, and follow-up studies at other wavelengths. This is now also possible because of the high astrometric accuracy achievable with *Chandra* data (~0.6 arcsec rms: Proposer's Observatory Guide v3.0). We may also address two interesting and related questions. The first is: what is the effect of an ionizing flux amounting to more than $10^{39}\,\mathrm{erg\,s^{-1}}$ upon its immediate surroundings? The second concerns the local galactic environment of the SES: what does this tell us about the nature of the source itself?

To these ends, we have recently acquired *Chandra* Advanced CCD Imaging Spectrometer (ACIS-S) X-ray data and William Herschel Telescope/INTEGRAL field spectrograph optical data for a number of prominent SES in the RW2000 sample. In this Letter we report an important early result of this programme, the possible identification of an optical counterpart to NGC 5204 X-1. This SES is located in the nearby ($d = 4.8$ Mpc : Tully 1988) magellanic-type galaxy NGC 5204. The presence of a luminous ($\log L_{\mathrm{X}} \sim 39.8\,\mathrm{erg\,s^{-1}}$) X-ray source in NGC 5204 was first shown in *Einstein* data (Fabbiano, Kim & Trinchieri 1992). This source has more recently been reported in *ROSAT* HRI data, where it is seen to be slightly offset from the nucleus of the galaxy (Colbert & Mushotzky 1999; RW2000; Lira, Lawrence & Johnson 2000) and is therefore identified as a possible SES as opposed to a low-luminosity active galactic nucleus candidate. In Section 2 we report the results of a 10-ks *Chandra* X-ray observation of this source. The William Herschel Telescope/INTEGRAL follow-up observation is then detailed in Section 3, followed (in Section 4) by a discussion of what this reveals about the nature of the SES.

2 X-RAY DATA

NGC 5204 X-1 was observed by *Chandra* on 2001 January 9 for a single exposure of 10.1 ks. The target was positioned on the back-illuminated ACIS-S S3 chip, which was operated in the standard 1/8 sub-array mode in order to alleviate the anticipated effects of pile-up in the target source. Data were reduced and analysed using the CIAO software version 2.0.1, starting with the level 2 event files. The in-orbit background was at a constant low level during the observation, and therefore we did not need to reject any exposure time because of background flare contamination.

Fig. 1 shows a Digitized Sky Survey 2 image of the galaxy. Only two X-ray sources are detected in the *Chandra* data: NGC 5204 X-1 (at $13^{\mathrm{h}}29^{\mathrm{m}}38\overset{\mathrm{s}}{.}6, +58°25'06''$), and a very faint source which lies ~15 arcsec to its south-east (at $13^{\mathrm{h}}29^{\mathrm{m}}40\overset{\mathrm{s}}{.}3, +58°24'54''$). The nucleus of the galaxy does not contain a luminous X-ray source. NGC 5204 X-1 appears point-like. Fitting the two-dimensional profile of the X-ray source with a Gaussian model confirms that it is unresolved – the half-energy width is found to be 0.8 arcsec, which matches that found in an on-axis ACIS observation of the point source PG 1634−706 [*Chandra* Proposer's Observatory Guide (2000), fig. 6.3]. We can therefore rule out any significant extended component of size greater than ~0.5 arcsec (≡12 pc in NGC 5204) contributing to the X-ray emission.

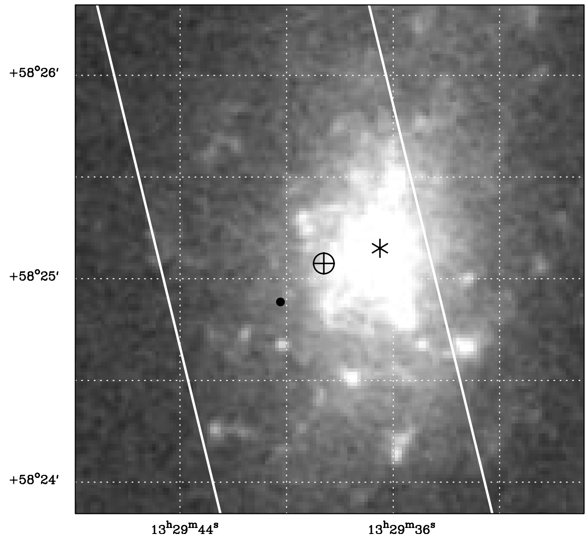

Figure 1. *Chandra* source positions overlaid on to the Digitized Sky Survey 2 image of the central $2.5 \times 2.5\,\mathrm{arcmin^2}$ region of NGC 5204. The coverage of the *Chandra* sub-array is shown by the parallel lines, and the galaxy nucleus is marked by an asterisk. The position of NGC 5204 X-1 is indicated by the crossed circle, and the faint *Chandra* detection by a small filled circle.

