Localization of the X-ray source in the globular cluster G1 with *Chandra*

A. K. H. Kong,1‡ C. O. Heinke,2 R. Di Stefano,3 H. N. Cohn,4 P. M. Lugger,4 P. Barmby,5 W. H. G. Lewin6 and F. A. Primini3

1 Institute of Astronomy and Department of Physics, National Tsing Hua University, Hsinchu 30013, Taiwan
2 Department of Physics, University of Alberta, 11322-89 Avenue, Edmonton, AB T6G 2G7, Canada
3 Harvard-Smithsonian Centre for Astrophysics, 60 Garden Street, Cambridge, MA 02138, USA
4 Astronomy Department, Indiana University, 727 East 3rd St., Bloomington, IN 47405, USA
5 Department of Physics & Astronomy, University of Western Ontario, London, ON N6A 3K7, Canada
6 Kavli Institute for Astrophysics and Space Research, Massachusetts Institute of Technology, Cambridge, MA 02139, USA

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**ABSTRACT**

We report the most accurate X-ray position of the X-ray source in the giant globular cluster G1 in M31 by using the *Chandra* X-ray Observatory, *Hubble Space Telescope* (HST) and Canada–France–Hawaii Telescope (CFHT). G1 is clearly detected with *Chandra* and by cross-registering with *HST* and CFHT images, we derive a 1σ error radius of 0.15 arcsec, significantly smaller than the previous measurement by *XMM–Newton*. We conclude that the X-ray emission of G1 is likely to come from within the core radius of the cluster. We have considered a number of possibilities for the origin of the X-ray emission but can rule out both scenarios: it could be due to either accretion on to a central intermediate-mass black hole (IMBH) or an ordinary low-mass X-ray binary (LMXB). Based on the X-ray luminosity and the Bondi accretion rate, an IMBH accreting from the cluster gas seems unlikely and we suggest that the X-rays are due to accretion from a companion. Alternatively, the probability that a 1.5 M\(_\odot\) cluster LMXB lies within the 95 per cent X-ray error circle is about 0.7. Therefore we cannot rule out a single LMXB as the origin of the X-ray emission. While we cannot distinguish between different models with current observations, future high-resolution and high-sensitivity radio imaging observations will reveal whether there is an IMBH at the centre of G1.

**Key words:** binaries: close – globular clusters: individual: G1 – X-rays: binaries.

**1 INTRODUCTION**

Intermediate-mass black holes (IMBHs) have been a subject of debate for a long time. If they exist, IMBHs represent the long sought-after link between stellar mass and supermassive black holes. Until recently, we only have had indirect evidence for IMBHs via X-ray observations. For instance, ultraluminous (L\(_X\) > 10\(^{39}\) erg s\(^{-1}\)) or hyperluminous (L\(_X\) > 10\(^{41}\) erg s\(^{-1}\)) X-ray sources have been the best candidates (e.g. Wolter, Trinchieri & Colpi 2006; Farrell et al. 2009) based on their X-ray luminosities which, assuming isotropic emission, are far in excess of the Eddington limit for stellar mass black holes. Furthermore, X-ray spectroscopy and X-ray timing also provide some support for IMBHs (e.g. Miller, Fabian & Miller 2004; Kong & Di Stefano 2005; Strohmayer & Mushotzky 2009). However, we still require dynamical evidence in order to confirm solidly that IMBHs exist.

