**Chandra observations of five X-ray transient galactic nuclei**

S. Vaughan,1,2* R. Edelson3 and R. S. Warwick2

1Institute of Astronomy, Madingley Road, Cambridge CB3 0HA
2X-Ray and Observational Astronomy Group, University of Leicester, Leicester LE1 7RH
3Astronomy Department, University of California, Los Angeles, CA 90095-1562, USA

Accepted 2004 January 12. Received 2003 December 23; in original form 2003 November 12

**ABSTRACT**

We report on exploratory Chandra observations of five galactic nuclei that were found to be X-ray bright during the ROSAT All-Sky Survey (with \( L_X \gtrsim 10^{39} \text{ erg s}^{-1} \)) but subsequently exhibited a dramatic decline in X-ray luminosity. Very little is known about the post-outburst X-ray properties of these enigmatic sources. In all five cases Chandra detects an X-ray source positionally coincident with the nucleus of the host galaxy. The spectrum of the brightest source (IC 3599) appears consistent with a steep power law (\( \Gamma \sim 3.6 \)). The other sources have too few counts to extract individual, well-determined spectra, but their X-ray spectra appear flatter (\( \Gamma \sim 2 \)) on average. The Chandra fluxes are \( \sim 10^2–10^3 \) fainter than was observed during the outburst (up to 12 yr previously). That all post-outburst X-ray observations have seen a similarly low X-ray luminosities is consistent with these sources having ‘switched’ to a persistent low-luminosity state. Unfortunately the relative dearth of long-term monitoring and other data mean that the physical mechanism responsible for this spectacular behaviour is still highly unconstrained.

**Key words:** galaxies: active – galaxies: nuclei – galaxies: Seyfert – X-rays: galaxies.

**1 INTRODUCTION**

Very large-amplitude variations in the X-ray luminosity (greater than a factor \( \gtrsim 100 \)) emanating from galactic nuclei are unquestionably an indicator of unusual and interesting phenomena. Such ‘transient-like’ behaviour has been observed in only a handful of galaxies to date (see Donley et al. 2002; Komossa 2002) through observations with ROSAT.1 These soft X-ray bright galactic nuclei detected during the ROSAT All-Sky Survey (RASS) were found in subsequent follow-up observations with the same satellite to be fainter, by factors of 70–400, than their initial RASS detection. Such spectacular long-term fading is markedly different from the persistent low-luminosity state. Unfortunately the relative dearth of long-term monitoring and data mean that the physical mechanism responsible for this spectacular behaviour is still highly unconstrained.

*E-mail: sav2@star.le.ac.uk

1 Piro et al. (1988) reported a factor of \( \gtrsim 20 \) decrease in the 0.5–4.5 keV luminosity of E1615+061 between HEAO-1 A2 and Einstein observations; however, ASCA measured rapid, persistent variability in this object (Guainazzi et al. 1998) suggesting that it does not fit the above definition.

**2 OBSERVATIONS AND DATA ANALYSIS**

**2.1 Observations**

The five targets were each observed close to the aim-point of the back-illuminated ACIS chip S3 (ACIS-S3). As the expected X-ray...
fluxes for these objects were uncertain by an order of magnitude, four of the observations were performed with the ACIS CCDs using the quarter-frame subarray. This reduced the CCD readout time (to 1.07 s) and thereby reduced any possible effects from photon pile-up (Ballet 1999) if the sources were brighter than expected. The observation of RX J1242.6−1119 was performed in full-frame mode.

The data were processed from the level-1 events files using CIAO v2.3. Only events corresponding to grades 0, 2, 3, 4 and 6 were used in the analysis of processed data. Flares in the background level were identified by examining the light curve from the whole ACIS-S1 chip. These showed that the observations of WPVS 007, IC 3599 and RX J1242.6−1119 were free from background flares. The observation of RX J1624.9+7554 showed an increase in the background level in the final ∼200 s of the observation; data taken during this time interval were removed prior to analysis. The observation of NGC 5905 suffered from a higher background level (compared with the other observations) such that the removal of the periods of high background would leave insufficient data for analysis. Therefore, the full exposure of NGC 5905 was accepted accepting that the background level was enhanced. Table 1 lists the basic properties of the five target sources and their Chandra observations.