NGC 5204 X-1 has an observed ACIS-S count rate of $0.41\,\mathrm{count\,s^{-1}}$ and so the observation suffers from pile-up at the ~10 per cent level. This leads to a small distortion of the X-ray spectrum towards a harder form, and a slight underestimate of the true count rate; however, for our present purpose we make a preliminary spectral analysis ignoring pile-up effects (a more complete study will be the subject of future work). An X-ray spectrum was extracted for NGC 5204 X-1 using the appropriate CIAO tools, and analysed using the standard X-ray spectral fitting package XSPEC. We limited spectral analysis to the 0.5–10 keV band; however, in reality very few counts were observed above 5 keV. The spectrum appears relatively featureless, and the best fits to the data were found to be either a simple power-law continuum absorbed by cold, neutral material ($N_{\mathrm{H}} = 1.6 \pm 0.3 \times 10^{21}\,\mathrm{atom\,cm^{-2}}$, $\Gamma = 2.4 \pm 0.1$, $\chi^2_\nu = 1.27$ for 112 degrees of freedom) or an absorbed thermal bremsstrahlung spectrum ($N_{\mathrm{H}} = 5.4 \pm 1.7 \times 10^{20}\,\mathrm{atom\,cm^{-2}}$, $kT = 2.6 \pm 0.3$ keV, $\chi^2_\nu = 1.25$). Both a pure thermal plasma (MEKAL) model and the MCD model favoured in *ASCA* studies of ULXs (e.g. Makishima et al. 2000) were rejected. More complex models do not significantly improve the spectral fit. It is notable that the source spectrum appears soft, even after any hardening arising from pile-up. The observed flux was $1.9 \times 10^{-12}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ (0.5–8 keV), which equates to a luminosity of $5.2 \times 10^{39}\,\mathrm{erg\,s^{-1}}$ assuming that the source is located at the distance of NGC 5204.

The temporal characteristics of the source were also investigated. The short-term light curve from the ACIS-S observation shows no detectable variability over the 10-ks observation (a χ^2 test against the hypothesis that the flux level remains constant gives $\chi^2 = 31$ for 50 degrees of freedom). However, long-term variability is detected. In Fig. 2 we show the long-term light curve, composed of archival measurements from the *Einstein* and *ROSAT* missions plus the new data point. The light curve uses the best-fitting model to the *Chandra* data and, using either PIMMS or XSPEC, folds it through the response of each mission that detected NGC 5204 X-1. In each case the flux is normalized to the observed count rate, and fluxes are compared in the 0.5–2 keV band (chosen as it is covered by all the relevant missions). The resulting light curve shows a doubling of the flux in the 20 yr between the *Einstein* Imaging Proportional Counter (IPC) and *Chandra* ACIS-S observations, suggesting that the rising flux may represent a long-term trend. However, medium-term variability is also apparent in the *ROSAT* Position Sensitive Proportional Counter (PSPC) observations, showing a flux increase of ∼50 per cent in 11 months between 1993 and 1994. The latter variability is a strong pointer to the origin of the X-ray emission in accretion on to a compact object.

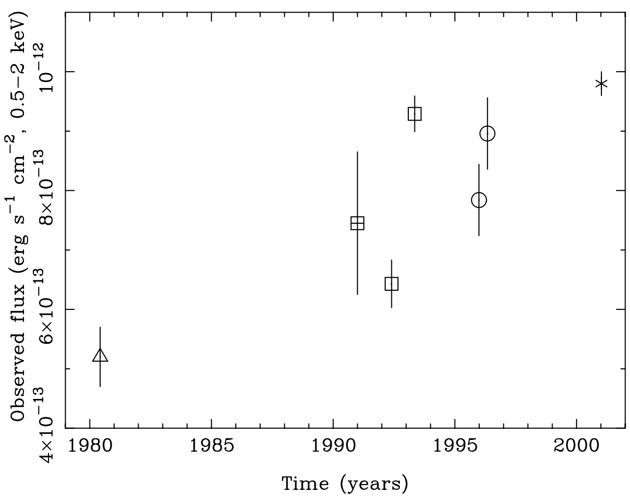

Figure 2. Long-term X-ray light curve of NGC 5204 X-1. This covers seven observations over 20 yr. *Einstein* data are indicated by a triangle, *ROSAT* PSPC data by squares, *ROSAT* HRI data by circles and the new *Chandra* data point by an asterisk. The count rates (converted to fluxes as per the text) were taken from Fabbiano et al. (1992; *Einstein* IPC), the *ROSAT* All-Sky Survey bright source catalogue (Voges et al. 1999) and WGACAT (White, Giommi & Angelini 1994) (*ROSAT* PSPC), and RW2000 (*ROSAT* HRI). Errors shown in the plot are 1σ.