The only dynamical mass measurement claimed for an IMBH candidate is the globular cluster G1 in M31. G1 is the most luminous star cluster in the Local Group, and also one of the most massive at (4–7) × 10\(^6\) M\(_\odot\) (Barmby et al. 2007; Ma et al. 2009). Based on Keck and *Hubble Space Telescope* (HST) observations, it has been claimed that G1 hosts a \(\sim 2 \times 10^4\) M\(_\odot\) object at the core (Gebhardt, Rich & Ho 2002, 2005). However, the suggestion of an IMBH is controversial and has been challenged by Baumgardt et al. (2003). Recently, X-ray emission near the core of G1 has been discovered based on *XMM–Newton* observations (Trudolyubov & Priedhorsky 2004; Pooley & Razaport 2006; Kong 2007) and it is suggested that the X-rays come from Bondi accretion from cluster gas on to a central IMBH. However, it is also possible that the X-ray emission is due to an ordinary low-mass X-ray binary (LMXB), or a collection of faint LMXBs near the core. By refining the relative astrometry between *XMM–Newton* and HST data, Kong (2007) concluded that we cannot distinguish between these two scenarios. As we will show in this Letter, if there exists an IMBH in G1, accretion likely comes from a companion star (see e.g. Patruno et al. 2006 for a scenario with a giant).

*E-mail: akong@phys.nthu.edu.tw
‡Kenda Foundation Golden Jade Fellow.
Alternatively, radio observations may be able to provide additional information about the nature of the X-ray source in G1. Ulvestad, Greene & Ho (2007) employed the Very Large Array (VLA) to obtain a low-resolution (~3 arcsec beam size at 8.4 GHz) image of G1 and a radio source was detected near the XMM–Newton source, about an arcsecond from the cluster core. The radio/X-ray flux ratio of G1 (~5 × 10^{-5}) is at least a few hundred times higher than that expected for a LMXB near the cluster centre (~5 × 10^{-8}; see Fender & Kuulkers 2001), but is consistent with the expected value for accretion on to a 2 × 10^5 M⊙ IMBH (Merloni, Heinz & di Matteo 2003). Furthermore, the radio/X-ray flux ratio is much lower than that of supernova remnants (~10^{-2}), but it is consistent with a pulsar wind nebula (Ulvestad et al. 2007).

However, it is still a question whether the X-ray and radio emission come from the same source because the resolution of both observations do not have sufficient accuracy to determine the precise position. While the VLA is still in its short baseline configuration and MERLIN is being upgraded, the first step is to use Chandra to obtain an accurate position for the X-ray source.

In this Letter, we localized the X-ray emission of G1 by performing precise relative astrometry using Chandra, HST and Canada–France–Hawaii Telescope (CFHT). In Section 2, we describe our X-ray and optical observations and data analysis. We present the localization of the X-ray source in Section 3. We finally discuss the nature of the X-ray source in Section 4.

2 OBSERVATIONS AND DATA ANALYSIS

2.1 Chandra

We observed G1 with the Chandra X-ray Observatory on 2008 September 30 for a total exposure time of 35 ks (ObsID 9525). The observation was taken using the Advanced CCD Imaging Spectrometer array (ACIS-S) with the telescope aim point at G1. Data were telemetered in the very faint mode and were collected with a frame transfer time of 3.2 s. We used CIAO version 4.1,1 ACIS Extract2 and XSPEC version 12.53 packages to perform data reduction and analysis. We reprocessed the raw data to make use of the very faint mode. In order to reduce the background count rates from the S1 chip and no flaring event was found in the data set. In this Letter, we only consider the S3 chip of ACIS-S.

Discrete sources in the Chandra images were found with wavdetect (Freeman et al. 2002) together with exposure maps. We performed source detection on the 0.3–7 keV image. We set the detection threshold to be 10^{-6}, corresponding to less than one false detection due to statistical fluctuations in the background. We performed source detection using sequences of wavelet scales that increased by a factor of $\sqrt{2}$ from scales of 1 to 16. A total of 28 X-ray sources were detected. The X-ray source in G1 was clearly detected with 126 counts.

