Chandra reveals a black-hole X-ray binary within the ultraluminous supernova remnant MF 16

T. P. Roberts$^{1,*}$ & E. J. M. Colbert$^2$

$^1$X-ray and Observational Astronomy Group, Dept. of Physics & Astronomy, University of Leicester, University Road, Leicester, LE1 7RH
$^2$Department of Physics and Astronomy, Johns Hopkins University, Baltimore, MD 21218, USA

$^*$E-mail: tro@star.le.ac.uk

ABSTRACT

We present evidence, based on Chandra ACIS-S observations of the nearby spiral galaxy NGC 6946, that the extraordinary X-ray luminosity of the MF 16 supernova remnant actually arises in a black-hole X-ray binary. This conclusion is drawn from the point-like nature of the X-ray source, its X-ray spectrum closely resembling the spectrum of other ultraluminous X-ray sources thought to be black-hole X-ray binary systems, and the detection of rapid hard X-ray variability from the source. We briefly discuss the nature of the hard X-ray variability, and the origin of the extreme radio and optical luminosity of MF 16 in light of this identification.

Key words: Galaxies: individual: NGC 6946 – X-rays: binaries – ISM: supernova remnants

1 INTRODUCTION

An observational definition of ultraluminous X-ray sources (ULX) is those X-ray sources detected coincident with nearby galaxies, that are both located outside the galactic nucleus and display an observed luminosity in excess of $10^{39}$ erg s$^{-1}$. There has recently been a lot of attention paid to this class of object based on the argument that if they are accretion-powered systems, then in many cases the observed X-ray luminosity exceeds the Eddington luminosity for a 10 $M_\odot$ black hole. Explanations for this apparent breach of the Eddington limit include accretion on to intermediate-mass black holes (e.g., Colbert & Mushotzky 1999; Miller & Hamilton 2002), super-Eddington radiation from bloated accretion discs in X-ray binaries (Begelman 2002), and anisotropic emission from X-ray binaries (e.g., King et al. 2001; Körding, Falcke & Markoff 2002; King 2002).

However, not all ULX are accreting systems. A minority of X-ray binaries (Begelman 2002), and anisotropic emission from X-ray binaries (e.g., Colbert & Mushotzky 1999; Miller & Hamilton 2002), super-Eddington radiation from bloated accretion discs in X-ray binaries (Begelman 2002), and anisotropic emission from X-ray binaries (e.g., King et al. 2001; Körding, Falcke & Markoff 2002; King 2002).

One supernova remnant that appears to have remained unusually X-ray luminous whilst becoming quite evolved is the remnant MF 16 in NGC 6946 (nomenclature from Martin & Fesen 1997). Though the X-ray source was detected in an Einstein IPC observation of NGC 6946 (Fabbiano & Trinchieri 1987), it was first identified as an extremely X-ray luminous supernova remnant (Lx $\sim 3 \times 10^{39}$ erg s$^{-1}$ at 5.1 Mpc, placing it firmly in the ULX regime) on the basis of ROSAT PSPC data (Schlegel 1994). The X-ray data appeared consistent with a young supernova remnant, but optical data revealed the remnant to be evolved, possibly $\sim 3500$ years old (Blair & Fesen 1994). The remnant appears extraordinarily luminous in X-rays, optical line emission and radio continuum emission (van Dyk et al. 1994) for a supernova remnant of this age. Subsequent HST observations revealed MF 16 to have a physical size of $\sim 34 \times 20$ pc, and a distinct morphology characterised by three “loops” apparent in narrow-band H$\alpha$ and [SII] images (Blair, Fesen & Schlegel 2001; hereafter BFS01), though an [OIII] image suggested a more elliptical structure with a possible young star at the heart of the nebula. In conjunction with optical spectral data, BFS01 suggest that the extraordinary luminosity of this remnant is due to the blast wave of a young supernova impacting on the dense shell of an older remnant. ROSAT and ASCA data were used to investigate the X-ray emission in detail by Schlegel, Blair & Fesen (2000), who found the spectral data to fit well to a dual Raymond-Smith thermal plasma model. This is consistent with the HST data if the hot component comes from the interaction zone and...
the soft component from within the supernova bubble. An alternate view is offered by Dunne, Gruendl & Chu (2000), who propose that the remnant originates in the interaction of a single supernova blast wave with a dense circumstellar nebula ejected from a massive progenitor star. They suggest that a hard component in the ROSAT PSPC spectral data may originate in a pulsar wind nebula.

