Mon. Not. R. Astron. Soc. **321**, L29–L32 (2001)

Chandra High-Resolution Camera observations of the luminous X-ray source in the starburst galaxy M82

P. Kaaret,[1]★ A. H. Prestwich,[1] A. Zezas,[1] S. S. Murray,[1] D.-W. Kim,[1] R. E. Kilgard,[1] E. M. Schlegel[1] and M. J. Ward[2]

[1]*Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA*
[2]*Department of Physics and Astronomy, University of Leicester, Leicester LE1 7RH*

Accepted 2000 November 21. Received 2000 August 30; in original form 2000 August 10

ABSTRACT

We analyse *Chandra* High Resolution Camera observations of the starburst galaxy M82, concentrating on the most luminous X-ray source. We find a position for the source of RA = $09^{\mathrm{h}}55^{\mathrm{m}}50\overset{\mathrm{s}}{.}2$, Dec. = $+69°40'46\overset{''}{.}7$ (J2000) with a 1σ radial error of 0.7 arcsec. The accurate X-ray position shows that the luminous source is neither at the dynamical centre of M82 nor coincident with any suggested radio AGN candidate. The source is highly variable between observations, which suggests that it is a compact object and not a supernova or remnant. There is no significant short-term variability within the observations. Dynamical friction and the off-centre position place an upper bound of 10^5–$10^6\,\mathrm{M}_{\odot}$ on the mass of the object, depending on its age. The X-ray luminosity suggests a compact object mass of at least $500\,\mathrm{M}_{\odot}$. Thus the luminous source in M82 may represent a new class of compact object with a mass intermediate between those of stellar-mass black hole candidates and supermassive black holes.

Key words: black hole physics – galaxies: individual: M82 – galaxies: starburst – galaxies: stellar content – X-rays: galaxies.

1 INTRODUCTION

One of the most enigmatic results to emerge from X-ray population studies of spiral and other luminous star-forming galaxies is the discovery of unresolved X-ray sources that appear to have luminosities of tens to hundreds of times the Eddington luminosity for a neutron star (e.g. Marston et al. 1995; Fabbiano, Schweizer & Mackie 1997; Colbert & Mushotzky 1999; Wang, Immler & Pietsch 1999; Zezas, Georgantopoulos & Ward 1999; Roberts & Warwick 2000; for a review of early results see Fabbiano 1989). The origin of such sources is controversial. Some are located near the dynamical centre of the host galaxy, and hence may be low-luminosity active galactic nuclei (AGN). However, many are well outside the central regions of the galaxies and require an alternative explanation. Some of these highly luminous X-ray sources may be very luminous supernova remnants exploding into a dense interstellar medium (Fabian & Terlevich 1996), or they may be accretion-powered binary sources, in which case they are excellent black hole candidates with masses near or above $10\,\mathrm{M}_{\odot}$ (Makishima et al. 2000). Deciding between these various alternatives has been complicated by the limited spatial resolution of pre-*Chandra* X-ray missions.

One of the most extreme and controversial examples of a highly luminous X-ray source in a nearby galaxy is the bright X-ray source that dominates the central region of the nearby starburst galaxy M82. Previous *Einstein*, *ROSAT* and *ASCA* observations have shown that this source is variable and is close to the centre of M82 (Watson, Stanger & Griffiths 1984; Collura et al. 1994; Ptak & Griffiths 1999). It has been interpreted as a low-luminosity AGN (Tsuru et al. 1997), a highly X-ray-luminous supernova (Stevens, Strickland & Wills 1999), and an accreting black hole with a mass in excess of $460\,\mathrm{M}_{\odot}$ (Ptak & Griffiths 1999). In this paper we discuss early *Chandra* observations of M82 made using the High Resolution Camera (Murray et al. 1997). The central X-ray 'source' in M82 is resolved into several sources in the HRC observations. We present an analysis of the brightest *Chandra* source. Our results suggest that this source may be a black hole with a mass intermediate between those of stellar-mass Galactic X-ray binaries and supermassive black holes. We describe the observations in Section 2 and our analysis in Section 3, and we conclude in Section 4.