3 OPTICAL DATA

The optical data were taken on the nights of 2001 February 1 and 2, using the INTEGRAL field spectrograph (Arribas et al. 1998) mounted on the William Herschel Telescope, La Palma. INTEGRAL provides simultaneous optical spectroscopy and, through the relative positions of the fibres, imaging. We used the 'SB2' fibre configuration, which gave us a field of view of 16.5 × 12.3 arcsec^2 covered by 189 fibres, each of diameter 0.9 arcsec. In this configuration an additional 30 fibres, at a radius of 45 arcsec, provide a measure of the local sky background for each observation. The R600R grating was used, giving a wavelength coverage of ∼4500–7500 Å and resolution ∼6 Å, and data were read out through WYFFOS. The target was observed for a total of 2 h, split into three sections over the two nights.

The fibre data were reduced in the standard fashion. This will be discussed in detail in a future paper (Goad et al., in preparation). The data reduction ultimately provided a flux-calibrated spectrum for each individual fibre, which were used to form the multicolour narrow-band images.

Fig. 3 shows six reconstructed images of the field centred on the position of NGC 5204 X-1, in a variety of narrow continuum bands and continuum-subtracted emission-line bands, with the *Chandra* X-ray emission contours overlaid. It is immediately obvious that an optical continuum source is present at or close to the position of the X-ray source. This source is not detected in any continuum-subtracted emission-line image. Inspection of the data shows that the continuum emission is detected in a single fibre, numbered 113, implying that the continuum source is point-like at the 0.9-arcsec resolution of INTEGRAL. This fibre is positioned immediately to

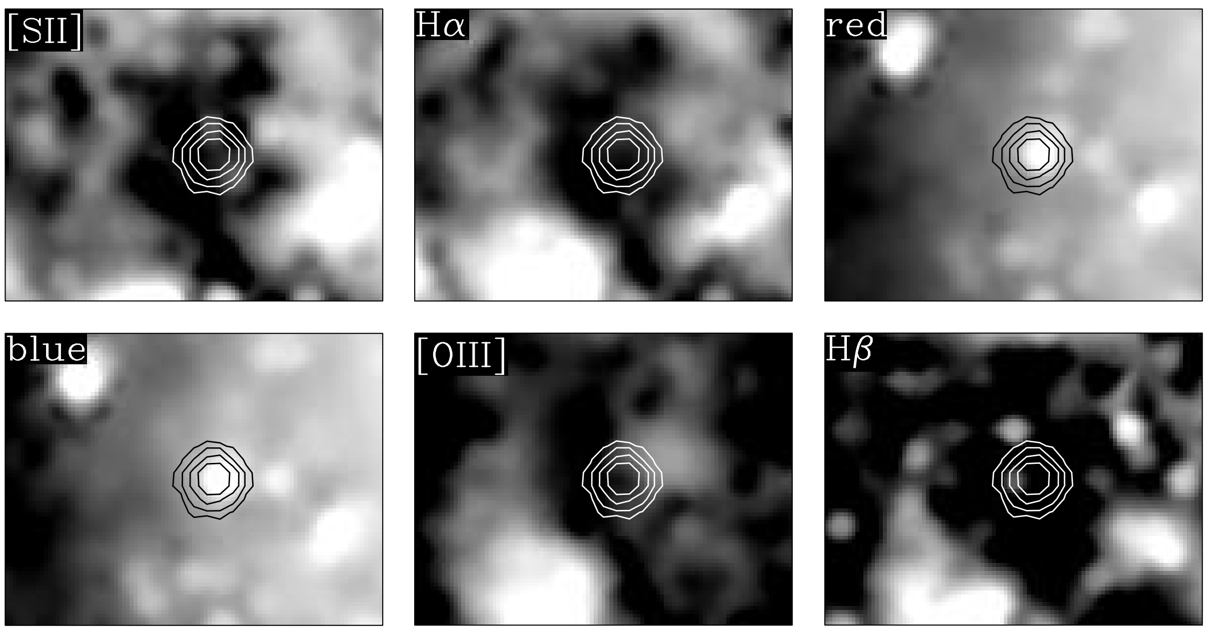

Figure 3. Reconstructed narrow-band INTEGRAL images. The images are in decreasing wavelength order, from top left to bottom right, and are in an arbitrary logarithmic grey-scale with white corresponding to the highest emission values. Note that all emission-line images are continuum-subtracted, and we use the 6000–6200 and 5100–5200 Å ranges for the red and blue continuum images respectively. X-ray contours from the *Chandra* data are overlaid.