### 2.2 X-ray imaging

Fig. 1 shows the X-ray contour plots derived from the ACIS images for the five targets after adaptive smoothing has been applied. Clearly in all cases there is an excess of photons coincident with the optical position of the galactic nucleus (i.e. within the expected ∼2 arcsec uncertainty in the optical position). The optical positions were taken from the references given in Section 3 and the NASA/IPAC Extragalactic Database (NED).

In the case of RX J1242.6−1119, the positional error circle of the RASS X-ray source contains a pair of inactive galaxies, labelled A and B by Komossa & Greiner (1999). From the ROSAT data it was not clear which of the two should be identified with the X-ray source. The X-ray source detected by the Chandra observation is clearly coincident with galaxy A (Fig. 1). Assuming that this is the same X-ray source as detected by ROSAT then the X-ray outburst should be associated with galaxy A. All the X-ray sources appear consistent with being point-like with the possible exception of NGC 5905, which displays a slightly asymmetric shape in the smoothed image. However, with only ∼25 counts in the source and an enhanced background level it is difficult to be more confident of this without a more sensitive observation. It is interesting to note that of the five targets NGC 5905 is the nearest (1 arcsec or 2 pixels corresponds to a spatial scale of ∼0.2 kpc at the source redshift) and thus might be most likely to show extended emission in the Chandra images.

#### 2.3 Count rates and softness ratios

Source counts were estimated by performing photometry on the raw (unsmoothed) images with a circular aperture of radius of 2 arcsec centred on the source. The background level was estimated from a concentric annulus with inner and outer radii of 3 and 60 arcsec, respectively (excluding nearby sources where present). The net counts associated with each source are given in Table 1. The brightest object, IC 3599, has ≥200 photons in its X-ray image, enough for crude spectral analysis (see below). The other four detections are based on far fewer counts. In the case of RX J1624.9+7554 there are only 4 counts in the source aperture, i.e. a ∼2σ confidence detection (with negligible background), but the coincidence with the optical position makes this a likely detection of the nuclear X-ray emission.

Softness ratios were calculated for use as a crude indicator of the spectral slopes of the faint sources. The softness ratio was defined as the ratio of counts in the bands 0.3−1.0/0.3−0.7 keV. These are given in Table 1 and show IC 3599 to have a very soft spectrum with the other four sources showing somewhat harder emission. For the three harder sources (RX J1242.6−1119, NGC 5905 and RX J1624.9+7554) the softness ratio corresponds to a power-law photon index Γ ≤ 2.5. The measured softness ratio of IC 3599 requires Γ ∼ 4 (see below).

In all cases the 0.3−7.0 keV flux was estimated using the pimms calculator at the Chandra X-ray Center. For this purpose the spectrum was assumed to be a power-law (with a photon index Γ = 3) modified by Galactic absorption. The estimated fluxes are listed in Table 1. If the underlying X-ray spectra differ substantially from the assumed spectral form then these flux estimates may change by a factor of a few. The 0.3−7.0 keV unabsorbed luminosities were estimated assuming the same spectral model and are also listed in the table.

---

Table 1. Source observation log and properties.

