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The Center of the Andromeda Galaxy

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Abstract.
We report on sensitive high-resolution surveys of the central part of the Andromeda galaxy (M31) with Chandra in X-Rays and with the VLA in the Radio at 4.9 and 8.4 GHz. The combination of the data has revealed a number of coincident sources of which two new extended X-Ray/Radio SNRs. Also, the presumed super-massive central black hole M31* shows short- and long-term variability at both Radio and X-Ray wavelengths.

1. Introduction

The center of the Andromeda galaxy (M31) is largely hidden by an extended bright central X-Ray and Radio core (e.g. Trudolyubov et al. 2001; Hjellming & Smarr 1982). High spatial resolution (and high sensitivity) is needed to resolve individual faint sources. In particular observations with the Chandra X-Ray Observatory (CXO) and observations with the Very Large Array (VLA) have demonstrated that many individual sources can be detected, embedded in the extended diffuse emission, in the central few hundred parsecs of M31. Previously, one Radio source was suggested to be associated with a central black hole candidate, M31* (Crane et al. 1992, 1993), and which since then also has been associated with an X-Ray source (Garcia et al. 2000; Kong et al. 2002a). Here we report on the short time scale variability of M31*, and on the detection of two extended X-Ray/Radio supernova remnants seen toward the core of M31 (Kong et al. 2003).

2. Sensitive Chandra X-Ray, and 4.9 GHz and 8.4 GHz VLA Radio images

The X-Ray data used in this project, the Chandra 0.3-7 keV ACIS-I image of the central $17' \times 17'$ of M31, is a collection of eight ~ 5 ks observations forming an almost 40 ks integration in total (Kong et al. 2002a). It has a spatial resolution of half an arcsecond (although the PSF degrades away from the center) and shows diffuse emission and numerous extended and point sources, most of which in M31 itself (e.g. globular clusters, supernova remnants (SNRs), planetary nebulae, X-Ray binaries and transients; Figure 1 in Kong et al. 2002a). A similar single 47 ks integration X-Ray image has been obtained with Chandra's HRC (Kaaret 2002).

The Radio data was obtained with the VLA, in first instance from the archive by combining the in total 120 hours of 8.4 GHz observations in A-array and B-array, taken by Crane et al. (1992, 1993) during 1990-1996. The usable part of this image contains a bit more than the central $5.5'$ (FWHP), i.e. almost 2 kpc in diameter where further out the VLA sensitivity drops considerably, and has a resolution of $0.2''$ and an rms noise level of 4 μJy/beam. These observations have detected at least three new shell-type SNRs within $\sim$ 250 pc of the center of M31 (Sjouwerman & Dickel 2000), i.e. here the sources 85, 95 and 101 listed by Braun (1990) were first recognized to be SNRs. As the large array configurations at this frequency are very efficient at filtering large scale diffuse emission with angular sizes of more than $10''$ (Hjellming & Smarr 1982), it also filtered out most of the faint emission of the just apparent SNRs.

Newly obtained 4.9 GHz Radio data with three epochs of 8 hours observing in the VLA B-array in the summer of 2002 detects a number of extended and point source objects, both in the extragalactic background as in M31 itself. This image has an angular resolution of 1.2 arcsec (4 pc) and an rms noise level of about 5 μJy/beam and clearly shows the three new shell-type SNRs. Two of them are shown as gray scale images in the right hand side of Fig. 1, which shows only a very small part of the $\sim$ 3 kpc diameter 4.9 GHz VLA B-array image.