2 OBSERVATIONS

M82 was observed with the *Chandra X-Ray Observatory* (Weisskopf 1988) using the High-Resolution Camera (HRC: Murray et al. 1997) and the High-Resolution Mirror Assembly (HRMA: van Speybroeck et al. 1997) on 1999 October 28 04:24–14:48 UT for

---

★ E-mail: pkaaret@cfa.harvard.edu

an exposure of 36 ks and on 2000 January 20 14:51–20:25 UT for an exposure of 18 ks. The HRC is a microchannel plate imager having very good spatial and time resolution, but essentially no energy resolution. Each photon detected by the HRC is time- and position-tagged, making possible timing studies of individual sources in crowded fields. The HRC contains a wiring error, discovered after launch (Murray et al. 2000), which induces a 3–4 ms error in the event time tags for this observation. As we restrict ourselves to frequencies below 1 Hz, this error has no effect on the analysis presented below. The HRC position tags have a precision of 0.132 arcsec, referred to as ‘one pixel’. This resolution oversamples the *Chandra* point spread function (PSF) which has a half-power diameter of 0.76 arcsec (Jerius et al. 2000). We used a 15.6-pixel radius to extract source light curves.

We applied aspect to X-ray events from the HRC and filtered the data using event screening techniques (Murray et al. 2000) to eliminate ‘ghost’ events produced by the HRC electronics. An image for each observation was generated from the filtered event lists: see Fig. 1. We used the standard *Chandra* software routine WAVDETECT to search for and determine the position of point sources (CIAO V1.1 Software Tools Manual, Dobrzycki et al. 1999). We found several sources in each observation, including both transients and persistent sources. Here, we concentrate on the brightest source found. The other data, including spectroscopy from observations with the *Chandra* Advanced CCD Imaging Spectrometer (ACIS: Bautz et al. 1998), will be described in a forthcoming paper (Ward et al., in preparation).

3 RESULTS

The brightest source in both observations is at a location of RA = $09^{\mathrm{h}}55^{\mathrm{m}}50\overset{\mathrm{s}}{.}2$, Dec. = $+69°40'46\overset{''}{.}7$ (J2000). Following the convention of naming sources in M82 via their offset from RA = $09^{\mathrm{h}}51^{\mathrm{m}}00^{\mathrm{s}}$, Dec. = $+69°54'00''$ (B1950), we refer to this source as X41.4+60 in the remainder of the paper. For wider use, we also denote the source as CXOU J095550.2+694047. The position uncertainty is dominated by the accuracy of the aspect reconstruction which we take to have a 1σ radial error of 0.7 arcsec (Aldcroft et al. 2000).

The source lies 9 arcsec from the kinematic centre of M82 (Weliachew, Fomalont & Greisen 1984), 12 arcsec from the 2.2-μm peak (Rieke et al. 1980), 4 arcsec from the very luminous supernova remnant 41.95+57.5 (Kronberg & Wilkinson 1975; Wills et al. 1997), and 13 arcsec from the suggested AGN candidate 44.01+59.6 (Wills et al. 1997, 1999; Seaquist, Frayer & Frail 1997). The radio source 41.31+59.6, which is probably a compact supernova remnant (Muxlow et al. 1994; Allen & Kronberg 1998), lies near the edge of the error circle. The highly variable radio source 41.5+59.7 (Kronberg & Sramek 1985) lies within the error circle. This radio source was bright in one observation in 1981 but not detected one year later or subsequently, and has been interpreted as being due to a supernova (Kronberg et al. 2000). However, as only one detection is available and unique identification is not possible based on the radio spectral index alone, the source may belong to a different class of radio transient (Muxlow et al. 1994). If the 1981 radio event was a

