A POSSIBLE DETECTION OF M31* WITH CHANDRA

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ABSTRACT

Two independent sets of Chandra and HST images of the nuclear region of M31 allow registration of X-ray and optical images to ~0′′1. This registration shows that none of the bright (∼1037 ergs s−1) X-ray sources near the nucleus is coincident with the central supermassive black hole, M31*. A 50 ks Chandra HRC image shows 2.5 σ evidence for a faint (∼1036 ergs s−1) discrete source that is consistent with the position of M31*. The Bondi radius of M31* is 0′′9, making it one of the few supermassive black holes with a resolvable accretion flow. This large radius and the previous detections of diffuse X-ray-emitting gas in the nuclear region make M31* one of the most secure cases for a radiatively inefficient accretion flow and place some of the most severe constraints on the radiative processes in such a flow.

Subject headings: accretion, accretion disks — black hole physics — galaxies: individual (M31) — galaxies: nuclei

1. INTRODUCTION

It is now accepted that a supermassive black hole (SMBH) is present in essentially every galactic core (Magorrian et al. 1998). However, most galactic nuclei appear inactive, raising the question: “Why are these SMBHs such embarrassingly faint X-ray sources, as compared to the SMBHs previously known to exist in AGNs?” Explanations fall into two broad classes: either the accretion rate is extremely low, i.e., the SMBHs are “starved,” or the accretion process is radiatively inefficient. A straightforward way to determine which explanation is correct is to resolve the accretion flow and therefore securely determine the mass accretion rate. We note that hybrid explanations are possible, i.e., the flow could start at the Bondi rate and then be slowed or stopped by winds, convection, and/or magnetic fields (Perna et al. 2003).

Because of the angular resolution of current X-ray telescopes, the best-studied examples of resolved accretion flows into SMBHs are limited to those in Sgr A* (Baganoff et al. 2003) and M87 (Di Matteo et al. 2003). Assuming the accretion flow in Sgr A* has the “normal” accretion efficiency, its expected luminosity would be roughly 7 orders of magnitude greater than the observed value. So we cannot escape the conclusion that the accretion flow in Sgr A* is radiatively inefficient (Yuan et al. 2003). M87 is underluminous by only 4 (not 7) orders of magnitude, so it must also have a radiatively inefficient flow, but the presence of a strong and resolved nuclear jet complicates the picture.

At a distance of 780 kpc (Stanek & Garnavich 1998; Macri et al. 2001), M31* is the nearest analog to Sgr A*. In addition to its highly unusual double nucleus (Lauer et al. 1993), the center of M31 houses a 3 × 10⁷ M☉ black hole (Kormendy & Bender 1999) spatially coincident with a compact cluster of UV-bright stars at the dynamical center of the galaxy (Lauer et al. 1998; Kormendy & Bender 1999). This cluster of stars is centered on the second-brightest optical peak, named P2, which becomes the brightest peak at UV wavelengths. The radio point source M31* is believed to be associated with the nuclear SMBH and is within ~0′′5 of the center of the galaxy (Crane et al. 1992). The radio source is unresolved at the ~0′′35 ~ 1 pc level. While M31* is 100 times farther away than Sgr A*, it suffers much less reddening: AV ~ 1 (Garcia et al. 2000), whereas AV ~ 30 for Sgr A*.

The first Chandra observations of M31 led us to associate a supersoft source near M31* with this SMBH (Garcia et al. 2000). Subsequently, we were able to register several Hubble Space Telescope (HST) WFPC2 images of the nuclear region with our ACIS mosaic using two globular clusters, reducing the error circles of the X-ray sources by a factor of ~10. This showed that our initial association was incorrect, and that none of the bright (LX ~ 10³⁷ ergs s⁻¹) sources near the center of the galaxy is spatially coincident with M31* (Garcia et al. 2001). Recently we have obtained an HST ACS image that fortuitously contains M31*. Registration of this image with a Chandra High Resolution Camera (HRC) image confirms our earlier results, and suggests that a previously unknown faint X-ray source may be coincident with M31*. In this paper we present both data sets and discuss M31* in the context of other low-luminosity SMBHs.

2. OBSERVATIONS

The absolute astrometric accuracy of both Chandra and HST images is only ~1′′, but by using common sources one can register the images to ~0′′1. As globular clusters are some of the most common X-ray point sources found in M31 and are easily identifiable on HST images, we searched for clusters near the nucleus that could provide the desired registration. We found two such clusters.