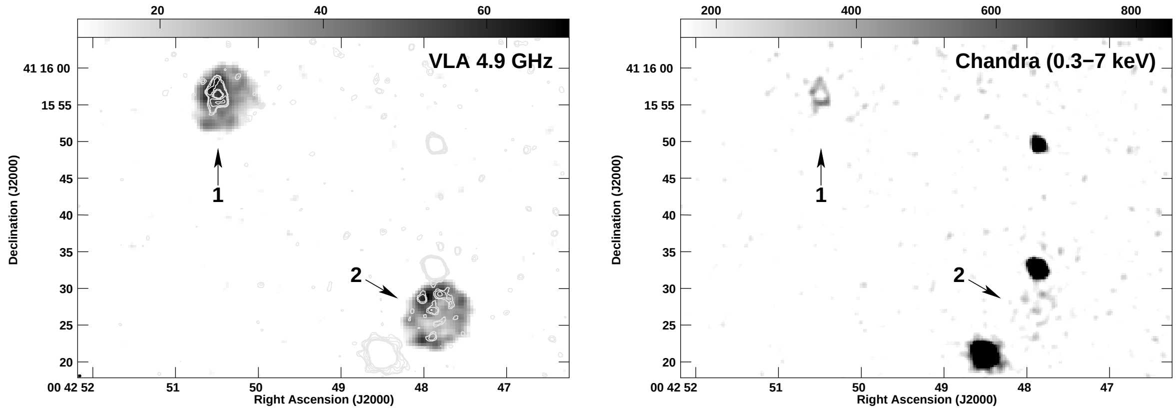

Figure 1. *Left*: VLA 4.9 GHz B-array ($1''.2$ resolution) Radio image (gray scale from 10 to 70 μJy) of CXO M31 J004250.5+411556 (a.k.a Braun 101; marked as #1) and nearby region with the Chandra X-Ray contours. The contour map was created from a smoothed image with a $0''.5$ σ Gaussian function. Contours are at 0.6, 0.9, 1.2 and 1.5 $\times$ 10^{-5} counts s^{-1} arcmin^{-2}. Also shown in the figure is another Radio SNR, Braun 95 (Sjouwerman & Dickel 2001; Braun 1990), on the southwestern side of M31 (marked as #2). The two arrows have a length of $5''$. *Right*: Chandra 0.3-7 keV image of the same smoothed field and at the same scale as the Radio image.

3. First resolved X-Ray/Optical/Radio SNRs in M31's center

The very first resolved X-Ray/Optical SNR in M31, which is the first extended X-Ray SNR in another galaxy comparable to our own, was detected by Kong et al. (2002b). It has been confirmed as an SNR in the Hα line by the Local Group Survey (Massey et al. 2001). The X-Ray image suggests a spatial dependence of chemical composition. Since its discovery, we have identified it with an extended Radio source, but it is hardly resolved in the 1.4 GHz $5''$ spatial resolution VLA B-array image (source 142 in Braun 1990, a.k.a. CXO M31 J004327.7+411829).

Inspired by the detection of this X-Ray/Optical and now also Radio SNR in M31 (Kong et al. 2002b), we inspected the Chandra X-Ray image at the positions of the three new Radio SNRs in the center of M31. It allowed us to identify the first (however faint) X-Ray/Optical/Radio SNR in the center of M31. It (labeled #1 in Fig. 1) was also detected in an archived HST Hα observation, but unfortunately the other SNRs were outside the HST field of view. Both in the X-Ray and Hα observations the source is ring-like and with the center offset from the center of the Radio image. A second Radio SNR (labeled #2 in Fig. 1) was also found in the Chandra data, but because of it's faintness at X-Ray wavelengths we cannot determine its properties. The faintest of our three new Radio SNRs was not seen in the Chandra image. Details have appeared in Kong et al. (2003).

4. Variability of the central super massive black hole candidate M31*

It is known that the central nuclear Radio source M31* varies on month-long time scales at 8.4 GHz in the period 1990-1996 (Crane et al. 1992, 1993, and further unpublished data from Crane et al.). The average flux density of M31* at 4.9 GHz in our 2002 VLA observations is actually a bit higher ($\sim$ 50 versus $\sim$ 30 μJy/beam), which allowed us to split our three 8 hour observations into chunks of four and into chunks of two hours and study the short term Radio variability of M31*. The 8.4 GHz flux density is too weak to split up into separate four-hour and two-hour intervals.

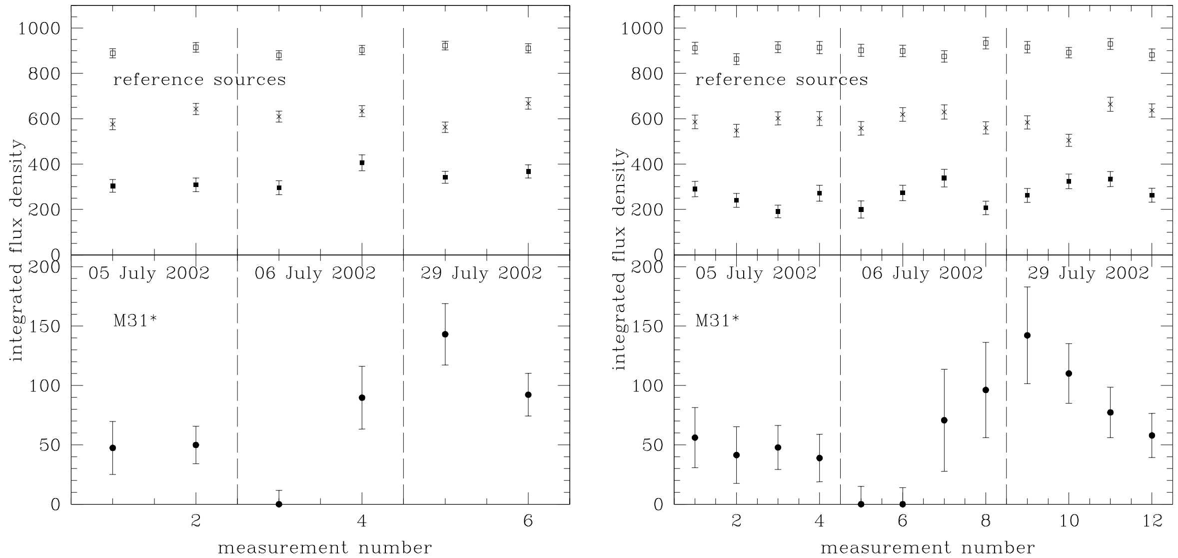

Figure 2. These figures show the VLA 4.9 GHz B-array observations of M31* in each lower panel compared to three reference sources in each top panel using the same data from three 8-hour observations in July 2002. *Left*: four-hour intervals and *Right*: two-hour intervals. The vertical dotted lines separate the individual runs of 8-hour observations. The error bars are the formal errors to the fit.