The first of the two Chandra observations reported in this letter has been presented by Holt et al. (2003). They conclude that the featureless X-ray spectrum of MF 16 excludes the interaction of a blast wave with circumstellar matter, and does not appear to fit to a pulsar wind nebula model either. They suggest that the X-ray emission may originate in an unusual, if not unique, set of circumstances. Here, we re-analyse this data in tandem with a later public observation of NGC 6946, and demonstrate that the X-ray source associated with MF 16 is in fact a black-hole X-ray binary (BHXRB), explaining the apparent dichotomy of an evolved remnant with a young supernova-like X-ray flux.

2 OBSERVATIONS & DATA REDUCTION

NGC 6946 has been observed by Chandra on two separate occasions. The details of the observations are given in Table 1. Both observations were pointed at its nuclear region, though the target of the latter observation was the recent supernova SN2002HH, and the large majority of the area of the galaxy falls on the ACIS-S3 chip. MF 16 lies about 2.5 arcmin north-east of the observation aimpoint, fortuitously on the S3 chip in both datasets.

The data was reduced and subsequently analysed using the CIAO v2.3 and HEAsoft v5.2 packages. The level 2 event lists were initially filtered down to an energy range of 0.3–10 keV, and images were created at the full detector spatial resolution (1 pixel = 0.492 arcsec). Source spectra and lightcurves were then extracted using the PSEXTRACT and LIGHTCURVE tools respectively, from within a 10-pixel radius circular aperture set to encompass the full point spread function of the X-ray source. Background regions were extracted from a similar-size aperture displaced by ~10 arcsec from MF 16. Neither event list was time-filtered for background flaring, as the total background measured from the unfiltered background regions amounted to less than 0.5% of the counts accumulated from the source in either observation, allowing us to exploit the full exposure time.

3 EVIDENCE THAT MF 16 CONTAINS AN X-RAY BINARY SYSTEM

The X-ray counterpart of MF 16 (hereafter NGC 6946 X-11, after Roberts & Warwick 2000) was detected in both observations as the brightest X-ray source on the Chandra ACIS-S3 chip, at a position 20°35′00.75", +60°11′30.9"1. A total of 8585 ± 94 and 3838 ± 63 counts were detected from the source in the 2001 September and 2002 November observations respectively. This is currently amongst the largest datasets for an ULX in the Chandra era. In the following sections we present the details of its X-ray characteristics.

3.1 Spatial

We test whether NGC 6946 X-11 is spatially extended by comparing its radial profile from the 2001 September observation to a modelled point spread function (PSF) for a point-like X-ray source at the same detector position and off-axis angle2. The model is interpolated from a library of model PSFs using the MKPSF tool, at an energy of 1.5 keV. We account for known residual aspect correction errors (c.f. section 2.2 of Zezas et al. 2002) by convolving the model PSF with a 2-D Gaussian function of HWHM = 0.75 arcsec. Radial profiles for the model and source data were extracted in one-pixel width annuli around the source centroid, and the model PSF was normalised to the same central peak as the source. Approximating the PSF shape by a Gaussian function showed the source data and the modelled PSF to match extraordinarily well, with the best fit to each giving a HWHM of 1.31 ± 0.02 arcsec for the data, and 1.33 ± 0.02 arcsec for the model (the fitting was performed using a $\chi^2$ minimization algorithm, and the errors quoted are 90% errors for one interesting parameter). The observed X-ray emission is therefore fully consistent with originating in a point-like source. However, by comparison with Roberts et al. (2002) we note that on-axis Gaussian fits to point-like sources give a HWHM of ~1 arcsec for a spatial resolution of 0.5 arcsec. Scaling this to our observation implies it is sensitive to structure on scales of > 0.7 arcsec, ruling out extended X-ray emission on the full scale of MF 16 (1.4 × 0.8 arcsec; BFS01), though some spatial extension on scales less than this cannot be excluded.