Below we show that we were then able to accurately register two completely independent data sets, one using the HST WFPC2 and the Chandra ACIS-I, and the other using the HST ACS and the Chandra HRC. Both confirm that none of the bright (LX ~ 10³⁷ ergs s⁻¹) sources near the nucleus are coincident with M31*. The HRC image shows marginal evidence for a
weak, previously unknown X-ray source at the position of M31\textsuperscript{+}. While the ACIS observations do not resolve this source from the nearby brighter sources, they are consistent with a source of the same flux at the M31\textsuperscript{+} position.

Our choice of which images to register was based on the availability of appropriate images. The first Chandra images of the nucleus were taken with the ACIS-I, and at that time the only HST images appropriate for our purposes were taken with the WFPC2. We therefore registered our ACIS-I mosaic with a pair of overlapping WFPC2 images which each contained an X-ray emitting globular cluster. Later, when HRC and ACS images of the nucleus became available, we registered these. We chose to do this second registration with no reference to the earlier images, so that it could serve as a completely independent check on the first registration.

In order to place the images in a standard coordinate system, we have also registered the HST images with the Local Group Survey (LGS) images of M31 (Massey et al. 2001). This registration has a rms error of \(0.06\). The LGS coordinate system has been registered to the USNO-A2.0 catalog with an accuracy of \(0.25\). The USNO-A2.0 catalog is registered to the J2000/ICRS frame, so the coordinates shown in our figures are J2000/ICRS to \(0.25\) accuracy.

2.1. HST WFPC2 and Chandra ACIS Observations

The Chandra observations of the nuclear region analyzed here consist of seven separate ACIS observations taken during the first 2 years of Chandra operations, which have been summed to generate an image with an effective exposure time of 34.7 ks. These observations are described in detail by Kong et al. (2002), who considered these and one additional (ObsID 1583) observation. In order to maintain the highest possible spatial resolution in the summed image, the individual images were first generated with \(0.125\) pixels, with the standard \(0.25\) position randomization removed. The images were then stacked using the positions of the point X-ray sources as registration marks. The resulting image has a radially averaged FWHM on-axis of \(0.06\) as determined by IRAF\textsuperscript{5} (image) profile fitting on numerous sources. We limited the image size to \(2048 \times 2048\) pixels, therefore covering the \(4.2 \times 4.2\) region shown in Figure 1 (top). The X-ray sources associated with the two globular clusters used to register the Chandra and HST data are indicated, as is the nucleus. The three bright nuclear X-ray sources are not easily resolvable on this large-scale image.

An archival WFPC2 image that includes M31\textsuperscript{+} also includes a recently discovered globular cluster (M31GC J004246+411737) identified by Barmby & Huchra (2001). This archival image was taken with the F300W filter (central wavelength 3000 Å, bandpass 300 Å) on 1995 June 19 and first discussed in Lauer et al. (1998). We obtained a WFPC2 image on 2000 February 2 in order to search for a UV counterpart to the new X-ray source at the position of M31\textsuperscript{+}. We obtained a WFPC2 image on 2000 February 2

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cluster. From the images, we measure \( r = 0.06 \) for mita213 (with 59 counts) and \( r = 0.07 \) for M31GC J004246+411737 (with 39 counts). We note that the Chandra wavdetect tool gives similar errors.

Of course, the position of the globular clusters within the HST image also has some error. The FWHM of the images of these clusters themselves, as measured from the HST images, is 0.50 for mita213 and 0.35 for M31GC J004246+411737. However, the much larger number of counts in the HST images (\( \geq 10,000 \)) indicates these position errors are \( \leq 0.01 \). Summing the r.m.s. of the HST fit and the errors for the two clusters used for registration in quadrature indicates a 1 \( \sigma \) error for position determination of 0.082. We note that this registration was done with a simple translation. We did not find any disagreement in scale factor or roll to within our ability to measure them of 0.1% and 0.03, respectively. Due to the fortuitous location of the nucleus between the two registration points, disagreements in scale or roll could contribute at most 0.014 and 0.01 to the registration of the nucleus. We therefore take 0.1 to be the registration error at the nucleus.

Once the images have been registered, we attempt to associate the nuclear sources at various wavelengths. The central region of the merged, registered ACIS-I image is shown in Figure 2. Two of the three bright nuclear sources are visible in this image, including the northernmost source (\( N = \) CXOM31 J004244.3+411608 = r-l-10) and the central supersoft source (\( SSS = \) CXOM31 J004244.3+411607 = r-1-9; Kong et al. 2002). The position of the peak of the UV emission, \( P2 \), is indicated by a circle of 0.1 radius, which is the 1 \( \sigma \) error in the registration of the Chandra and HST images.

