A FIRST LOOK AT THE NUCLEAR REGION OF M31 WITH CHANDRA

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ABSTRACT

We report on the first observation of the nuclear region of M31 with the Chandra X-ray Observatory. The nuclear source seen with the Einstein and ROSAT HRIs is resolved into five point sources. One of these sources is within 1 arcsec of the M31 central super-massive black hole. As compared to the other point sources in M31, this nuclear source has an unusual x-ray spectrum. Based on the spatial coincidence we identify this source with the central black hole, and note that the unusual spectrum is a challenge to current theories. A bright transient is detected ~ 26 arcsec to the west of the nucleus, which may be associated with a stellar mass black hole.

Subject headings: Galaxies: individual (M31) – black holes

1. INTRODUCTION

As our nearest Milky Way analog, M31 offers us a chance to study a galaxy like our own without the obscuring effects of living in the middle of the Galactic plane. For example, the nucleus of our Galaxy (Sgr A*), is obscured by ~ 30 magnitudes of visual extinction (Morris and Serabyn 1996), while the nucleus of M31 likely suffers ~ 2 magnitudes of extinction (see Section 2.3.1). In addition, the study of x-ray binaries in the Galactic plane is hindered by reddening sometimes reaching > 10 magnitudes, which can be compared to an average E(B-V) = 0.22 magnitudes for globular clusters in M31 (Barnby et al. 2000).

Ground based measurements of the rotational velocity of stars near the core of M31 provide strong evidence of a central dark, compact object of mass 3.0 × 10^6 M⊙, presumably a black hole (Kormendy and Bender 1999 and refs therein). HST observations resolved the M31 nucleus into two components (P1 and P2) separated by ~ 0.5″ (Lauer et al. 1993). These observations support the model of the nucleus as a double torus of stars orbiting the core in a slightly eccentric orbit (Tremaine 1995). Post COSTAR HST observations have shown that there is a group of partially resolved UV-bright stars between P1 and P2 at the position of the central black hole (Brown et al. 1998).

The first identification of an x-ray source with the M31 nucleus came with Einstein observations, which found a source within 2.1″ of the nucleus with Lx = 9.6 × 10^37 erg s⁻¹ (0.2-4.0 keV, Van Speybroeck et al. 1979). While this source was not variable in this first observation, subsequent Einstein observations showed the nucleus to be variable by factors of ~ 10 (Trinchieri and Fabbiano 1991) on timescales of 6 months. Published ROSAT observations show Lx = 2.1 × 10^37 erg s⁻¹, which is at the faint end of the Einstein range (Primini, Forman and Jones 1993).

Radio observations reveal a weak (~ 30 μJy) source at the core (Crane, Dickel and Cowan 1992). The luminosity at 3.6 cm is ~ 1/5 that of Sgr A*, a puzzle given that the M31 nucleus is ~ 30 times more massive (Melia 1992). The correlation between the radio and x-ray properties of low-luminosity supermassive black holes (Yi and Boughn 1999) might be explained by an ADAF model, but M31 is an outlier in these correlations.

The point sources distributed throughout M31 are likely x-ray binaries and supernova remnants similar to those in our galaxy. The fact that ~ 40% of these sources are variable is consistent with this hypothesis (Primini, Forman and Jones 1993). As in the galaxy, some of these point sources are transient. Comparison of Einstein and ROSAT images shows that ~ 6% of the sources are transient (Primini, Forman and Jones 1993). A comparison of Einstein and EXOSAT observations allowed discovery of two transients (White & Peacock 1988), and a study of the ROSAT archive allowed discovery of a supersoft x-ray transient (White et al. 1995).

The sensitivity and high spatial resolution of Chandra (van Speybroeck et al. 1997, Weisskopf and O’Dell 1997) provide new insights into the x-ray properties of M31. A few of those new insights, concerning the nucleus and a new transient, are reported in this letter.