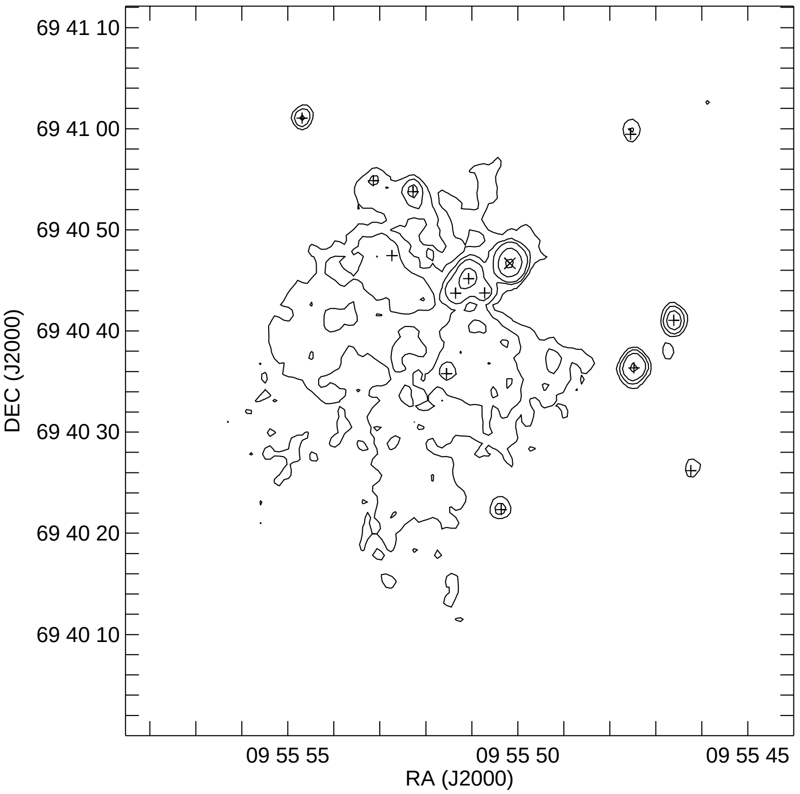

Figure 1. The central region of M82 from the 1999 October observation. The contours were calculated using a counts map with 0.53-arcsec pixels smoothed with a Gaussian with FWHM = 1.06 arcsec. The contours indicate 2.5, 5, 10, 40 and 160 count pixel^{-1} in the smoothed map. The position of X41.4+60 is marked with a ‘×’. Pluses indicate positions of other sources.

supernova, it is probably unrelated to the X-ray source as a bright X-ray source was detected at this position in 1979 with the *Einstein* High Resolution Imager (Watson et al. 1984). The 408-MHz radio flux at the position of X41.4+60 is below 2 mJy (Wills et al. 1997). The 6-cm radio flux is below 2 mJy except during 1981 (Kronberg et al. 2000).

X41.4+60 is a highly variable X-ray source. In the first observation, the HRC count rate from the source is 0.07 count s^{-1}, while in the second it is 0.52 count s^{-1} – a factor of 7 brighter. In the first observation, X41.4+60 accounts for roughly 40 per cent of the counts within 6 arcsec (i.e. comparable to the resolution of the *ROSAT* High Resolution Imager) of the source position and only 8 per cent of the counts within 4 arcmin [i.e. comparable to the resolution of the *ASCA* Solid-State Imaging Spectrometer (SIS)] of the source position. In the second observation, X41.4+60 accounts for more than 90 per cent of the counts within 6 arcsec and 40 per cent within 4 arcmin. Thus, even in the brightest states of X41.4+60, *ASCA* spectra of the source are significantly contaminated by flux from other point sources and diffuse emission. The time-scale of the variability places an upper limit on the size of the emitting region of 0.08 pc.