| Source Name | RA (J2000) | Dec. (J2000) | z | N_H^e | Observation Date | Exposure (ks) | Counts^b | SR^c | Flux^d | L_X^e |
|-------------|------------|-------------|---|--------|------------------|--------------|----------|------|--------|-------|
| WPVS 007    | 00 39 15.8 | −51 17 03   | 0.029 | 2.6    | 2002 Aug 2       | 9.3          | 9.8 ± 4.2 | 2.4 ± 1.7 | 0.89   | 2 × 10^{40} |
| IC 3599     | 12 37 41.2 | 26 42 29    | 0.022 | 1.3    | 2002 Mar 7       | 10.2         | 247.8 ± 16.8 | 5.2 ± 0.9 | 17    | 2 × 10^{41} |
| RX J1242.6−1119 | 12 42 38.5 | −11 19 21  | 0.05 | 3.6    | 2001 Mar 9       | 4.5          | 17.9 ± 5.3 | 1.3 ± 0.6 | 2.8    | 2 × 10^{41} |
| NGC 5905    | 15 15 23.4 | 55 30 57    | 0.011 | 1.4    | 2002 Oct 4       | 9.6          | 25.3 ± 6.6 | 1.3 ± 0.6 | 1.8    | 6 × 10^{39} |
| RX J1624.9+7554 | 16 24 56.5 | 75 54 56    | 0.064 | 3.8    | 2002 Sep 15      | 10.1         | 3.5 ± 3.2 | 0.3 ± 0.4 | 0.24   | 3 × 10^{40} |

---

^eGalactic column density from Dickey & Lockman (1990).
^bLarger of the two 1σ error bounds using the approximation of Gehrels (1986).
^cSR is the 0.3−1.0/0.3−0.7 keV softness ratio.
^dFlux in the 0.3−7.0 keV band (10^{-14} erg s^{-1} cm^{-2}).
^fThe estimated unabsorbed X-ray luminosity in the same band (erg s^{-1}).
^gOptical position of galaxy A (Komossa & Greiner 1999).
Figure 1. Contour plots of the X-ray intensity derived from full-band (0.3–7.0 keV) ACIS-S3 images of the five target sources. Each image spans 60 × 60 arcsec² and has been adaptively smoothed at the 2σ level (Ebeling, White & Rangarajan 2003). Crosses mark the optical positions of the galactic nuclei. The nucleus of each member of the galaxy pair is indicated in the case of RX J1242.6–1119.

2.4 X-ray spectrum of IC 3599

Spectra were extracted from the source and background regions of the observation of IC 3599. A response matrix and an ancillary response file were generated with MKRMF and MKW ARF, respectively. The low number of counts meant that applying standard binning (i.e. \( N \geq 20 \) counts per energy bin) would result in too few bins for spectral fitting. Therefore the unbinned spectrum was fitted by minimizing the \( C \) statistic (Cash 1979), appropriate for situations when spectra contain few counts. The fitting was performed in XSPEC v11.2 (Arnaud 1996).

The spectral fitting was restricted to the 0.6–7.0 keV band since the ACIS calibration is uncertain below 0.6 keV. A power-law model with Galactic absorption gave a best-fitting photon index of \( \Gamma = 3.56^{+0.37}_{-0.34} \) (90 per cent confidence limits) which is steeper than that normally seen in Seyfert galaxies. This fit is shown in Fig. 2. Fitting with alternative spectral models (blackbody or bremsstrahlung continuum or a MEKAL plasma model) gave noticeably larger data/model residuals. The best-fitting temperatures were \( kT \sim 0.16 \) keV for a blackbody and \( \sim 0.26 \) keV for a MEKAL plasma model.

3 COMPARISON WITH OTHER OBSERVATIONS

3.1 X-ray light curves and softness ratios

In order to better understand how these sources have changed since their X-ray outbursts, long-term light curves were constructed for each of the five sources, as shown in Fig. 3. For this purpose the Chandra 0.3–7.0 keV count rates were converted into 0.3–2.0 keV fluxes using PIMMS, assuming the energy spectrum is a steep power law (with \( \Gamma = 3 \)) modified by Galactic absorption. The 0.3–2.0 keV band was chosen as both the Chandra ACIS and ROSAT PSPC cover this energy range with reasonable effective area. The ROSAT data points were derived from both the RASS and pointed observations of each source (see below for references). The 0.1–2.4 keV PSPC count rates were converted to 0.3–2.0 keV fluxes assuming the same spectrum as above. In addition a single ROSAT HRI observation of NGC 5905, taken in 1996 October, is included. Since the largest uncertainty associated with these flux estimates is caused by the model dependence of the counts-to-flux conversion the fluxes were...
consistent with the estimates from Section 2.3). The 0.3–2 keV flux was well-constrained at \( \approx 1.8 \times 10^{-14} \text{ erg s}^{-1} \text{ cm}^{-2} \) over a time-scale \( \lesssim 2 \text{ yr} \) following the stellar disruption. A measurement of this X-ray light curve following stellar disruption should be:

\[ L_X \sim 10^{40} - 10^{41} \text{ erg s}^{-1} \] over a time-scale \( \lesssim 2 \text{ yr} \). The Chandra softness ratios also indicate changes. For all five objects the ROSAT X-ray spectrum was extremely soft during outburst. In fact WPVS 007 was the softest spectrum AGN observed during the RASS (Grupe et al. 1995b) with an effective photon index \( \Gamma \approx 8 \). The other objects showed slopes in the range \( \Gamma = 3 - 5 \) (Brandt, Pounds & Fink 1995; Komossa & Bade 1999; Grupe, Thomas & Leighly 1999a; Bade, Komossa & Dahlem 1996). In the case of IC 3599 the spectrum remains rather soft. For the other four objects the Chandra softness ratios suggest harder spectra (\( \Gamma \lesssim 2.5 \)). However, it is difficult to make a more quantitative comparison owing to the different energy ranges of the ROSAT and Chandra/ACIS spectra and the small number of source photons in the Chandra data.

### 3.2 Optical spectra and classification

**WPVS 007.** Two years prior to its RASS detection an optical spectrum was obtained by Winkler, Stirpe & Sekiguchi (1992). They classified the source (\#7 in their notation) as a Seyfert 1. Observations by Grupe et al. (1995b) taken two years after the RASS detection identified WPVS 007 as a narrow-line Seyfert 1 galaxy (NLS1; Boller, Brandt & Fink (1996). An HST/FOS ultraviolet spectrum taken in 1996 also showed broad permitted lines as well as intrinsic, ionized absorption (Crenshaw et al. 1999; Goodrich 2000).

**IC 3599.** The optical spectrum taken five months after its initial RASS detection showed IC 3599 to be a NLS1 (Brandt et al. 1995). However, further observations 14 months after the RASS detection showed the optical spectrum to have changed to resemble that of a Seyfert 1.9 (Komossa & Bade 1999). Observations in subsequent years confirmed this (Grupe et al. 1995a; Komossa & Bade 1999).

**NGC 5905.** This source was identified as an H II/starburst galaxy six years after its RASS detection (Bade et al. 1996; Komossa & Bade 1999). However, higher spatial resolution spectroscopy with HST revealed narrow, high-ionization lines originating from the nucleus (Gezari et al. 2003). These imply the presence of a low-luminosity Seyfert 2 nucleus that was swamped by the surrounding H II emission in the previous observations. Gezari et al. (2003) used the correlation between Hα and soft X-ray luminosity described by Boller et al. (2001) to estimate the soft X-ray luminosity of the nucleus to be \( L_{\text{soft}} \sim 9 \times 10^{48} \text{ erg s}^{-1} \) (erratum of Gezari et al. 2003), a factor \( \lesssim 3 \) lower than the X-ray luminosity actually observed by Chandra.

**RX J1242.6−1119 and RX J1624.9+7554.** These appeared as otherwise inactive galaxies when observed several years after their initial RASS detections (Komossa & Greiner 1999; Grupe et al. 1999a). Gezari et al. (2003) report no detectable non-stellar continuum or high-ionization line emission in their HST observations.

### 4 DISCUSSION

As is clear from the light curves, in all five cases the flux recorded by Chandra falls 2–3 orders of magnitude below the maximum flux observed by ROSAT. Although the light curves are sparsely sampled, this does strongly suggest that the X-ray light curves are best characterized by a single, dramatic decline in luminosity on a time-scale \( \lesssim 2 \) yr followed by a period of relative quiescence. This is consistent with the X-ray outbursts being non-recurring events (at least on time-scales \( \lesssim 10 \) yr). In the most extreme example, RX J1624.9+7554 faded by a factor \( \gtrsim 1000 \) between its RASS observation in 1990 October and its Chandra observation in 2002 September. The optical spectra seem to indicate a wide variety of source types, ranging from genuine AGN to inactive galaxies.