2. OBSERVATIONS

2.1. Chandra

Chandra was pointed at the nucleus of M31 for 17.5 ks on Oct 13, 1999. This pointing occurred immediately before Chandra operations paused for the passage through the Earth radiation belts, and the radiation environment was already higher than average. This caused high counting rates in the ACIS-S3 chip, which saturated telemetry and caused data dropouts. The S3 counting rate was used as an indicator of high background, and whenever it increased beyond 1.5 c s⁻¹ we rejected the data. Consequently we obtained 8.8 ks of active observing time.

The standard four ACIS-I (Garmire et al. 1992) chips were on; therefore a ~ 16” × 16” region of the center of M31 was covered. In this letter we concentrate on the observations of the central ~ 1” only. The image of this nuclear region is shown in Figure 1.

Data were analyzed with a combination of the CXC Caio V1.1 (Elvis et al. 2000), HEASARC XSPEC V10.0 (Arnaud 1996), and software written by Alexey Vikhlinin (Vikhlinin et al. 1998). Unless otherwise specified, all error regions herein are 68% confidence bounds and include a 20% uncertainty in the ACIS effective area below 0.27 keV. We note that this calibration uncertainty is < 50% of the statistical uncertainties for the sources considered herein.

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2.2. **ROSAT**

ROSAT imaged the central region of M31 six times from 1990 to 1996, with exposure times ranging from 5 ks to 84.5 ks (see Primini, Forman and Jones 1993. and Primini et al. 2000). The last of these exposures was 84.5 ks in 1996 January. The image of the nuclear region from this observation is shown in Figure 1 (top).

![Figure 1: Top: The nuclear region of M31 as it appears in an 84.5 ks ROSAT HRI observation in January 1996. Bottom: The same as seen in an 8.8 ks Chandra ACIS-I observation on Oct 13, 1999. The cross-like shadow seen in the ACIS-I observation is due to the gaps between the 4 ACIS-I chips. These images are 4 arcmin on a side.](image)

In order to get a first look at the spectra of the point sources, we performed a wavelet deconvolution (Vikhlinin et al. 1998) of the image and found 121 point sources in the full 16' × 16' FOV of ACIS-I (these sources will be discussed in a separate paper). We then computed the hardness ratio of the 79 sources with more than 20 counts. In the histogram of this ratio (Figure 3) the nuclear source is one of three outliers with extremely soft spectra. The fact that the nuclear spectrum is distinctly different from the mean may indicate that there is something fundamentally different about this source.

![Figure 2: An enlargement of Figure 1(bottom), showing the nuclear region in detail. The circle surrounding the central sources is 5" in diameter, approximating the resolution of the ROSAT HRI. This image is 1 arcmin on a side.](image)

![Figure 3: The hardness ratio for 79 sources with > 20 total counts found in the ACIS-S image of M31. The nuclear source, CXO J004244.2+411608, has the third lowest hardness ratio, and is indicated by the “N”. The nearby transient is indicated by the “T”. The source 1'' North of the nucleus is in the first bin below 0.0, the source ∼1.5'' to the South of the nucleus is in the bin indicated by the “T”.](image)

2.3. **Data Analysis**

**The Nucleus:** The central object seen with the ROSAT HRI is clearly resolved into 5 sources (Figure 2). The Chandra aspect solution is based on 5 stars from the Tycho (Hipparcos) catalog, so has the potential to be good to a few tenths of an arcsec (Aldcroft et al.2000). Based on the aspect solution alone, we find that one of these five sources, CXO J004244.2+411608, is within < 1'' of the position of the radio nucleus (Crane et al. 1992). As an independent check on the aspect, we computed a plate solution for the x-ray image using the positions of 10 x-ray detected globular clusters from the Bologna catalog (Battistini et al. 1987). This solution has an uncertainty of ∼ 0.7'' rms in RA and Dec, and agrees (within the errors) with the Chandra aspect.