The ACIS contours from Figure 2 are overlaid. \( P2 \) is indicated by the arrow, and the circle represents the error in the location of the nuclear radio source M31+ on this HST image. The J2000/ICRS position of the peak flux from the UV bright cluster (i.e., the position of \( P2 \)) is R.A. 00:42:44.344, decl. 41:16:08.54, with an error limited by the registration to the USNO-A2.0 frame of 0.25.

2.2. HST ACS and Chandra HRC Observations

An HST ACS image of the M31 nucleus was obtained by us on 2004 January 23 as part of our Chandra AO5 program searching for the optical counterparts of black hole X-ray novae in M31. The 2200 s image was obtained with the F435W (=B-band) filter in a standard four-point dither pattern and reduced with standard HST drizzle tools. Figure 4 shows the region of this image surrounding the nucleus, overlaid with X-ray contours from the archival 47 ks HRC-I observation shown in Figure 5 (ObsID 1912, obtained on 2001 November 1; see Kaaret 2002). The registration
of the ACS and HRC images necessary to transfer the contours is described below. The contours in Figure 4 show the supersoft source (SSS) on the bottom, with source N1 above it. Approximately 0\textdegree 0.5 to the right a separate contour is seen overlying P2. The position of P2 in this image is R.A. 00h42m44.3329, decl. 41\textdegree 16\textquoteleft 08\textquoteleft 49, which is consistent with the position from the PC image above.

Figure 5 shows the 47 ks HRC image at its intrinsic 0\textdegree 125 pixel\textsuperscript{-1} scale. At a position consistent with P2 and M31\textsuperscript{1}, there appears to be a weak X-ray source that is resolved from N1 and SSS. The position of this source is R.A. 00h42m44.329, decl. 41\textdegree 16\textquoteleft 08\textquoteleft 42, with a statistical error in the X-ray centroid of ±0\textdegree 1. As can be seen from Figure 5, a 3 pixel diameter circle encloses this source and falls into the dip in counts between this source, N1, and the SSS. This circle contains the peak 25\% of the flux from a typical on-axis point source (see Fig. 4.15 of the Chandra Observers Guide\textsuperscript{6}). We use this somewhat smaller than typical extraction radius to compute the observed flux because of the presence of nearby sources and diffuse background from M31.

There are 13 counts within this 3 pixel diameter circle, some of which are background due to the scattering wings of N1 and SSS and the unresolved diffuse emission in the core of M31. By summing the counts in 3 pixel diameter circles placed in a ring equidistant from N1, we determined the background contribution from N1 and the diffuse emission to be 3.4 ± 2.3 counts at the location of M31\textsuperscript{1}. In the same way we determined the contribution from SSS to be 2 ± 1.9 counts. The 13 counts at the position of M31\textsuperscript{1} therefore represents a ~2.5 \( \sigma \) detection. While very suggestive, this clearly needs confirmation.

Assuming the typical M31 source spectrum of \( N_H = 7 \times 10^{20} \text{ cm}^{-2} \) and \( \alpha = 1.7 \), the 7.6 counts above the background in this circle corresponds to an observed flux of 2.9 \( \times \) 10\textsuperscript{-15} ergs cm\textsuperscript{-2} s\textsuperscript{-1} (0.3–7.0 keV), or a luminosity of 1.9 \( \times \) 10\textsuperscript{35} ergs s\textsuperscript{-1} at M31.

Correcting for the small extraction radius and the absorption in this circle corresponds to an observed flux of 2.9 \( \times \) 10\textsuperscript{-15} ergs cm\textsuperscript{-2} s\textsuperscript{-1} (0.3–7.0 keV), or a luminosity of 1.9 \( \times \) 10\textsuperscript{35} ergs s\textsuperscript{-1} at M31.

Alternatively, we can use the data to derive a 3 \( \sigma \) upper limit to the emitted luminosity that is only slightly higher, at \( L_X = 1.0 \times 10^{36} \) ergs s\textsuperscript{-1}.

\textsuperscript{6} See http://asc.harvard.edu/proposer/POG.

2.2.1. Registering the ACS and HRC Images

The ACS image described above contains both M31\textsuperscript{1} and mita213, but no other globular clusters. We therefore used mita213 to register the two images, and using the same type of error analysis as for the ACIS-I/WFPC images we find a 1 \( \sigma \) position error of 0\textdegree 11. We note that because we are limited to a single registration object, in this case we are not able to directly check for roll or plate scale errors.