3.2 Spectral

Before undergoing spectral analysis, the auxiliary response files for both datasets were corrected for the known quantum efficiency degradation of the ACIS-S3 chip using the CORRARF tool. The extracted source spectra were binned to a minimum of 20 counts per bin before analysis in XSPEC v11.2, and only data in bins located above an energy of 0.5 keV were considered. The observed 0.3–10 keV count rates of ~0.12 – 0.14 count s$^{-1}$ were accumulated in a full-frame exposure mode in both observations which, even allowing for their off-axis positions, implies that the source data will have suffered from a moderate level (~10 – 15%) of pile-up. We account for this in the following analysis using the XSPEC v11.2 parameterisation of the Davis (2001) CCD pile-up mitigation algorithm.

---

1 This is an average of the two positions from the separate observations, though the difference between the measured positions was a mere 0.4".

2 Combining the data from both observations to produce a higher quality radial profile is not an option, since the source is at different off-axis angles and detector positions in the two observations.
The observed X-ray spectra (data points) and best fitting models (solid lines; c.f. Table 2) from the Chandra reveals a black-hole X-ray binary within the ultraluminous supernova remnant MF 16 Table 2.

Two-component fits to the continuum the only model to have a reduced-

component simple models, with an absorbed powerlaw con-

the fit at a significance of $\chi^2$-value below 2

for both datasets. We note that in both cases a correction for pile-up was justified since it provided an improvement to

$\chi^2$/dof, though the resulting fits were still poor ($\chi^2$/dof = 239.8/157 and 159.2/114 for the 2001 September and 2002 November). This seems physically implausible, since the observation of no absorption intrinsic to MF 16 is at odds with the total extinction of $E(B - V) = 0.65$ observed for its optical emission lines (BFS01). This extinction converts to a column of $4.3 \times 10^{21}$ atoms cm$^{-2}$ (c.f. Zombeck 1990).

On the other hand, the MCDBB or classical blackbody plus powerlaw continuum model fits are consistent with the inferred column to the central regions of MF 16. Crucially, the MCDBB plus powerlaw continuum model has recently been found to describe the Chandra or XMM-Newton X-ray spectra of several ULX that are known or suspected BHXRB (e.g. Miller et al. 2003). Furthermore, the derived parameters, and in particular the inner-disc temperature and normalisation (constrained at $870^{+660}_{-170}$ and $1600^{+1700}_{-1300}$ km s$^{-1}$ (10 kpc)$^{-2}$ in epochs A and B respectively) of the MCDBB appear extraordinarily similar when our fits are compared to the ULX studied by Miller et al. (2003). This suggests that the X-ray emission processes in NGC 6946 X-11 are those of a BHXRB. The data also suggest that the spectrum changes between observations, though as the error ranges for each of the parameters overlap none of the changes are very statistically significant. This tentative suggestion of spectral

| Model $^a$ | Epoch $^b$ | $\alpha$ $^c$ | $N_H$ $(10^{22}$ cm$^{-2})$ | $kT_1$ (keV) | Abundance (Solar units) | $kT_{IVA}$ (keV) | $\Gamma$ | $kT_2$ (keV) | $\chi^2$/dof |
|------------|------------|---------------|-----------------|-------------|---------------------|--------------|----------|-------------|-------------|
| PU*WA*(D+PO) | A | 0.16$^{+0.06}_{-0.04}$ | 0.37$^{+0.04}_{-0.02}$ | - | - | 0.16$^{+0.04}_{-0.02}$ | - | - | 178.0/155 |
| B | < 0.19 | 0.47$^{+0.02}_{-0.08}$ | - | 0.14$^{+0.01}_{-0.02}$ | - | 2.38$^{+0.14}_{-0.18}$ |
| PU*WA*(B+PO) | A | 0.16$^{+0.06}_{-0.04}$ | 0.38$^{+0.02}_{-0.06}$ | 0.12$^{+0.01}_{-0.02}$ | - | - | 2.46$^{+0.07}_{-0.21}$ |
| B | < 0.31 | 0.44$^{+0.01}_{-0.11}$ | 0.12$^{+0.01}_{-0.01}$ | - | - | 2.23$^{+0.22}_{-0.22}$ |
| PU*WA*(M+PO) | A | 0.38$^{+0.04}_{-0.08}$ | $2^f$ | 0.66$^{+0.13}_{-0.07}$ | 0.33$^{+0.02}_{-0.02}$ | 0.07$^{+0.02}_{-0.02}$ | - | 2.15$^{+0.12}_{-0.12}$ |
| B | 0.30$^{+0.07}_{-0.15}$ | $2^f$ | 0.77$^{+0.08}_{-0.15}$ | 5.7$^{+3.0}_{-4.0}$ | - | - | 2.32$^{+0.1}_{-0.13}$ |
| PU*WA*(M+M) | A | 0.42$^{+0.04}_{-0.02}$ | $2^f$ | 0.33$^{+0.02}_{-0.02}$ | 0.14$^{+0.01}_{-0.04}$ | - | - | 2.43$^{+0.78}_{-0.69}$ |
| B | 0.34$^{+0.07}_{-0.02}$ | $2^f$ | 0.64$^{+0.05}_{-0.04}$ | 0.14$^{+0.01}_{-0.04}$ | - | - | 135.4/112 |