We extracted 100 counts from a 3 square-arc-sec region surrounding the nucleus. In order to limit contamination from CXO J004244.2+411609, which is only 1.0'' to the North, we excluded photons more than 0.5'' to the North of the nuclear source. The resulting PHA spectrum was fit with XSPEC, after first binning the data such that each fitted bin had > 10 counts. Gehrels weighting was used for the fits (Gehrels 1986). The fits were limited to the 0.2-1.5 keV region, as there were insufficient counts outside of this region.
Simple models (powerlaw, black-body, bremsstrahlung, with interstellar absorption) provide acceptably good fits to the data. The power law fits find a slope $\alpha = 5^{+2.4}_{-2.3}$, and limit $N_{\text{H}} = 4.9^{+3.8}_{-5.4} \times 10^{21}$ cm$^{-2}$. In order to reduce the error range on the fitted slope we choose to limit the allowed range of absorption to that found for the nearby transient (below), i.e., to $N_{\text{H}} = 2.8 \pm 1.0 \times 10^{21}$ cm$^{-2}$. This then allows us to further restrict the slope (or temperature) of the spectrum to $0.5 < \alpha < 1.5$, kT = 0.15$^{+0.06}_{-0.03}$, or kT = 0.43$^{+0.17}_{-0.08}$ for power-law, black-body or bremsstrahlung fits (respectively).

The detected 0.3-7.0 keV flux, assuming the further restricted range of parameters for the power law model, is $5.8\pm0.5 \times 10^{-14}$ erg cm$^{-2}$ s$^{-1}$, corresponding to an observed luminosity of $3.9^{+0.6}_{-0.3} \times 10^{36}$ erg s$^{-1}$ at 770 kpc (Stanek and Garnavich 1998). At the lowest $N_{\text{H}}$ and flattest $\alpha$ in this range, approximately 60% of the 0.3-7.0 keV flux is absorbed by the ISM, while at the highest $N_{\text{H}}$ and steepest $\alpha$, nearly 98% of the flux is absorbed. The corresponding emitted luminosity ranges from $1.2 \times 10^{37}$ erg s$^{-1}$ to $1.6 \times 10^{38}$ erg s$^{-1}$, and has a nominal value at the best fit parameters of $4.0 \times 10^{37}$ erg s$^{-1}$.

In order to test our assumption that the $N_{\text{H}}$ measured for the transient is appropriate to apply to the nucleus, we fit power law spectra to four other bright nearby sources. These sources are all further away from the nucleus, with distances ranging from 30$''$ to 2', and have between 237 and 823 detected counts. In every case the 90% confidence regions for $N_{\text{H}}$ overlap with the transient. Given that there is no evidence for large variations in $N_{\text{H}}$ in the region around the nucleus, it is reasonable to assume the nuclear $N_{\text{H}}$ is the same as that of the transient. Note that the Galactic $N_{\text{H}} = 7 \times 10^{20}$ cm$^{-2}$ in the direction of M31 (Dickey & Lockman 1990), so our results are consistent with additional local absorption within M31 itself. If the gas/dust ratio in M31 is similar to that in the Galaxy, the nuclear $A_V = 1.5 \pm 0.6$ (Predehl and Schmitt 1995).

The Nearby Transient: We extracted 763 counts for a 1" radius circle at the position of CXO J004242.0+411608. This data was similarly grouped into bins with >10 counts, and fit to simple models with XSPEC. Chi-squared fitting with Gehrels weighting was used to find the minimum chi-squared spectral parameters. Power law, bremsstrahlung, and blackbody fits are all acceptable ($\chi^2 / \nu < 1.13$ for 71 DOF), but the power law fits produce the lowest $\chi^2 / \nu \sim 0.56$. Significant counts are seen out to 7.0 keV. The best fitting power law number slope is $1.5 \pm 0.3$, with a best fit $N_{\text{H}} = 2.8 \pm 1.0 \times 10^{21}$ cm$^{-2}$.