We extracted the energy spectrum from a 2-arcsec circular region centred on G1. For the background, we selected a source-free region with a radius of 15 arcsec. Response matrices were generated by CIAO. We then fitted the background-subtracted spectrum with an absorbed power-law model. In order to employ $\chi^2$ statistics, the spectrum was grouped into at least 10 counts per spectral bin. Since the statistics in the spectrum are poor, it can be fitted equally well with numerous spectral models (e.g. power law, bremsstrahlung and thermal plasma), although a blackbody model can be ruled out. However, the absorbed power-law model is adopted as it is typical for a globular cluster X-ray source. The power-law model provides the best fit ($\chi^2$/d.o.f. = 7.56/9) to the data with $N_H = 4.7^{+7.6}_{-4.5} \times 10^{20}$ cm$^{-2}$ and $\Gamma = 1.8^{+0.4}_{-0.2}$ (90 per cent confidence level). The 0.3–7 keV unabsorbed luminosity is $(2.3^{+0.3}_{-0.2}) \times 10^{39}$ erg s$^{-1}$ assuming a distance of 780 kpc (Macri et al. 2001). The X-ray spectrum and luminosity are very typical for a globular cluster X-ray source in M31 (Di Stefano et al. 2002; Kong et al. 2002a).

The X-ray luminosity as well as the spectrum of G1 are consistent with previous XMM–Newton observations (Pooley & Rappaport 2006) indicating it is a persistent source. We also calculated the Kolmogorov–Smirnov statistic to examine whether G1 is a variable source during our Chandra observation; there is over 25 per cent probability that G1 is a constant source. We therefore cannot reject the null hypothesis that G1 is a constant source. We also applied the Gregory–Loredo variability algorithm (Gregory & Loredo 1992) in CIAO to examine our G1 data and the variability index is 0, implying no variability.

2.2 Optical Observations

G1 was observed with the HST Wide Field Planetary Camera 2 (WFPC2) on 1995 October 2 with a total integration time of 30 min in the F814W filter. We downloaded the F814W image from the Hubble Legacy Archive3 for which cosmic ray free, science-quality images are dithered, co-added and corrected for astrometry. By comparing to the 2MASS catalogue (Skrutskie et al. 2006), the astrometry of the image is better than 0.2 arcsec. Although G1 was also observed with the Advanced Camera for Surveys (ACS) in High Resolution Channel (HRC) mode (see Kong 2007), we do not use the ACS/HRC data because they have a much smaller field of view (29 × 26 arcsec$^2$) which is not useful for refining the relative astrometry with ground-based telescope and Chandra data.

Since the field of view of WFPC2 is small compared to Chandra, it is difficult to improve the relative astrometry between HST and Chandra. We therefore obtained a wide-field optical image centred on G1 with the MegaPrime/MegaCam at the CFHT on 2008 September 5. The MegaCam has an array of 36 CCDs, giving a total of 1° × 1° field of view. We obtained a series of $i'$-band images under a seeing condition of 0.7 arcsec with a total exposure time of 721 s. The images were processed by Terapix4 which provides co-added and astrometrically calibrated images for data analysis. By matching over 3000 stars in the field with the 2MASS catalogue, the astrometry of the CFHT image is accurate to about 0.3 arcsec.

3 LOCALIZATION OF THE X-RAY SOURCE IN G1

To localize the precise position of the X-ray source in G1, we have to improve the relative astrometry of the X-ray and optical images. To achieve this, we need to match the Chandra, HST and CFHT images into a common reference frame (see e.g. Lu et al. 2009). We first compared the Chandra image with the CFHT image. By

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1 http://cxc.harvard.edu/ciao/
2 http://www.astro.psu.edu/xray/docs/TARA/ae_users_guide.html
3 http://heasarc.gsfc.nasa.gov/docs/xanadu/xspec/
4 http://hla.stsci.edu/
5 http://terapix.iap.fr/
0.3–7 keV band, yielding RA 00h32m46.