Notes: $^a$ Model components are: PU - pileup correction; WA - cold absorption; D - multicolour disc blackbody; PO - powerlaw continuum; B - classical blackbody; M - MEKAL optically thin thermal plasma model. $^b$ Epoch of observation, with A $\equiv$ 2001 September and B $\equiv$ 2002 November. $^c$ Grade migration parameter in the pile-up mitigation model. $^f$ Parameter value fixed at that shown.

| Figure 1 | The observed X-ray spectra (data points) and best fitting models (solid lines; c.f. Table 2) from the Chandra observations of NGC 6946 X-11. The datasets are plotted on identical axes for direct comparison. |
variation is also indicative of BHXRB behaviour. We note that the observed 0.5 – 8 keV luminosity of NGC 6946 X-11 from this model is $\sim 2.5 \times 10^{39}$ erg s$^{-1}$, of which $\sim 20\%$ originates in the MCDDB component.

Finally, we also fit a dual MEKAL model to the data, similar to the dual Raymond-Smith plasma model used to provide a fit to the combined ROSAT PSPC/ASCA spectral data (Schlegel, Blair & Fesen 2000). We are again required to constrain the absorption column to the foreground galactic value. Our fits provide reasonably similar results to the low-Z ROSAT PSPC/ASCA fit, albeit with our substantially lower fit abundances allowing the temperatures of both components to be lower in the Chandra data. However, this model is clearly the least preferred of the four two-component spectral models for both Chandra datasets, arguing that the blast wave interaction interpretation of Schlegel, Blair & Fesen (2000) is not favoured by the Chandra data.

### 3.3 Temporal

Previous analyses of this object have suggested that the X-ray flux remains constant over a timescale of years (e.g. Holt et al. 2003), as would be expected for the X-ray emission from an object up to 30 pc in diameter. Here, we detect a drop of $\sim 13\%$ in the 0.3 – 10 keV count rate over a year, from 0.144 count s$^{-1}$ to 0.125 count s$^{-1}$, clearly inconsistent with such an extended X-ray source. However, the Chandra CCDs have a known problem with their quantum efficiency, and hence effective area to incoming photons, degrading with time. This could lead to drops in the detected count rate for separate observations of constant X-ray fluxes, particularly for sources with soft X-ray spectra. We checked this by running simulations in XSPEC, using the best fit model to the 2001 September data, and the auxiliary response file (corrected to the degraded area) from the 2002 November observation. An overall drop of $\sim 3\%$ in the count rate was predicted, clearly smaller than the observed deficit, implying that the source displays at least small amplitude variability on long timescales.

The X-ray variability was further investigated by deriving short-term lightcurves from both observations. Both lightcurves were extracted in the full 0.3 – 10 keV range and binned to a temporal resolution equivalent to 25 counts per bin for a constant source count rate, in order to maximise the temporal resolution whilst maintaining a reasonable average signal-to-noise ratio of five per bin. Two simple tests for variability were then applied to these lightcurves. Firstly, a classic standard deviation of the count rate per bin from the mean count rate over the course of the observation was calculated, and then compared to the expected deviation of ±20% expected from Gaussian counting noise. Secondly, a $\chi^2$ test was performed against the hypothesis that the source count rate remained constant during the observation. The results of these tests, including a probability that the data is variable, $P$(var), shown for the cases where it exceeds 90%, and the binning of the lightcurves are reported in Table 4. They show that the full band lightcurve for the 2002 November observation was statistically consistent with a flat count rate. However, both a large excess in the standard deviation and in the $\chi^2$ statistic show the 2001 September data to be variable to very high probabilities (99.7 and > 99.9% likelihood, respectively). We investigated this variability further by splitting each dataset into two arbitrary energy bands containing approximately the same number of counts, a 0.3 – 1.1 keV “soft” band and a 1.1 – 10 keV “hard” band. The lightcurves for these bands are shown in Figure 2 again binned to the equivalent of an average of 25 counts per bin (c.f. Table 4 for actual bin sizes). Both the tests on the binned lightcurves show no strong evidence for variability in the soft band. However, strong evidence for variability is present in the hard band lightcurve in the 2001 September observation (at over 99.9% likelihood in both tests), and may also be present in the 2002 November observation ($\sim 96\%$ likelihood according to the $\chi^2$ test).