Bremsstrahlung and black body fits formally allow $N_{\text{H}} = 0$ cm$^{-2}$, but as the Galactic value to M31 is $N_{\text{H}} = 7 \times 10^{20}$ cm$^{-2}$, we restrict the fitting space to values larger than this. Bremsstrahlung fits are not able to set an upper limit to the temperature, but set a lower limit of kT$>6$ keV. Black body fits limit the temperature to kT = 0.75$^{+0.25}_{-0.05}$ keV. Assuming a power law model, the detected flux is $7.4\pm0.7 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$, corresponding to a observed luminosity of $5.1\pm0.5 \times 10^{37}$ erg s$^{-1}$, and an emitted luminosity of $7.0\pm0.8 \times 10^{37}$ erg s$^{-1}$ (0.3-7.0 keV). The hardness ratio is typical of other point sources (Figure 3).

We examined each of the 5 ROSAT HRI observations of the center of M31, and find that there is no source apparent at the position of this transient in any of these exposures. For the deepest (and last) observation, we find 78 counts in a a 7.5" arcsec radius at the position of this transient, which is consistent with the background caused by the diffuse emission in M31 (Primini et al. 1993). From this we compute a 95% (2 $\sigma$) upper limit of 17.7 counts. Assuming the power law spectrum determined above for this source in outburst, and applying a small correction for the flux not contained in the 7.5" circle, this corresponds to an upper limit to the emitted luminosity of the source of $3.0 \times 10^{36}$ erg s$^{-1}$ in the 0.3-7.0 keV band. Thus the transient brightened by at least a factor of $\sim 20$.

2.4. Discussion

The Nucleus: Several authors have previously noted the unusual x-ray and radio luminosity of the nucleus of M31 (Melia 1992, Yi and Boughn 1999). We note that the x-ray luminosity we find herein is substantially lower than that quoted in several recent papers comparing x-ray and radio luminosities of low luminosity super-massive black holes (e.g. Franceschini, Vercellone and Fabian 1998, Yi and Boughn 1999). At this revised luminosity the M31 nucleus appears to be even more of an outlier on the correlations between radio luminosity, x-ray luminosity, and black hole mass found for low luminosity super-massive black holes (Yi and Boughn 1999, Figures 4 & 5).

The unusual x-ray and radio luminosity has lead to the suggestion that perhaps the source may not be associated with the central black hole, but is merely a chance co-incidence (van Speybroeck et al. 1979, Yi and Boughn 1999). The probability of a chance co-incidence depends upon what search region one uses, and a posteriori, it is hard to know what the relevant search region is. If we use the full ACIS FOV as the search region, then the chance of any one of the 121 detected sources being within 1$''$ of the nucleus is $\sim 4 \times 10^{-4}$. However, the surface density of sources increases towards the nucleus, so the chance probability may be higher than this. If one limits the search region to the 25 square arc-sec area which contains the five sources ROSAT and Einstein were not able to resolve, the chance probability is $\sim 20\%$. This is most likely an overestimate, as can been seen by carrying this argument to its extreme (and non-sensible) limit: if one limits the search region to the 1 square arc-sec region around the nucleus, the chance that the one source within that region is within 1$''$ of the nucleus is 100%!

While it may be unclear what the appropriate search region is, it seems clear that a chance alignment cannot be dismissed out of hand. This motivated us to search for other unusual characteristics of the central source, which led to the discovery that it has an unusually soft spectrum. We speculate that the unusual spectrum is due, at least in part, to the high mass of the nucleus, and that the unusual spectrum may provide a clue to the origin of the unusually weak radio emission.

However, because there are no observational precedents or strong theoretical arguments which would lead us to expect the spectrum of the a $\sim 10^{7}M_{\odot}$ low luminosity black hole to be very soft, we cannot identify the unusual spectrum as a signature of the central black hole. Our identification is based solely on the positional co-incidence, and the unusual spectrum is left as a challenge to models.

