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Chandra Observations of M31

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Abstract.
As part of the Chandra GTO program we are monitoring and surveying M31 using the HRC and ACIS cameras. These observations have resolved the nuclear X-ray source into five separate sources, one of which is very soft and may (or may not!) be associated with the central supermassive black hole. In addition, the superb spatial resolution and low scattering of the Chandra telescope allows us to unambiguously resolve the diffuse emission from the point sources. This emission is clearly softer than the point sources, and also increases with temperature radially. The monitoring nature of the observations allows detailed study of the variability of the point sources.

Introduction: M31 has been imaged with Chandra monthly as part of the AO1 GTO program. Each month five HRC observations provide a complete image of the galaxy to a sensitivity of 10^{37} erg s^{-1}. Transient sources are re-observed with the ACIS camera, typically yielding $\sim$ 100 counts per source. Thus the known (Galactic) types of accretion powered x-ray transients are being detected, their spectra measured, and their lightcurves studied. In the first observation we discovered a bright transient $26''$ to the west of the nucleus (Murray et al 1999), which may be associated with a stellar mass black hole. The next 8 ACIS images were centered on the nucleus, to follow the evolution of this transient. More recently a second bright transient was discovered in the HRC images which included M32 (Garcia et al 2000a). The most recent ACIS imaging has therefore been centered on this transient, which is likely in M32.

During AO2 the GTO monitoring program will be cut in $\sim 1/2$, but there are two GO programs which also will image M31. A program lead by R. Di Stefano will use the ACIS to repeatedly image the area surrounding three super-soft sources, and a program lead by P. Kaaret will use the HRC to study the variability of sources in the nuclear region. These studies (and others likely to come) should allow much of what has been considered 'galactic X-ray astronomy' to be carried out in our nearest neighbor galaxy, M31.

The Nucleus: The central object seen with the ROSAT HRI is clearly resolved into 5 sources by Chandra (Figure 1). The celestial location of these sources can be determined to $\sim 1''$ based on the Chandra aspect solution alone. To verify the Chandra coordinates we registered the X-ray image against the Bologna catalog of M31 globular clusters (Battistini et al 1987). Based on the positional coincidence of the soft nuclear source and the radio/UV nucleus, we previously suggested that these sources may be associated (Garcia et al 2000b).

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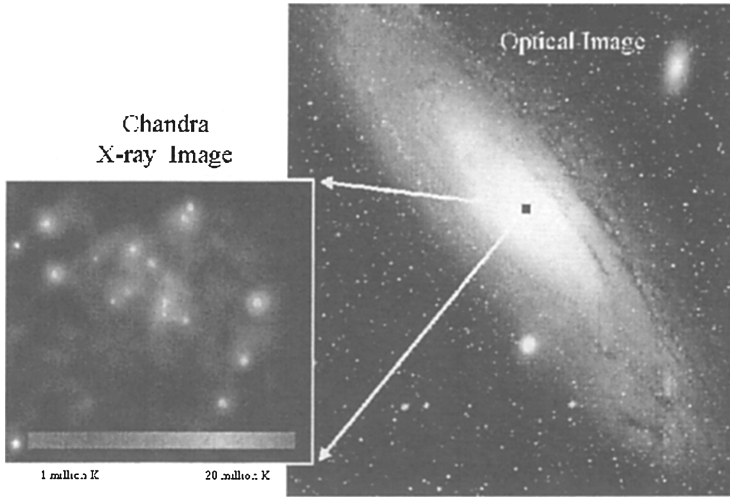

Figure 1. Chandra and DSS images of M31. The L-shaped central region contains 5 sources, one of which is very soft (see Garcia et al 2000b).

However, the positional accuracy was insufficient to exclude an association with another source located $\sim 1''$ to the north (CXO J004244.2+411609; Garcia et al 2000b); furthermore, it is also possible that neither source is associated with the nucleus.

By finding UV counterparts in HST images, it should be possible to determine the position of the Chandra nuclear sources relative to the UV nucleus to $\sim 0.1''$. This is challenging given the small region of M31 currently covered by HST images and the expected UV faintness of likely counterparts. Thus far we have been able to find only a single secure common source (the globular cluster MITa 213, Magnier 1993). This allows us to determine the translational offset between the X-ray and UV images, but does not allow us to determine the rotational offset. If we assume there is no rotational offset, then the bright UV nucleus is within $\sim 0.5''$ of CXO J004244.2+411609, and is $\sim 1.5''$ North of the soft nuclear source. We caution that this registration is inconclusive because the possible rotational offset could create $\sim 1''$ position errors.

The soft nuclear source is highly variable. The emitted luminosity as seen on 6 separate Chandra observations is shown in Figure 2. While previous X-ray missions were not able to resolve this source from its surrounding 4 neighbors, those neighbors appear relatively constant in the Chandra data. Assuming they are constant allows us to determine that the soft nuclear source had an emitted luminosity of $\sim 4 \times 10^{38}$ erg s^{-1} when first observed with the Einstein observatory (Van Speybroeck et al 1979). The calculation of the emitted luminosity is very sensitive to the assumed absorption, and the peak emitted luminosity may have been as low as 1.2×10^{38} erg s^{-1}.