The month-long variability is contrasted with our recent 4.9 GHz data, which shows a much more rapid fluctuation, i.e. significant variations on time scales of hours (Fig. 2). Note that the 4.9 GHz "light curves" are different integration intervals of the same three sets of VLA data. Of course it needs to be verified that the Radio source M31* is indeed associated with the central super massive black hole and not a source in the line of sight. Furthermore, it needs to be confirmed whether the intra-day Radio variability is intrinsic to the source or due to e.g. interstellar scintillation.

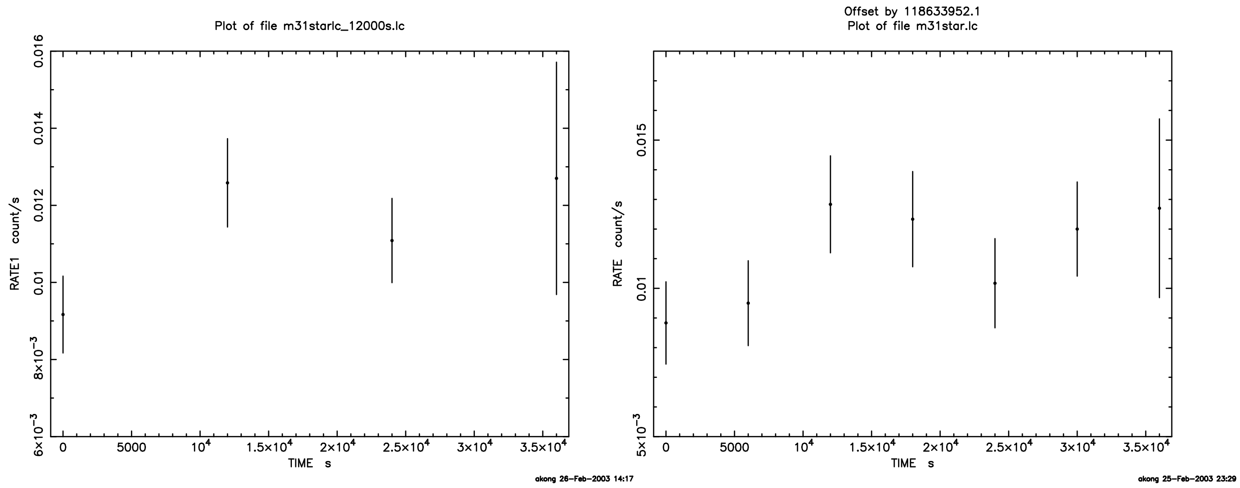

Figure 3. These figures show the result of splitting up the only (40 ks) long archival Chandra ACIS observation of M31* as in the Radio (Fig. 2. *Left*: four-hour intervals and *Right*: two-hour intervals. The error bars are the formal errors to the fit.

In Fig. 3 we played the same game with a 40 ks long Chandra ACIS observation as we did with the 4.9 GHz Radio data. Unfortunately this is the only long ACIS exposure and doesn't show without doubt that M31* also significantly varies in X-Rays on short time scales. However, M31* does flare in the X-Rays on month-long time scales over the past few years. Unfortunately we cannot study the direct relation between the X-Ray and Radio variability, because none of the X-Ray and Radio data are taken simultaneously. Obviously more observations are required.

5. And More ..

Of the few hundred X-Ray point sources detected by Chandra and XMM only a fraction has been identified or associated with individual sources. More work is needed to classify the small number of about 20-30 Radio sources (less because of a smaller field of view) with sources in M31 or in the background. Combination of the Radio and X-Ray data already yielded some coincidences.

VLBI observations are difficult because M31* is so weak. However it is possible to determine the morphology of M31* with μas resolution to reveal the true nature of M31*, e.g. a small Radio core-jet. With respect to Radio background sources, acting as beacons, accurate relative astrometry can be performed and proper motion of sources in M31 (M31*!) can be measured.

References

Braun 1990, ApJS 72, 761
Crane et al. 1992, ApJ 330, L9
Crane et al. 1993, ApJ 417, L61
Garcia et al. 2000, ApJ 537, L23
Hjellming & Smarr 1982, ApJ 257, L13
Kaaret 2002, ApJ 578, 114
Kong et al. 2002a, ApJ 577, 738
Kong et al. 2002b, ApJ 580, L125
Kong et al. 2003, ApJ 590, L21
Massey et al. 2001, BAAS 199, 130.05
Sjouwerman & Dickel 2001, in AIP Conf 155 p433
Trudolyubov et al. 2001, ApJ 563, L119