Using various spectral models consistent with the spectrum of this source extracted from a *Chandra* ACIS observation of M82 (Ward et al., in preparation), we estimate that 1 count s^{-1} in the HRC corresponds to an observed flux of $0.9\text{–}1.4 \times 10^{-10}\,\mathrm{erg\,cm^{-2}\,s^{-1}}$ in the 0.2–10 keV band. The range in the conversion factor is due to uncertainty in the ACIS spectral fits. The source flux in the ACIS observation corresponds to an HRC rate of 0.03 count s^{-1}, so the true conversion factors may differ from these values if the source spectrum varies with flux. The flux in the second observation is comparable to the highest fluxes observed from the central source in M82 with *ASCA* (Ptak & Griffiths 1999). Taking a distance to M82 of 3.63 Mpc (Freedman et al. 1994), the inferred isotropic source luminosity from the absorbed flux in the two observations would then be $1.0\text{–}1.5 \times 10^{40}\,\mathrm{erg\,s^{-1}}$ in the 0.2–10 keV band for the first observation and $7\text{–}11 \times 10^{40}\,\mathrm{erg\,s^{-1}}$ for the second. Correcting for absorption would increase these luminosities; conversely, the true luminosity may be lower if the X-rays are beamed. These luminosities are near or above the highest values found for non-nuclear sources in a *ROSAT* sample of nearby galaxies (Roberts & Warwick 2000).

For each observation, we extracted a light curve for X41.4+60: see Fig. 2. The source appears to have roughly constant flux in both observations. In particular, the light curve for the 2000 January observation shows no evidence of significant change in flux level over the observation, so it is unlikely that the high flux represents a flare of short duration. In both observations, the power spectra show no significant short-term variability with the power comparable to the Poisson noise limit over the frequency range 0.0005–1 Hz.

We comment that oscillations with a frequency near 600 s were reported in a preprint version of this paper. In subsequent analysis, these oscillations were found to be due to instrumental effects related to the HRC response to bright sources and the algorithms used to screen ‘ghost’ events produced by the HRC electronics.

4 DISCUSSION

The luminosity of X41.4+60 in the 2000 January observation, given the assumptions concerning the spectral shape and isotropic emission noted above, corresponds to the Eddington luminosity for a 500–900 $\mathrm{M}_\odot$ object. The strong variability between observations argues against this luminosity being due to an aggregate of sources. The variability also suggests that the source is a compact object and not a supernova, although the possibility of a supernova expanding into a highly non-uniform medium cannot be excluded. Soft gamma repeaters (SGRs) produce sufficient flux; however, the longest, bright, so-called ‘giant’, outbursts from SGRs last only ~300 s, over which they show substantial decay (Hurley et al. 1999). The fact that X41.4+60 shows no evidence of decay or variability over 15 ks (see Fig. 2) argues against it being an SGR. An origin of the high luminosity and variability in an accreting massive compact object appears plausible.

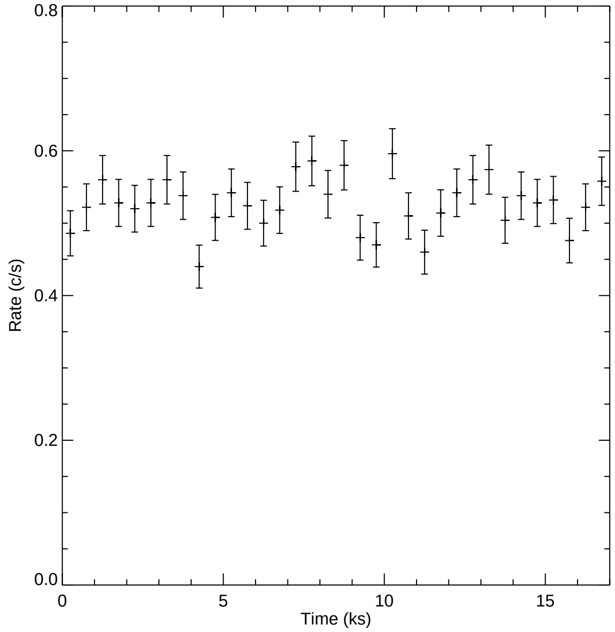

Figure 2. Light curve for X41.4+60 from the HRC observation in 2000 January. The time bin size is 500 s. Statistical error bars are shown.