Transients: In addition to the two bright transients mentioned above, there are numerous fainter transients seen in the ACIS images of the M31 nuclear region. We define a 'transient' as a source that is clearly detected on one image and clearly absent on another. For the faintest of these transients, the range of variability is constrained to be only a factor of > 3, while for the brightest it is

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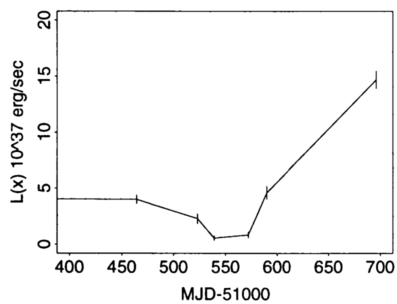

Figure 2. Chandra Light Curve of the M31 Soft Nuclear Source

a factor of > 30. Within the central 4′ box there are 8 transients out of a total population of 40 sources. Previous estimates for the number of transients in M31 were lower ($\sim$ 6%; Primini, Forman and Jones 1993), Our current estimate of $\sim$ 20% transient sources is comparable to the estimate for the transient population in the Milky Way ($\sim$ 16%; Primini et al 1993).

The two brightest transients have peak luminosities $\lesssim 10^{38}$ erg s^{-1}, consistent with X-ray novae seen in the Galaxy. Two somewhat fainter transients have peak luminosities $\sim 10^{37}$ erg s^{-1}, consistent with the pulsing X-ray transients and post-minimum period transients (King 2000) seen in the Galaxy. Five other transients have peak luminosities of only $\sim 10^{36}$ erg s^{-1}. While this is consistent with pulsing X-ray transients in the Galaxy, one does not expect to find large numbers of such objects in the bulge of M31: they are associated with young stars, not the old stellar population of the bulge. The recent discovery of an X-ray novae in the Galaxy with a peak outburst luminosity of only $\sim 2 \times 10^{35}$ erg s^{-1} (XTE J1118+480; McClintock et al 2000) emphasizes that these object do not always reach peak luminosities near Eddington, and that therefore the fainter transients in M31 could indeed be X-ray novae.

Diffuse Emission: The azimuthally-averaged surface brightness profile and hardness ratio of the M31 diffuse emission is shown in Figure 3 of Primini et al (2000). It is clear that the diffuse emission is substantially softer than nearly all the point sources. The hardness ratio within the inner 3′ is that expected from a Raymond-Smith thermal spectrum with a temperature kT$\sim$ 0.3 keV, consistent with the temperature found by XMM for this diffuse emission (Shirey et al 2000). Beyond 3′ the temperature of the diffuse emission increases until it reaches a hardness ratio consistent with that typical of the point sources.

Point Source Luminosities: Figure 3 shows a histogram of the point source luminosities, based on the first 8.8 ks observation of M31. The histogram is consistent with the break in the luminosity function at $\sim 10^{37.5}$ seen with ROSAT (Primini et al 1993) and XMM (Shirey et al 2000). The luminosity function is incomplete below $\sim 10^{36}$ erg s^{-1}, but the sum total GTO observations should extend the detection threshold to $\lesssim 10^{35}$ erg s^{-1}. The brightest source has $L_x \sim 1.4 \times 10^{38}$ erg s^{-1}, consistent with the Eddington limit for a solar mass star. This is very different from what is seen in star-forming galaxies, where the peak point source luminosity approaches 10^{40} erg s^{-1} (Prestwich 2000; Fabbiano 2000). The most straightforward explanation for these very high luminosities

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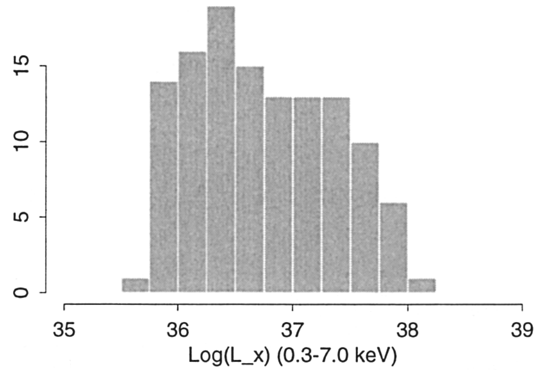

Figure 3. Histogram of M31 Point Source Luminosities

is that these sources are ~ $100M_\odot$ accretors (Kaaret et al 2000). However, it is relevant to note that the ~ $10M_\odot$ black holes in our galaxy have been seen to have peak X-ray luminosities which are super-Eddington. For example, the X-ray nova SAX J1819.3-2525 had a peak luminosity of $10^{39.5}$ erg s^{-1}, likely due to beaming of the X-ray flux in our direction (Orosz et al 2000). X-ray novae often have jets (Fender 2000) and therefore may often have beamed X-ray emission.

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