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* at X-ray wavelengths and with the Very Large Array at radio wavelengths – 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 supernova remnants. 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, Borozdin & Priedhorsky 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 (*Chandra*) 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. The central radio source has been associated with the central black hole candidate, M31* (Crane, Dickel & Cowan 1992, Crane et al. 1993), and, recently, 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 (SNRs) 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 is a *Chandra* 0.3–7 keV ACIS-I image of the central $17' \times 17'$ of M31, a collection of eight ~ 5 ks observations forming an almost 40 ks integration in total (Kong et al. 2002a). The observation has a spatial resolution of half an arcsecond (although the point-spread function degrades away from the center) and shows diffuse emission and numerous extended and point sources, most of which reside in M31 itself (e.g., globular clusters, SNRs, planetary nebulae, X-ray binaries and transients; Fig. 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 a total of 120 hours of 8.4 GHz observations in A- and B-configuration, taken by Crane et al. (1992, 1993) during 1990–1996. The usable part of this image contains a bit more than the central $5\overset{'}{.}5$ (full-width at half-power), i.e., almost 2 kpc in diameter. Further out the VLA sensitivity drops considerably, and has a resolution of $0.2''$ and an rms noise level of 4 μJy beam^{-1}. These observations have detected at least three new resolved shell-type SNRs within 250 pc of the center of M31 (Sjouwerman & Dickel 2000; i.e., sources 85, 95 and 101 listed by Braun 1990) were first recognized to be SNRs. Large configurations at this frequency are very efficient at filtering out large scale diffuse emission with angular sizes of more than $10''$ (Hjellming & Smarr 1982), therefore we see only part of the total flux of these SNRs.

Newly obtained 4.9 GHz radio data with three epochs

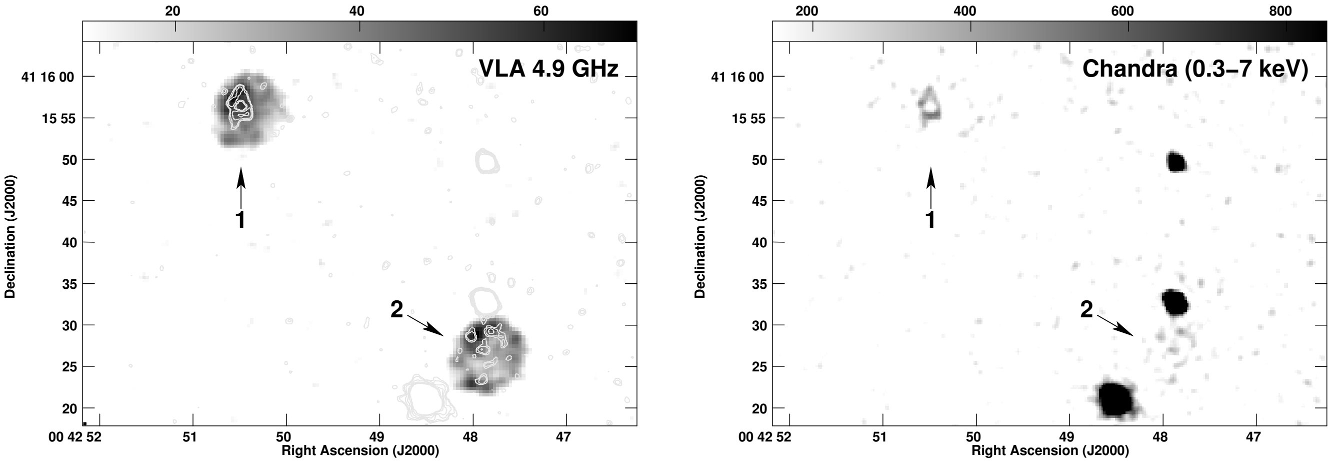

Figure 1: Left: VLA 4.9 GHz B-configuration ($1.2''$ resolution) radio image (grayscale from 10 to 70 μJy) of *Chandra* M31 J004250.5+411556 (a.k.a Braun 101; marked as #1) and nearby region with the *Chandra* X-ray contours. The contour map was created from a smoothed image with a $0''.5\sigma$ Gaussian function. Contours are at 0.6, 0.9, 1.2 and 1.5 $\times10^{-5}$ 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.

of 8 hours observing in the VLA B-configuration in the summer of 2002 detect several extended and point sources, both in the extragalactic background and in M31 itself. This image has an angular resolution of 1.2 arcseconds (4 pc) and an rms noise of about 5 μJy beam^{-1}; clearly showing three new shell-type SNRs. Two of them are shown as grayscale 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-configuration image.