While previous Einstein and ROSAT observations are unable to separate the nuclear source from the surrounding four sources, the fluxes indicate that the nucleus (or surrounding emission) is highly variable. In order to compare these fluxes to the Chandra flux, we assume the nuclear power law spectrum found above, and use the counting rates from the literature (Van Speybroeck et al. 1979, Trinchieri & Fabbiano 1991, Primini et al. 1993) to calculate 0.2-4.0 keV detected fluxes. The uncertainty in the nuclear spectrum allows up to 40% uncertainty in the conversion from counting rate to flux. In order to make
a fair comparison, Table 1 lists the summed flux from all 5 nuclear sources in the Chandra image.

| Date    | Observatory | Flux (10^{-12} erg cm^{-2} s^{-1}) |
|---------|-------------|------------------------------------|
| 1979 Jan| Einstein    | 7.07 ± 0.06                        |
| 1979 Aug| Einstein    | 0.60 ± 0.18                        |
| 1980 Jan| Einstein    | 3.50 ± 0.64                        |
| 1990 July| ROSAT      | 1.70 ± 0.12                        |
| 1999 Oct| Chandra (5) | 1.43 ± 0.15                        |

Strong variability of unresolved sources is often cited as evidence for a small number of sources, simply because it is more likely that a single source varies rather than a group of sources varies coherently. If we apply this argument to the M31 nucleus, it implies that one of these five sources (perhaps the nucleus itself?) is highly variable. It would then be appropriate to assume that the average flux of the surrounding four sources is constant, and subtract this flux from the Einstein and ROSAT measurements in order to determine the flux of the nucleus alone. From the Chandra image, the flux from these four sources is 0.85 × 10^{-13} erg cm^{-2} s^{-1}. Subtracting this, we see that the lowest Einstein flux measurement is consistent with zero flux from the nucleus, and indicates a factor of ∼ 40 variability.

As an aside, we note that the detection of Sgr A* with Chandra (Garmire 1999) does not necessarily rule out an M31-like spectrum. The much higher 2V ∼ 30 to Sgr A* would reduce the observed count rate from an M31-like spectrum by ∼ 60 times, but the ∼ 100 times smaller distance would more than make up for this.

Standard ADAF models are not able to explain the ratio of x-ray to radio luminosity of the nucleus (Yi and Boughn 1999). However, models including winds (Di Matteo et al. 1999) and/or convective flows (Narayan, Igumenshchev & Abramowicz 1999) may be able to explain this ratio. These models generally predict hard spectra in the x-ray region, so may not be able to explain the extremely soft spectrum reported herein (Quataert 2000, pc). We note that the x-ray luminosity of M31 is several orders of magnitude below that typically considered in these models, implying that the models may not fully describe this parameter space.

**The Nearby Transient:** The nature of the bright transient is uncertain. By analogy to Milky Way sources, its transient nature and luminosity imply that it is either a massive X-ray binary, typically consisting of a Be-star and a pulsar, or an x-ray nova, often consisting of a late-type dwarf and a black hole (White, Nagase and Parmar 1995, Tanaka and Lewin 1995). The spectral slope of α = 1.5 is between the hard spectra typically seen in x-ray pulsars (0 < α < 1.0, White, Nagase and Parmar 1995) and the softer spectra seen in x-ray novae in outburst (α ∼ 2.5, Ebisawa et al. 1994; Sobczak et al. 1999). At late times in the decay of an x-ray nova the spectrum often hardens to α ∼ 1.5, but this would imply that the peak outburst luminosity of this transient was ∼ 10^{39} erg s^{-1}.

The absorption of N_H = 2.8 ± 1.0 × 10^{21} cm^{-2} is more typical of x-ray novae than Be-star pulsar systems, which often have N_H > 10^{22}. Perhaps the strongest argument in favor of an x-ray nova hypothesis is the location of the transient: stars in the inner bulge of M31 are likely old, disk/bulge population stars typical of those in x-ray novae, rather than the young, Be stars typically found in star forming regions and in Be-star pulsar systems.

We note that in either case the optical magnitude of the transient in outburst is likely to be V ∼ 22, making the object visible with HST. An x-ray nova would be expected to show a large variation in V from quiescence to outburst, while a Be-star pulsar would show a more moderate variation. HST observations are underway in an attempt to clarify the nature of this transient.

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