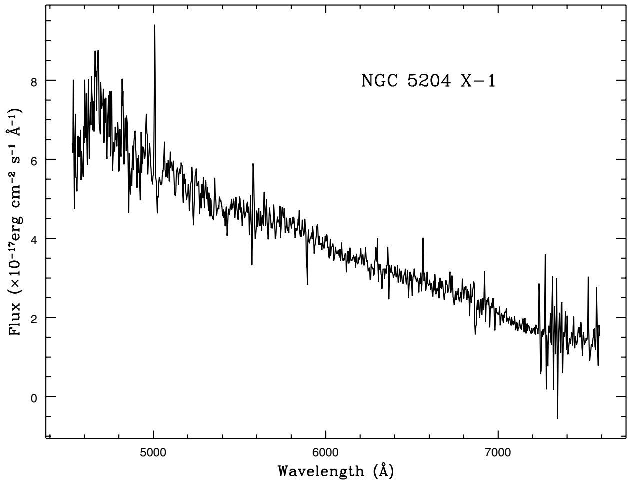

Figure 4. INTEGRAL optical spectrum of the counterpart to NGC 5204 X-1.

the west of the central fibre (number 110) of the field of view, but lies within the error circle for the X-ray source position,[2] and so the source is confirmed as a potential optical counterpart to the X-ray source.

It is possible that this source could be an unrelated interloper at the X-ray source position. We have estimated the probability of it being a background or foreground object, unrelated to NGC 5204, using an APM source list for a blank 30×30 arcmin^2 field offset to the north-east of NGC 5204. The observed magnitude of the counterpart is $m_v = 19.7$; the chance of a background or foreground object of this magnitude falling within the error circle is very small ($P \approx 3 \times 10^{-4}$). Similarly, we can use the INTEGRAL data to estimate the chance of a random coincidence with a comparably bright source in the region of NGC 5204 containing the counterpart, which gives a probability $P \approx 0.08$. It is very likely then that the optical counterpart is indeed associated with the X-ray source.

In Fig. 4 we present the INTEGRAL optical spectrum of the source. The source has a very obvious blue continuum spectrum, with little evidence for emission lines (indeed, the shallow emission lines present such as Hα are likely to be due to the small amounts of ionized gas seen in the environment of NGC 5204 X-1 in Fig. 3). Note that the presence of strong sky lines and low signal-to-noise ratio made the background subtraction and flat-fielding particularly difficult at either end of the wavelength range, but despite this the spectrum is essentially featureless. We discuss the implications of this in detail in the next section.

A second interesting feature of Fig. 3 is an apparent ‘hole’ in the ionized gas, seen predominantly to the east of NGC 5204 X-1 in the [S II], Hα and [O III] images, and also observed to extend to the west in the Hβ image. The continuum images show no obvious sign of this being due to absorption, for example in a dust lane. It is at least plausible therefore that this is a cavity in the interstellar medium of NGC 5204, apparently centred on the position of the X-ray source, with a diameter of ~100–200 pc.

[2] The positional error radius is a combination of the $\lesssim$1 arcsec *Chandra* positional error and a similar error on the INTEGRAL position, which in practice encompasses the central fibre plus its six immediate neighbours.

4 THE NATURE OF THE BEAST

4.1 A foreground or background source?

In the previous section we showed that the optical counterpart is very likely to be associated with the X-ray source. However, in the absence of strong features in the optical spectrum, we cannot confirm that the counterpart is associated with NGC 5204. This means that we must consider the merits of known classes of featureless blue continuum foreground and background sources as potential identifications.

A possible foreground identification, based on the very blue optical spectrum, would be an isolated white dwarf in our galaxy. However, the X-ray properties are not consistent with such a white dwarf, which would typically only display X-ray emission at energies up to a few hundred eV as opposed to the several keV observed (e.g. Marsh et al. 1997).