In order to provide a separate test of the variability free of any gross photon binning effects we employed a Kolmogorov-Smirnov test, in which we compared the cumulative photon arrival times to the expected cumulative arrival times for a constant-flux source$^3$. This provided separate confirmation of the strong variability in the 2001 September hard band data, and possible variability in the

---

$^3$ Though note that the data is strictly limited by the 3.24104 s temporal resolution (which is the sum of the exposure time plus the frame readout time) of the ACIS-S3 chip in the course of performing this test.
Chandra reveals a black-hole X-ray binary within the ultraluminous supernova remnant MF 16

Table 3. Tests of the short-term variability of NGC 6946 X-11.

| Epoch       | Band^a | Bin size | Expected^b | Observed^b | Standard deviation, σ | $P_\chi^2$(var) | $P_\sigma$(var) | K-S statistic |
|-------------|--------|----------|------------|------------|------------------------|----------------|----------------|---------------|
| 2001 September | Full   | 174      | 2.88 ± 10^{-2} | (3.37 ± 0.18) × 10^{-2} | 99.7% | 534/340 > 99.9% | 〜 94% |
|             | Soft   | 367      | 1.36 ± 10^{-2} | (1.38 ± 0.11) × 10^{-2} | - | 145/160 - | - |
|             | Hard   | 330      | 1.51 ± 10^{-2} | (1.97 ± 0.15) × 10^{-2} | 99.9% | 402/178 > 99.9% | 〜 99% |
| 2002 November | Full   | 199      | 2.51 ± 10^{-2} | (2.65 ± 0.22) × 10^{-2} | - | 158/152 - | - |
|             | Soft   | 464      | 1.08 ± 10^{-2} | (1.03 ± 0.13) × 10^{-2} | - | 69/65 - | 〜 99% |
|             | Hard   | 351      | 1.43 ± 10^{-2} | (1.55 ± 0.17) × 10^{-2} | - | 110/86 〜 96% | 〜 95% |

Notes: a as defined in the text. b in count s^{-1}. We only show $P$(var) in the instances where it highlights the variability.

2002 November hard data. Interestingly, it also showed the 2002 November soft data to be variable at high significant (〜 99%), which was not picked up by any other test. An examination of the photon arrival time distribution for the data shows this result is due to a slight increase in the average soft count rate over the latter stages of the 2002 November observation, when compared to the earlier stages, which the standard deviation and $\chi^2$ tests were insensitive to. The actual average count rate change was from $(5.25 ± 0.17) × 10^{-2}$ count s^{-1} in the first 18.5 ks to $(5.61 ± 0.22) × 10^{-2}$ count s^{-1} in the latter 11.5 ks. We note this probably a real change, and is certainly not due to a change in the background count rate for the source, which remains at 〜 10^{-4} count s^{-1} in the soft band throughout the observation.

Our statistical tests, and the amplitude of the variability shown by Figure 2 demonstrate that the majority of the hard X-ray emission of NGC 6946 X-11 is varying at least on the timescale of the binning size we use to maximise our statistics, 〜 330 – 350 s. The hard X-ray emission is therefore originating in a region with a light crossing time of less than six minutes ($\approx 10^8$ km). This is consistent with a compact accretion-driven X-ray source such as an X-ray binary, and not with a spatially-extended supernova remnant. Note, however, that we cannot currently exclude the majority of the soft X-ray emission from originating in a more widespread component.