However, we can make an indirect check by comparing the HRC image to the ACIS-I image, and comparing the ACS image to the WFPC2 image. When we register the HRC and ACIS-I images using the brightest eight X-ray sources, we find that allowing for roll and scale reduces the rms offsets by 0\textdegree 03, which is negligible given our 0\textdegree 11 position error. Similarly, when we register the ACS and WFPC2 images and allow for roll and scale changes, the rms offsets are reduced by 0\textdegree 01, which again is negligible given our 0\textdegree 11 position error.

3. DISCUSSION

The discovery of the point radio source M31\textsuperscript{1} predates the discovery of the double nucleus of M31. In their 1992 paper, Crane et al. take the optical position of the nucleus from de Vaucouleurs & Corwin (1985) and assign a ±0\textdegree 05 error to this position. They note that the unresolved radio source is 0\textdegree 08 north and 0\textdegree 48 west of the nucleus. This offset, which appears to be within the errors, has taken on new significance with the discovery that the dynamical and photometric peaks are offset by a similar amount and the subsequent discovery of the double nucleus. The position of the radio point source M31\textsuperscript{1} is known to within 0\textdegree 15 because of the presence of a nearby radio calibrator.

Melia (1992) summarizes the known properties of the nucleus based on the two papers mentioned above and the work of Dressler & Richstone (1988), who find that the dynamical center is 0\textdegree 05 to the southwest of the peak of the V- to I-band light. The dynamical data indicate the presence of a dark, massive, compact object, i.e., a central SMBH. Dressler & Richstone (1988) note that different measures of the offset give 0\textdegree 62 and 0\textdegree 37, so we can take the offset to be ~0\textdegree 05 ± 0\textdegree 15 along the major axis of M31. Lauer et al. (1998) and Kormendy & Bender (1999) both conclude that the central SMBH is located at the UV-bright clump of stars within P2 (the fainter of the two peaks), which is located at the dynamical center.

Because we have registered both sets of HST images here to the LGS, we are able to determine the J2000 position of P2 and compare it directly with the position of M31\textsuperscript{1}. As can be seen in Figures 3 and 4, the position of M31\textsuperscript{1} is consistent with P2, and inconsistent with the brighter of the two nuclear peaks, P1. The average position of P2 from our work is R.A. 00h42m44.341, decl. 41\textdegree 16\textquoteleft 08\textquoteleft 51. Given our registration to the LGS and USNO-A2.0 catalogs, this position should have a rms error of 0\textdegree 3.

Having resolved M31\textsuperscript{1} from the surrounding point and diffuse X-ray sources, we can now investigate the accretion properties of this nearby SMBH. The presence of a hot and truly diffuse emission component in the core of M31 was first noted in Einstein observations (Trinchieri & Fabbiano 1991) and later confirmed with Röntgensatellit (ROSAT); Primini et al. 1993), XMm-Newton (Shirey et al. 2001), and Chandra (Dosaj et al. 2002) observations. Any of this gas within the Bondi radius of the SMBH will accrete and possibly generate accretion luminosity. In order to compute the Bondi accretion rate, we use the X-ray observations to estimate the temperature and density of this gas.

The temperature in the inner ~5\textdegree has been estimated as ~0.35 keV based on XMM-Newton observations (Shirey et al.
and has been found to fall radially from 0.50 to 0.26 keV based on Chandra ACIS-I observations (Dosaj et al. 2002). Recently Takahashi et al. (2004) combined XMM-Newton and Chandra ACIS-S observations to reveal that there are three distinct soft temperature components with slightly different radial surface brightness variations, which explains the slight discrepancy between the earlier two results. The dominant component in terms of emission measure and particle density has a temperature of \( \sim 0.3 \) keV.

The density of the diffuse gas near the SMBH can be estimated from the emission measure and surface brightness profile fits. Dosaj et al. (2002) measured the profile within the central 1' and find that it appears to flatten. They estimate a gas density of \( \rho \sim 0.1 \text{ cm}^{-3} \). Takahashi et al. (2004) measure a separate surface brightness profile for each of the three temperature components they find, in 1' bins. Summing the flux from all three in the inner bin also indicates a density of \( \sim 0.1 \text{ cm}^{-3} \) within 1' (\( \sim 200 \text{ pc} \)) of M31*. We note that this density is similar to that found in other nearby galaxies (Di Matteo et al. 2003; Loewenstein et al. 2001), but a factor of 10 below that found near Sgr A* (Baganoff et al. 2003).