It is difficult to make a simple comparison with the fading predicted in the tidal disruption scenario (Rees 1988): \( L_X \propto (t - t_0)^{-5/3} \) (where \( t_0 \) is the time of the outburst event). The Chandra X-ray luminosities could contain a significant contribution from unrelated galactic emission such as star-forming regions, bright X-ray binaries, diffuse emission components, etc. Indeed, individual ultraluminous X-ray (ULX) sources in nearby galaxies can reach X-ray luminosities \( \sim 10^{40} \) erg s\(^{-1}\) (Fabbiano & White 2003). This ‘background’ emission is an unknown quantity and, if dominated by a few bright X-ray binaries, could also be variable. Thus the X-ray light curve following stellar disruption should be: \( L_X \sim N \).
Five X-ray transient galactic nuclei

The model therefore has three unknowns \((N, t, C)\) but the light curves unfortunately have only 2–5 data points making the test rather meaningless. In the best-sampled light curves (IC 3599 and NGC 5905) the last ROSAT flux is comparable to the Chandra flux, implying no further fading has occurred on a time-scale of \(\sim 10\) yr. Unfortunately, in all five cases, it is not clear whether the quiescent source is a residual low-luminosity nuclear source or unrelated, background galactic emission.

The question of whether the ‘switch off’ marked the end of a single, isolated accretion episode (such as a tidal disruption event) or a rapid decrease in the luminosity of a persistent AGN (Seyfert galaxy to LLAGN) remains largely open. The peak luminosities were \(L_X \gtrsim 10^{35}\) erg s\(^{-1}\), comparable with bright Seyfert 1 galaxies, while the quiescent luminosities are only \(L_X \sim 10^{39–41}\) erg s\(^{-1}\). The latter are rather high compared with the nuclear emission expected from normal/inactive or starburst galaxies (see Fabbiano 1989), but quite comparable to those of low-luminosity AGN (LLAGN; Ptak et al. 1999; Roberts & Warwick 2000; Ho et al. 2001; Ptak 2001). Thus the evidence does favoue the presence of LLAGN in these galaxies. The existence of long-lasting, high-ionization optical line emission from the nuclei of WPVS 007, IC 3599 and NGC 5905 further suggests these may harbour some kind of long-lived AGN. However, it is difficult to make any strong claims about their prior X-ray activity, since no suitable observations exist.

The remaining two galaxies, RX J1242.6–1119 and RX J1624.9+7554, show no evidence for a luminous AGN in their optical spectra and remain the best candidates for tidal disruption events, although their (relatively) high residual X-ray luminosity may indicate some residual nuclear activity (as argued above). The optically inactive galaxy RX J1242.6–1119 is particularly interesting as this was the only one of the target sources to have been observed (although not detected) just prior to its outburst detection (see Komossa & Bade 1999). This suggests a rise time for the outburst of less than two years.

Transient galactic nuclei represent a relatively new and exciting avenue of X-ray astronomy research (see Komossa 2002, for a review). So little is known about these objects that any future X-ray observations are potentially of great importance. For example, a longer observation of NGC 5905 could reveal whether the X-ray emission is extended (and hence due to the circumnuclear starburst, not a LLAGN). Deeper observations of IC 3599 would better define the X-ray spectrum and thereby help clarify the origin of the remaining low-luminosity X-ray emission. Future monitoring of these sources is needed to see whether they are consistently variable (which would imply ongoing accretion) and, in particular, to see whether any show repeat outbursts. A severe hindrance to such a project is the dearth of known sources. Future large-area monitoring missions such as Lobster (Fraser et al. 2002) are well suited to finding transient galactic nuclei and providing the most likely route to a reasonably sized sample of such objects (see discussions in Sembay & West 1993; Donley et al. 2002) on which a concerted programme of follow-up observations might be based.