Figure 1. HST WFPC2 F814W images of G1. The red circle is the 95 per cent error circle (0.36 arcsec in radius) of the Chandra source and its centre is marked by a plus sign. The white dashed circle at the centre is the core radius (0.2 arcsec; Ma et al. 2007; Barmby et al. 2007) of G1, while the white circle is the 95 per cent error circle (1.47 arcsec in radius) of the VLA source.

comparing the Chandra source list with the CFHT image, we found five likely matches (in addition to G1) that are optically bright and isolated. They are likely to be foreground stars or background galaxies. Based on these five matches, we corrected the astrometry of the Chandra image using the IRAF\(^6\) task ccmp. The resulting registration errors are 0.062 arcsec in RA and 0.117 arcsec in declination.

We next transformed the astrometry of WFPC2 to the CFHT image. We found 55 stars in both images that appeared stellar and unblended. We obtained an astrometric solution giving residuals of 0.037 arcsec in RA and 0.036 arcsec in declination. After registering all the images to the CFHT image, we located the optical centre of G1 in the WFPC2 images and the position of the X-ray source. We determined the centroid of G1 in the WFPC2 image (RA 00h32m46.532, Dec. +39\(^\circ\)34\(^\prime\)40.58 with 1σ error of 0.002 arcsec) by fitting the elliptical isophotes to the globular cluster using the IRAF task ellipse.

For the X-ray position, we used ACIS Extract to derive the mean position of events within the 90 per cent point spread function in the 0.3–7 keV band, yielding RA 00h32m46.532, Dec. +39\(^\circ\)34\(^\prime\)40.47 with 1σ statistical error radius of 0.04 arcsec. We then determined the 1σ radius error circle (0.15 arcsec) of the Chandra position of G1 by computing the quadratic sum of the positional uncertainty for the X-ray source (0.04 arcsec), the registration error between WFPC2 and CFHT images (0.05 arcsec) and the residuals between Chandra and CFHT alignment (0.13 arcsec). Hence, the 95 per cent radius (two-dimensional) error circle will be 0.36 arcsec. Fig. 1 shows the WFPC2 images of G1 and the 95 per cent radius X-ray error circle.

4 DISCUSSION

By utilizing Chandra, HST/WFPC2 and CFHT/MegaCam data, we determined the precise position of the X-ray emission of G1. The X-ray source, previously seen by XMM–Newton (see Pooley & Rappaport 2006; Kong 2007), is very close (~0.11 arcsec) to the cluster centre. Based on the calculation by Pooley & Rappaport (2006), if the X-ray emission is from Bondi accretion of ionized cluster gas by a central IMBH, the X-rays should come from the central 50 mas of the cluster. However, given the uncertainty of the error circle, we cannot rule out that the X-ray source is slightly offset from the cluster core (see Fig. 1). If the X-ray emission is not from a central IMBH, it could come from a luminous LMXB located within or very close to the core radius (0.21 arcsec in Ma et al. 2007; 0.19 arcsec in Barmby et al. 2007) of G1. As Kong (2007) points out, nearly half of the LMXBs in Galactic globular clusters are found within the core radius; it would not be surprising to find a luminous LMXB within the core of G1.

We estimated the probability of a 1.5 M\(_{\odot}\) object being found in the X-ray error circle. The mass of 1.5 M\(_{\odot}\) is the average quiescent LMXB mass, estimated from the radial distribution of 20 quiescent LMXBs in seven globular clusters (Heinke et al. 2003). We adopted the single-mass King model fit from Ma et al. (2007), which has \(r_c = 0.21\) arcsec, and also considered the core radius value of \(r_c = 0.19\) arcsec from Barmby et al. (2007). We assumed that the King model profile describes the distribution of turn-off mass objects; we took the turn-off mass to be 0.9 M\(_{\odot}\). This gives a mass ratio of \(q = 1.67\) between the LMXBs and the turn-off-mass stars. It is straightforward to integrate the radial density profile for the LMXBs analytically. As a check, half of the probability is within the core radius for \(q=1.67\). We then integrated the probability over angle numerically to compute the probability within the off-centre X-ray error circle. We found that a 1.5 M\(_{\odot}\) LMXB would have a probability of 0.756 (\(r_c = 0.19\) arcsec) and 0.718 (\(r_c = 0.21\) arcsec) of being found within our 95 per cent confidence Chandra error circle. Therefore the possibility that the X-ray source represents a single LMXB is significant.