In computing the Bondi radius we follow the prescription of Baganoff et al. (2003) exactly, thereby allowing direct comparisons. The radius is \( R_B = 2GM_{BH}/c^2 \), where the sound speed \( c_s = (\gamma kT/\mu m_H)^{1/2} \). Here the adiabatic index \( \gamma = 5/3 \) and the mean atomic weight of the gas \( \mu = 0.7 \) (which implies twice the solar abundance). Given \( M_{BH} = 3 \times 10^7 M_\odot \) and the density and pressure found in the previous paragraphs, and using the dominant temperature component of 0.3 keV, we find for M31* \( R_B = 3.4 \text{ pc} \), or \( R_B = 0.9' \) at the 780 kpc distance of M31.

This can be compared to Sgr A*, with \( R_B = 0.072 \text{ pc} \) or \( R_B = 1.8' \) (Baganoff et al. 2003), and to M87, with \( R_B = 17' \) (Di Matteo et al. 2003). Pellegrini (2005) has collected the measurements of the mass, \( L_X \), nuclear gas density, and temperature for nearby quiescent SMBHs. From this compilation, we see that IC 1459, NGC 4594, and NGC 4649 also have Bondi radii greater than or equal to that of M31*, and so are also resolvable with Chandra.

While resolving the Bondi radius allows one to securely measure the magnitude of the accretion flow, the next most fundamental number is likely the ratio of the observed luminosity to the Bondi luminosity \( L_B = 0.1GM_{BH}c^2 \). The Bondi luminosity is the maximum luminosity that one could expect, assuming that the initially spherical flow eventually forms a classical thin accretion disk. Following Baganoff, \( M_B = \pi(GM_{BH}/c^2)^{1/2} = 3.4 \times 10^{50} \text{ g s}^{-1} \). For M31* we compute \( L_B = 3 \times 10^{40} \text{ ergs s}^{-1} \). The possible detection of M31* indicates \( L_X = 9 \times 10^{35} \text{ ergs s}^{-1} \) and therefore \( L_X/L_B = 3 \times 10^{-5} \).

The Bondi radii and \( L_X/L_B \) for nearby SMBHs are plotted in Figure 6. This figure shows that M31* is one of approximately a half dozen nearby SMBHs with a Bondi radius larger than the Chandra resolution. These objects therefore allow the most secure measurements of the accretion rate at the outer edge of the flow. Knowing this, we may be able to determine if the flows contain winds (ADIOS) convection (CDAFs), or if the emission is dominated by jet processes (Falcke 2001) rather than thermal emission. For example, Gallo et al. (2003) recently found that in quiescent stellar mass black holes there is a correlation between the radio and X-ray luminosity \( L_R \propto L_X^{0.7} \). The correlation also applies in AGNs (Merloni et al. 2003), but the normalization of the correlation depends on the mass of the SMBH powering the AGN. Yuan & Cui (2005) model these correlations in terms of emission from an accretion-jet system, predicting that the correlation should steepen at the very low luminosity found here for M31*. The observed X-ray and radio luminosity of M31* fall on this steeper correlation of \( L_R \propto L_X^{1.23} \) (Yuan & Cui 2005). Interpreting in terms of this model, our observations imply that the X-ray and radio emissions from M31* are both dominated by emission from an unresolved jet.

While objects on the extreme right of Figure 6 provide the most secure measurements of the accretion rate because \( R_B \) is resolvable, those at the extreme lower end provide the most severe constraints on the accretion processes because the flows are the most underluminous. We see that M31* is exceeded only by Sgr A* and NGC 4649. The point labeled M31 corresponds to the possible detection reported here, and the line labeled M31 U.L. corresponds the upper limit possible with a planned 200 ks Chandra HRC I observation.

4. SUMMARY

The observations we present here provide evidence for a marginal detection of X-ray emission from M31* at the level of \( L_X \sim 10^{36} \text{ ergs s}^{-1} \), which is \( 3 \times 10^{-5} \) times below the expected Bondi accretion luminosity. The Bondi accretion radius of the diffuse X-ray plasma surrounding M31* is \( R_B = 0.9' \), larger than the resolution of the X-ray observations. The estimated Bondi accretion rate is therefore very securely known. These two points taken together show that M31* is exceeded only by Sgr A* and NGC 4649 in providing the most secure and severe evidence for radiatively inefficient accretion flows in SMBHs.

This work was supported in part by NASA LTSA grant NAG5-10889 and Contract NAS8-39073 to the Chandra X-ray Center.
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