Dynamical friction will cause massive objects orbiting in the stellar field surrounding a galactic nucleus to spiral into the nucleus (Tremaine, Ostriker & Spitzer 1975). The lifetime, t, before reaching the nucleus is related to the mass of the object, M, its distance from the nucleus, and the stellar velocity dispersion. From the position given above for X41.4+60 and adopting a velocity dispersion for M82 of 100 $\mathrm{km\,s^{-1}}$ (Gaffney, Lester & Telesco 1993), a rough upper bound can be placed on the mass of X41.4+60, $M \lesssim 10^5\,\mathrm{M}_\odot(t/10^{10}\,\mathrm{yr})^{-1}$. If the object was formed during the initial formation of M82 then $t \sim 10^{10}$ yr, and hence $M \lesssim 10^5\,\mathrm{M}_\odot$. Higher masses are allowed if shorter lifetimes are assumed, e.g. $M \lesssim 10^6\,\mathrm{M}_\odot$ for $t \sim 10^9$ yr. This may be possible if the object was formed recently, in a process likely to be distinct from that for the formation of supermassive black holes in galactic nuclei, or if the object was ejected from the nucleus in an encounter with one or two equally or more massive black holes. If the object was formed recently and outside the nucleus, it is likely to be less massive than the super star clusters found in M82 – the most massive of which is $2 \times 10^6\,\mathrm{M}_\odot$ (O’Connell et al. 1995; Smith & Gallagher 2000). Rapid formation of a compact object with mass greater than 100 $\mathrm{M}_\odot$ in the collapse of a super star cluster appears possible (Portegies Zwart et al. 1999; Taniguchi et al. 2000).

In conclusion, the accurate X-ray position determination for the most luminous X-ray source in M82, made possible by the high angular resolution of *Chandra*, excludes identification with suggested radio AGN candidates (Wills et al. 1997). The strong variability of the source argues against the possibility that it could arise from a supernova (Ptak & Griffiths 1999; Matsumoto & Tsuru 1999) and the high flux places a lower bound on the compact object mass of $500\,\mathrm{M}_\odot$ if the emission is isotropic. The low radio flux at the X-ray position and the displacement of the source from the dynamical centre of M82 argue against X41.4+60 being a supermassive black hole similar to that seen at the centre of the Milky Way. The most plausible explanation for the object is that it is an accreting black hole with a mass of $500\text{–}10^5\,\mathrm{M}_\odot$. The *Chandra* data strengthen this suggestion made previously on the basis of *ASCA* data by Ptak & Griffiths (1999), and also clearly establish that the source is non-nuclear (Matsumoto & Tsuru 1999). In this case, it would represent a new class of compact object (Colbert & Mushotzky 1999) with a mass intermediate between those of stellar-mass black hole candidates and supermassive black holes found in the centres of galaxies. Understanding the formation of such an object (Portegies Zwart et al. 1999; Taniguchi et al. 2000) may provide insights into the formation of supermassive black holes in galactic centres (Quinlan & Shapiro 1990; Gebhardt et al. 2000).

ACKNOWLEDGMENTS

We thank Tom Aldcroft for information concerning the dither and aspect solution, and thank Doug Richstone, Andy Fabian, Avi Loeb, Roger Blandford, Martin Weisskopf, Frank Primini, Hironori Matsumoto and Wallace Tucker for useful discussions. We gratefully acknowledge the efforts of the *Chandra* team and support from NASA *Chandra* contract NAS8-39073. PK acknowledges partial support from NASA grant NAG5-7405.