ACKNOWLEDGMENTS

We thank Steve Allen for help with CIAO, Tim Roberts for useful discussions and an anonymous referee for a helpful report. SV acknowledges financial support from PPARC. This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

REFERENCES

Arnaud K., 1996, in Jacoby G., Barnes J. eds, ASP Conf. Ser. Vol. 101, Astronomical Data Analysis Software and Systems. Astron. Soc. Pac., San Francisco, p. 17
Bade N., Komossa S., Dahlem M., 1996, A&A, 309, L35
Ballet J., 1999, A&AS, 135, 371
Boller Th., Brandt W. N., Fink H., 1996, A&A, 305, 53
Brandt W. N., Pounds K. A., Fink H., 1995, MNRAS, 273, L47
Cash W., 1979, ApJ, 263, 119
Crenshaw D. M., Kraemer S. B., Boggess A., Maran S. P., Mushotzky R. F., Wu C.-C., 1999, ApJ, 516, 750
Dickey J. M., Lockman F. J., 1990, ARA&A, 28, 215
Donley J. L., Brandt W. N., Eracleous M., Boller Th., 2002, AJ, 124, 1008
Ebeling H., White D. A., Rangarajan F. V. N., 2003, MNRAS, submitted
Edelson R., Vaughan S., Warwick R., Pucharewicz E., George I. M., 1999, MNRAS, 307, 91
Fabbiano G., 1989, ARA&A, 27, 87
Fabbiano G., White N. E., 2003, in Lewin W., van der Klis M. eds, Compact Stellar X-ray Sources. Cambridge Univ. Press, in press (astro-ph/0307077)
Fraser G. W., et al., 2002, Proc. SPIE, 4497, 115
Gehrels N., 1986, ApJ, 303, 336
Gezari S., Halpern J. P., Komossa S., Grupe D., Leighly K. M., 2003, ApJ, 592, 42 (Erratum: 2004, ApJ, 601, 1159)
Goodrich R. W., 2000, New Astron. Rev., 44, 419
Grupe D., Beuermann K., Mannheim K., Bade N., Thomas H.-C., de Martin D., Schwepe A., 1995a, A&A, 299, L5
Grupe D., Beuermann K., Mannheim K., Thomas H.-C., Fink H. H., de Martin D., 1995b, A&A, 300, L21
Grupe D., Thomas H.-C., Leiglly K. M., 1999a, A&A, 350, L31
Grupe D., Beuermann K., Mannheim K., Thomas H.-C., 1999b, A&A, 350, 31
Guainazzi M., et al., 1998, A&A, 339, 337
Gurzadian V. G., Ozernoi L. M., 1980, A&A, 86, 315
Halderson E. L., Moran E. C., Filippenko A. V., Ho L. C., 2001, AJ, 122, 637
Ho L. et al., 2001, ApJ, 549, L51
Komossa S., 2002, Rev. Modern Astron., 15, 27
Komossa S., Bade N., 1999, A&A, 343, 775
Komossa S., Greiner J., 1999, A&A, 349, L45
Magorrian J., et al., 1998, AJ, 115, 2285
Piro L., Massaro E., Perola G. C., Melenti D., 1988, ApJ, 326, L25
Ptak A., Serlemitsos P., Yaqoob T., Mushotzky R., 1999, ApJ, 120, 179
Ptak A., 2001, in White N. E., Malaguti G., Palumbo G. G. C. eds, AIP Conf. Proc. Vol. 599, X-ray Astronomy: Stellar Endpoints, AGN, and the Diffuse X-ray Background. Am. Inst. Phys., New York, p. 326
Rees M. J., 1988, Nat, 333, 523
Roberts T. R., Warwick R. S., 2000, MNRAS, 315, 98
Sembay S., West R. G., 1993, MNRAS, 262, 141
Siemiginowska A., Czerny B., Kostyunin V., 1999, ApJ, 458, 491
Terashima Y.,伊 Knoto N., Ho L. C., Ptak A. F., 2002, ApJS, 139, 1
Winkler H., Stirpe G. M., Sekiguchi K., 1992, A&A, 94, 103

This paper has been typeset from a TeX/XeTeX file prepared by the author.