If the X-ray source is from an accreting IMBH, the observed luminosity (\(2 \times 10^{36}\) erg s\(^{-1}\)) and the spectrum would be consistent with a black hole in the hard state (Remillard & McClintock 2006). There are also two possibilities if G1 has an accreting IMBH. The X-ray emission could be due to accretion either from cluster gas (Pooley & Rappaport 2006) or from a companion star.

\(^6\) http://iraf.noao.edu/
We list in Table 1 a few examples of nearby supersmassive black holes and dynamically confirmed stellar mass black holes for comparison. All three quiescent supersmassive black holes in the local universe have very low Eddington ratios of $10^{-11}$ to $10^{-9}$. On the other hand, quiescent stellar mass black holes tend to have a higher Eddington ratio. V404 Cyg is the most X-ray luminous stellar mass black hole, while A0620+00 and GS2000+25 are the faintest ones (with detection). The Eddington ratio of G1 (assuming a mass of $2 \times 10^4 M_\odot$) is at least two orders of magnitude higher than that of quiescent supersmassive black holes, but is in the range of stellar mass black holes. We also compare the X-ray luminosity in units of Bondi luminosity. This is a better indicator of accretion luminosity than the Eddington ratio as it relates the X-ray luminosity to the available mass transfer rate. For G1, it is about 0.01 (see Pooley & Rappaport 2006), which is substantially higher than quiescent supersmassive black holes (see Table 1). It is an indication that the accretion efficiency of G1 must be high if cluster gas is the source of the accretion.

| Source | $M_{BH}$ ($M_\odot$) | $log L_X$ | $log \left( L_X/L_{Edd} \right)$ | $log \left( L_{\nu}/L_{Edd} \right)$ | $log \left( L_X/L_{Edd} \right)$ | References |
|--------|-----------------|-----------|-------------------------------|--------------------------------|-------------------------------|------------|
| G1     | $2 \times 10^4$ | 36.3      | −6.11                         | −4.11                         | −2.00                         | 38.6       |
| Sgr A* | $2.6 \times 10^6$ | 33.3–35   | −11.22 to −9.52               | −3.85                         | −7.26 to −5.57               | 42–43.7    |
| M31*   | $1.4 \times 10^7$ | 35.8–37.3 | −10.52 to −9.00               | −4.36                         | −5.45 to −3.93               | 41.3–42.8  |
| M32*   | $2.5 \times 10^7$ | 36        | −8.52                         | −5.93                         | −2.83                         | < 41.8     |
| V404 Cyg | 10            | 33–33.9   | −6.11 to −5.22                | −6.11                         | 33.8–34.6                    | 5, 6       |
| A0620+00 | 10          | 30        | −6.25                         | −8.62                         | −3.85                         | 7, 8       |
| GS2000+25 | 7            | 30.4      | −8.44                         | −3.85                         | −3.85                         | 9          |

Note. Columns are as follows: (1) name of the object; (2) black hole mass; (3) X-ray luminosity ($erg \ s^{-1}$); (4) X-ray-to-Eddington luminosity ratio; (5) Bondi-to-Eddington luminosity ratio; (6) X-ray-to-Bondi luminosity ratio and (7) ratio between radio luminosity and $L_{\nu}/L_{Edd}$.