### 4 DISCUSSION

NGC 6946 X-11 is a point-like X-ray source, its X-ray spectrum is well-fit by models used to describe ultraluminous BHXB, and its hard X-ray emission varies on timescales of less than six minutes. The simplest interpretation of this evidence is that the extraordinary X-ray luminosity of NGC 6946 X-11 originates in the accretion of matter in a BHXB system, and not from the interaction of supernova blast waves with circumstellar material, or a pulsar wind nebula, as previously suggested. Of course, we cannot exclude some spatial extension in the X-ray source, which the lightcurves tell us would be to soft X-ray emission. If we ignore for a moment the unrealistically low column to the MEKAL plus powerlaw continuum model, the MEKAL could still describe the hot gas phase of a supernova remnant. However, the spectral modelling implies that only 〜 10% of the observed flux originates in the MEKAL component, implying that the contribution to the observed luminosity from a hot plasma is limited to 〜 2.5 × 10^{38} erg s^{-1}.

If we are dealing with an ultraluminous BHXB, it appears quite typical for the limited knowledge we have of this exotic class of object. A similar spectral model has been derived for the few other ULX with reasonable quality X-ray spectral data (Miller et al. 2003; Krauss et al. 2003; Kaaret et al. 2003), with the low inner-disc temperatures for the MCDBB component interpreted as possible evidence for the presence of intermediate-mass black holes. We also note that the dominant powerlaw continuum component has a value very similar to that observed for Galactic BHXBs in the high state (〜 2.5; c.f. Ebisawa, Titarchuk & Chakrabati 1996). One curious feature we have identified is that the X-ray variability in this ULX is predominantly above 1.1 keV, implying that it is the powerlaw continuum spectral component that is varying, and not the thermal emission from the accretion disc. This exclusively hard X-ray variability could quite conveniently explain the observed spectral hardening with increased flux seen in many ULX (e.g. Fabbiano et al. 2003). However, the scenario they describe where the hardening is due to a hotter inner accretion disc at higher accretion rates may not be consistent with our observations, due to the short variability timescales and the softness of the thermal disc component in the X-ray spectrum. The rapid variation of the hard X-rays may instead originate in other physical mechanisms, for instance variations at the base of a jet (c.f. Georgakopoulos, Aharonian & Kirk 2002), or magnetic reconnection events in the accretion disc corona (c.f. Reeves et al. 2002 for a discussion of the latter mechanism applied to the quasar PDS 456).

Now that we have identified the X-ray emission from MF 16 with a BHXB, where does this leave the physical models for the extreme radio and optical luminosity of the supernova remnant? It may be possible that the radio emission could originate from the BHXB in a relativistically-beamed jet, similar to that reported for an ULX in NGC 5408 by Kaaret et al. (2003). It is also quite possible that the optical line emission may be a result of the presence of the BHXB; we note that nebulae have been reported to be present at or around the positions of several ULX by Pakull & Mirioni (2003a,b). Some of these nebulae are present as giant (d 〜 100 – 400 pc) bubbles encircling the ULX position; they may be supernova remnants related to the birth of the ULX, as could be the case around IC 342 X-1 (see also Roberts et al. 2003), or may be inflated by the winds from young stars or relativistic jets from the BHXB. Other nebulae, such as that present near the Holmberg II ULX, shows signs of X-ray ionization. We note that two of the key diagnostics of X-ray ionization, the presence of a He
II λ4686 emission line (c.f. Pakull & Angebault 1986) and an abnormally high [OIII]/Hβ ratio (Remillard, Rappaport & Macri 1995) are present in the optical spectrum of MF 16 presented by BFS01. The similarity between MF16 and other ULX nebulae is noted by Pakull & Mirioni (2003b); we suggest here that at least some of the extraordinary optical emission-line luminosity of MF 16 may originate in X-ray excitation. Furthermore, we speculate that the nebula itself may be a young precursor of the giant bubbles seen by Pakull & Mirioni (2003a,b) around other ULX systems. Further studies of MF 16 in this context would be of great interest. Finally, we note that the HST images of MF 16 suggest the presence of a young stellar object at the centre of the nebula. Young stars or stellar clusters have been discovered coincident with at least two other ULX (Goad et al. 2002; Liu et al. 2002), hence it is possible that this object may be the optical counterpart of the BHXRB itself.

ACKNOWLEDGMENTS

The authors the referee, Eric Schlegel, for his useful comments that helped to improve this paper. We also thank Andy Ptak for assisting us in the use of XASSIST. TFR thanks Bob Warwick and Graham Wynn for useful discussions, and PPARC for financial support.