In terms of a background object, the best candidate would appear to be a BL Lac object. The featureless blue optical and X-ray continua, its point-like nature in both X-rays and optical, and the long-term X-ray variability are all consistent with the known properties of BL Lacs. In order to investigate this possibility further, given that BL Lac objects are radio-loud active galactic nuclei (AGN), we searched the NRAO VLA Sky Survey (NVSS: Condon et al. 1998) for a point-like radio continuum source at the position of NGC 5204 X-1. No source is found at the position of NGC 5204 X-1; however, an NVSS source of strength 16.3 mJy is present 26 ± 14 arcsec to its south-west. The difference in positions implies that the NVSS source is unlikely to be a radio counterpart to NGC 5204 X-1 [the astrometry of the survey is good to ~1 arcsec compared with US Naval Observatory A1.0 catalogue (USNO) optical positions]; however, this cannot be ruled out given that the spatial resolution of the survey is only 45 arcsec. In fact, we note that another candidate exists that may be the source of the radio continuum emission, namely a supernova remnant detected by Matonick & Fesen (1997), NGC 5204 #3, at a distance of 20 ± 12 arcsec from the NVSS detection. At the very least, the presence of the radio source may limit the sensitivity with which we can claim a non-detection at the position of NGC 5204 X-1, above the typical survey limit of ~2.5 mJy.

To ascertain whether NGC 5204 X-1 is actually a BL Lac, we derived α_{ro} and α_{ox} values as per Laurent-Muehleisen et al. (1999), for the cases in which the NVSS source is/is not the counterpart. If it is, then $\alpha_{ro} = 0.49$ and $\alpha_{ox} = 1.1$, which by fig. 3 of Laurent-Muehleisen et al. (1999) places NGC 5204 X-1 firmly in the parameter space occupied by BL Lac objects. If the NVSS source is not a counterpart, and we assume an upper limit of 2.5 mJy for the NVSS source flux, then we get $\alpha_{ro} \leq 0.33$ which implies that the source has at best a low α_{ro} value for a BL Lac. A further tightening of the constraints on radio continuum emission by a factor of a few would clearly put NGC 5204 X-1 outside the parameter space occupied by BL Lac objects, and so a high-resolution radio continuum follow-up of this source is essential.

4.2 NGC 5204 X-1 as an SES

A further possibility for the origin of the blue continuum optical spectrum is the emission from one or more O stars.[3] The observed

[3] We note that, although O-star spectra generally display absorption features, these are low-contrast features and we do not have the signal-to-noise ratio to distinguish them in the current optical spectrum.

magnitude ($m_v = 19.7$) is far too faint for a Galactic O star. Instead, if the emission comes from a source in NGC 5204, then its absolute magnitude is $M_v = -8.7$ (for a distance of 4.8 Mpc); this corresponds to the emission of ~8–20 'typical' supergiant/giant O stars (Zombeck 1990) within a ~12-pc region in NGC 5204. Although it seems unlikely that such a compact cluster of O stars may exist in apparent isolation in the galaxy, it is possible that we may be observing one or more unusually luminous O stars. If the optical counterpart is indeed stellar, then this would appear to confirm that the X-ray emission is originating in a binary system.

Recent theoretical work (King et al. 2001) has discussed the likely physical nature of the ULXs that constitute the accreting subset of SES. They come to the conclusion that, whilst accretion on to an intermediate-mass (10^2–$10^4\,M_\odot$) black hole cannot be ruled out in individual cases, the majority of ULXs may represent a short-lived but extremely common stage in the evolution of many X-ray binaries, in which the X-ray emission is mildly beamed. The best candidate for this epoch is a period of thermal-time-scale mass transfer in intermediate- and high-mass X-ray binaries. The short lifetimes of high-mass X-ray binaries and their association with star formation explain the unusually high numbers of these objects present in very actively star-forming galaxies (e.g. 'The Antennae': Fabbiano, Zezas & Murray 2001). This explanation is fully consistent with our observation of an O-star companion to the accreting source, and may, if the mass transfer is occurring as a result of the O star filling its Roche lobe as it crosses the Hertzsprung gap, also explain in part the unusual optical luminosity of the O star.

One final point to consider is the possible cavity in the interstellar medium of NGC 5204 identified in the INTEGRAL emission-line images. If this is a true cavity centred on NGC 5204 X-1 then it is very plausible that NGC 5204 X-1 may be in some way responsible for this, possibly because of the stellar wind from the O star (and its companions), or the progenitor supernova of the compact source. In either case, the presence of such a cavity is further evidence that NGC 5204 X-1 lies within the confines of the host galaxy.

5 CONCLUSIONS

We have used new *Chandra* ACIS-S X-ray data and William Herschel Telescope/INTEGRAL field spectroscopy to study the X-ray emission from the suspected SES NGC 5204 X-1, and have identified a possible counterpart with a blue continuum optical spectrum. Although we cannot completely rule out the scenario in which we are observing a BL Lac object behind NGC 5204, the observational evidence is consistent with the scenario in which we are viewing the beamed emission of a high-mass X-ray binary, containing either a black hole or a neutron star with an O-star companion, in a period of high mass transfer.

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