We can rule out that the X-ray emission is from combination of low-luminosity supermassive black holes as shown in fig. 14 of Soria et al. (2006). According to the standard advection-dominated accretion flow (ADAF) model, the X-ray luminosity of G1 should be two orders of magnitude lower. This implies that the putative IMBH of G1 is extremely efficient in accreting cluster gas. It is worth noting that apart from 47 Tuc (Freire et al. 2001), we do not have evidence of cluster gas in Galactic globular clusters (van der Marel et al. 2001). We can confirm that the radio source is related to the X-ray source, which will provide a strong support that there is an IMBH near the centre of G1 because the radio/X-ray flux ratio of G1 ($\sim 5 \times 10^{-5}$) is several hundreds times higher than that of a LMXB, but is consistent with a $2 \times 10^6 M_\odot$ IMBH using the relationship in the ‘Fundamental Plane’ linking radio/X-ray flux ratios and black hole masses (van der Marel et al. 2003; see also Table 1). The radio/X-ray flux ratio of G1 is also substantially lower than that of supernova remnants ($\times 10^{-2}$) and low-luminosity active galactic nuclei (see Ulvestad et al. 2007 and Table 1). If the radio/X-ray flux ratio is consistent with a pulsar wind nebula, though we have no evidence for pulsars with such high rotational energy losses having been born in old populations such as G1. A radio spectrum (with EVLA or e-MERLIN) or milliarcsecond-resolution VLBI observations, as suggested by Ulvestad et al. (2007), could rule this possibility out, as could detection of strong X-ray variability. It is also possible that the radio source is not coincident with the X-ray source. If we can confirm that the radio source is the X-ray source, the radio source may be a background source, a radio-loud X-ray binary in G1 or a jet from the central IMBH.

**Table 1.** Comparison of G1 (assuming X-ray emission from G1 is from the putative IMBH), supermassive black holes and stellar mass black holes.

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This research has made use of data provided by the Chandra X-ray Center, which is operated by the Smithsonian Astrophysical Observatory on behalf of NASA, and is based on observations made with the VLA (Ulvestad et al. 2007), both the LMXB and supernova remnant scenarios are unlikely based on the radio/X-ray flux ratio (see below). The probability of positional coincidence between G1 and an unrelated X-ray source is very small. We estimated the background AGN/foreground star rate within the half-mass radius of G1 ($\sim 1$ arcsec; Barmbly et al. 2007) using the Chandra Deep Field (Brandt et al. 2001). At a 0.5–2 keV flux of $1.2 \times 10^{-14} erg \ s^{-1} cm^{-2}$, we expect to find on average $4 \times 10^{-5}$ background or foreground objects within the half-mass radius. Using the VLA, Ulvestad et al. (2007) detected a radio source coincident with G1 at 8.4 GHz with a flux density of $28 \pm 6 \mu$Jy. However, the radio position is offset from the X-ray and optical centre by about 1.3 arcsec (see Fig. 1) using our refined Chandra and HST observations. Because of the short baseline (3.5 km) of the VLA observations, the rms error of the VLA position is about 0.6 arcsec in each dimension. Therefore, the cluster core is still within the 95 per cent error radius (see Fig. 1). In order to confirm if the radio source is associated with the X-ray source, we will require high-resolution and high-sensitivity radio observations using the Expanded VLA (EVLA) in its long baseline configuration, e-MERLIN or VLBI.
the NASA/ESA Hubble Space Telescope, and obtained from the Hubble Legacy Archive, which is a collaboration between the Space Telescope Science Institute (STScI/NASA), the Space Telescope European Coordinating Facility (ST-ECF/ESA) and the Canadian Astronomy Data Centre (CADC/NRC/CSA). Ground-based observations were obtained with MegaPrime/MegaCam, a joint project of CFHT and CEA/DAPNIA, at the Canada–France–Hawaii Telescope (CFHT) which is operated by the National Research Council (NRC) of Canada, the Institut National des Science de l’Univers of the Centre National de la Recherche Scientifique (CNRS) of France and the University of Hawaii. Access to the CFHT was made possible by the Institute of Astronomy and Astrophysics, Academia Sinica, Taiwan. The CFHT data products were produced at the TERAPIX data centre located at the Institut d’Astrophysique de Paris. AKHK thanks L. Sjouwerman for discussion. This project is supported by the National Science Council of the Republic of China (Taiwan) through grant NSC96-2112-M-007-037-MY3.

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