REFERENCES

Begelman M.C., 2002, ApJ, 568, L97
Blair W.P., Fesen R.A., 1994, ApJ, 424, L103
Blair W.P., Fesen R.A., Schlegel E.M., 2001, AJ, 121, 1497 (BFS01)
Bregman J.N., Pildis R., 1992, ApJ, 398, L107
Colbert E.J.M., Mushotzky R.F., 1999, ApJ, 519, 89
Davis J.E., 2001, ApJ, 562, 575
Dunne B.C., Gruendl R.A., Chu Y.-H., 2000, AJ, 119, 1172
Ebisawa K., Titarchuk L., Chakrabati S.K., 1996, PASJ, 48, 59
Fabian A.C., Terlevich R., 1996, MNRAS, 280, L5
Fabbiano G., Trinchieri G., 1987, ApJ, 315, 46
Fabbiano G., Zezas A., King A.R., Ponman T.J., Rots A., Schweizer F., 2003, ApJ, 584, L5
Fox D.W., et al., 2000, MNRAS, 319, 1154
Georganopoulos M., Aharonian F., Kirk J., 2002, A&A, 388, L25
Goad M.R., Roberts T.P., Knigge C., Lira P., 2002, MNRAS, 335, L67
Holt S.S., Schlegel E.M., Hwang U., Petre R., 2003, ApJ, in press
Immler S., Lewin W.H.G., 2002, astro-ph/0202231
Immler S., Pietsch W., Aschenbach B., 1998, A&A, 331, 601
Kaaret P., Corbel S., Prestwich A.H., Zezas A., 2003, Science, 299, 365
King A., 2002, MNRAS, 335, L13
King A., Davies M.B., Ward M.J., Fabbiano G., Elvis M., 2001, ApJ, 552, L109
Körding E., Falcke H., Markoff S., 2002, A&A, 382, L13
Krauss M., Kilgard R., Garcia M., Roberts T.P., Prestwich A., 2003, ApJ, submitted
Liu J.-F., Bregman J.N., Seitzer P., 2002, ApJ, 580, L31
Matonick D.M., Fesen R.A., 1997, ApJS, 112, 49
Miller J.M., Fabbiano G., Miller M.C., Fabian A.C., 2003, ApJ, 585, L37
Miller M.C., Hamilton D.P., 2002, MNRAS, 330, 232
Mitsuda K., et al., 1984, PASJ, 36, 741
Pakull M.W., Angebault L.P., 1986, Nature, 322, 591
Pakull M.W., Mirioni L., 2003a, in Proceedings of the Symposium “New Visions of the Universe in the XMM-Newton and Chandra era”, ed. F. Jansen, ESA SP-488, astro-ph/0202488
Pakull M.W., Mirioni L., 2003b, RMxAA, 15, 197
Reeves J.N., Wynn G., O’Brien P.T., Pounds K.A., 2002, MNRAS, 336, L56
Remillard R.A., Rappaport S., Macri L.M., 1995, ApJ, 439, 646
Roberts T.P., Goad M.R., Ward M.J., Warwick R.S., 2003, MNRAS, in press
Roberts T.P., Warwick R.S., 2000, MNRAS, 315, 98
Roberts T.P., Warwick R.S., Ward M.J., Murray S.S., 2002, MNRAS, 337, 677
Ryder S., Staveley-Smith L., Dopita M., Petre R., Colbert E.J.M., Malin D., Schlegel E., 1993, ApJ, 416, 167
Schlegel E.M., 1994, ApJ, 424, L99
Schlegel E.M., Blair W.P., Fesen R.A., 2000, AJ, 120, 791
Snowden S., Mukai K., Pence W., Kuntz K., 2001, AJ, 121, 3001
Stark A., Gammie C.F., Wilson R.W., Bally J., Linke R.A., Helles C., Hurwitz M., 1992, ApJS, 79, 77
van Dyk S.D., Sramek R.A., Weiler K.W., Hyman S.D., Virden R.E., 1994, ApJ, 425, L77
Wang Q.D., 1999, 517, L27
Zezas A., Fabbiano G., Rots A., Murray S., 2002, ApJ, 577, 710
Zombeck M.V., 1990, Handbook of Astronomy and Astrophysics, Second Edition (Cambridge, UK: CUP)