REFERENCES

Aldcroft T. L., Karovska M., Cresitello-Dittmar M. L., Cameron R. A., Markevitch M. L., 2000, Proc. SPIE, 4012, 650
Allen M. L., Kronberg P. P., 1998, ApJ, 502, 218
Bautz M. W. et al., 1998, Proc. SPIE, 3444, 210
Colbert E. J. M., Mushotzky R. F., 1999, ApJ, 519, 89
Collura A., Reale F., Schulman E., Bregman J. N., 1994, ApJ, 420, L63
Dobrzycki A., Ebeling H., Glotfelty K., Freeman P., Damiani F., Elvis M., Calderwood T., 1999, CHANDRA Detect 1.1 User Guide (http://asc.harvard.edu/udocs/docs/swdocs/detect/html/index.html)
Fabbiano G., 1989, ARA&A, 27, 87
Fabbiano G., Schweizer F., Mackie G., 1997, ApJ, 478, 542
Fabian A. C., Terlevich R., 1996, MNRAS, 280, L5
Freedman W. et al., 1994, ApJ, 427, 628
Gaffney N. I., Lester D. F., Telesco C. M., 1993, ApJ, 407, L57
Gebhardt K. et al., 2000, ApJ, 539, L13
Hurley K. et al., 1999, Nat, 397, 41
Jerius D., Donnelly R. H., Tibbetts M. S., Edgar R. J., Gaetz T. J., Schwartz D. A., van Speybroeck L. P., Zhao P., 2000, Proc. SPIE, 4012, 17
Kronberg P. P., Sramek R. A., 1985, Sci, 227, 28
Kronberg P. P., Wilkinson P. N., 1975, ApJ, 200, 430
Kronberg P. P., Sramek R. A., Birk G. T., Dufton Q. W., Clarke T. E., Allen M. L., 2000, ApJ, 535, 706
Makishima K. et al., 2000, ApJ, 535, 632
Marston A. P., Elmegreen D., Elmegreen B., Forman W., Jones C., Flanagan K., 1995, ApJ, 438, 663
Matsumoto H., Tsuru T. G., 1999, PASJ, 51, 321
Murray S. S. et al., 1997, Proc. SPIE, 3114, 11
Murray S. S. et al., 2000, Proc. SPIE, 4012, 68
Muxlow T. W. B., Pedlar A., Wilkinson P. N., Axon D. J., Sanders E. M., de Bruyn A. G., 1994, MNRAS, 266, 455
O'Connell R. W., Gallagher J. S., III, Hunter D. A., Colley W. N., 1995, ApJ, 446, L1
Portegies Zwart S. F., Makino J., McMillian S. L. W., Hut P., 1999, A&A, 348, 117
Ptak A., Griffiths R., 1999, ApJ, 517, L85
Quinlan G. D., Shapiro S. L., 1990, ApJ, 356, 483
Rieke G. H., Lebofsky M. J., Thompson R. I., Low F. J., Tokunaga A. T., 1980, ApJ, 238, 24
Roberts T. P., Warwick R. S., 2000, MNRAS, 315, 98
Seaquist E. R., Frayer D. T., Frail D. A., 1997, ApJ, 487, L131
Smith L. J., Gallagher J. S., III, 2000, in Lançon A., Boily C., eds, ASP Conf. Ser. Vol. 211, Massive Stellar Clusters. Astron. Soc. Pac., San Francisco, p. 90
Stevens I. R., Strickland D. K., Wills K. A., 1999, MNRAS, 308, L23
Taniguchi Y., Shioya Y., Tsuru T. G., Ikeuchi S., 2000, PASJ, 52, 533
Tremaine S. D., Ostriker J. P., Spitzer L., Jr, 1975, ApJ, 196, 407
Tsuru T. G., Awaki H., Koyama K., Ptak A., 1997, PASJ, 49, 619
van Speybroeck L. P., Jerius D., Edgar R. J., Gaetz T. J., Zhao P., Reid P. B., 1997, Proc. SPIE, 3113, 89
Wang Q. D., Immler S., Pietsch W., 1999, ApJ, 523, 121
Watson M. G., Stanger V., Griffiths R. E., 1984, ApJ, 286, 144
Weisskopf M. C., 1988, Space Sci. Rev., 47, 47
Weliachew L., Fomalont E. B., Greisen E. W., 1984, A&A, 137, 335
Wills K. A., Pedlar A., Muxlow T. W. B., Wilkinson P. N., 1997, MNRAS, 291, 517
Wills K. A., Pedlar A., Muxlow T. W. B., Stevens I. R., 1999, MNRAS, 305, 680
Zezas A. L., Georgantopoulos I., Ward M. J., 1999, MNRAS, 308, 302

This paper has been typeset from a TEX/LATEX file prepared by the author.