3 First resolved X-ray/optical/radio SNRs in M31's center

The very first resolved X-ray/optical SNR in M31 (the first external, extended X-ray SNR in a Milky Way type galaxy) 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, slightly resolved in the 1.4 GHz $5''$-resolution VLA B-configuration image (source 142 in Braun 1990, a.k.a. *Chandra* 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. We identified the first (faint) X-ray/optical/radio SNR in the center of M31 (labeled #1 in Fig. 1). It 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, 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 its 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* varied by a factor of $\sim$ 2 on month-long time scales at 8.4 GHz during the period 1990–1996 (Crane et al. 1992, 1993, and further unpublished data from Crane). 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^{-1}), therefore we split our three 8 hour observations into two-hour and four-hour segments in order to study the short term radio variability of M31*. The 8.4 GHz flux density is too weak to subdivide.

The month-long variability is contrasted with our recent 4.9 GHz data, which shows much more rapid fluc-

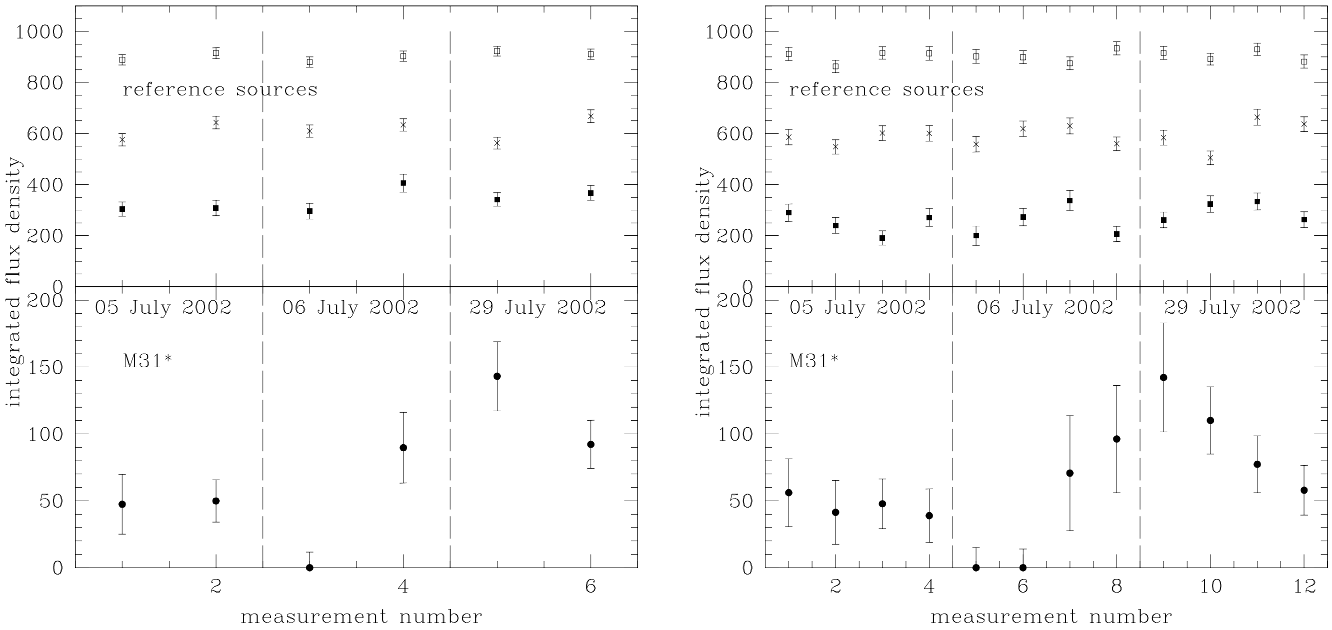

Figure 2: These figures show the VLA 4.9 GHz B-configuration observations of M31* in each lower panel compared to three reference sources in each top panel using the same data from three 8-hour observations in July 2002. Left: split into four-hour intervals. Right: split into two-hour intervals. The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

tuations 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. This variability may tell us something about the size of the central black hole in M31. However work remains to be done to prove that the radio source and/or variability is actually associated with the black hole. The radio variability could be caused by, e.g., interstellar scintillation.

In Fig. 3 we analyzed the 40 ks long *Chandra* ACIS observation in the same way. Unfortunately this is the only long ACIS exposure and does not demonstrate convincingly that M31* varies in the X-ray on this time scale. However, M31* flared in the X-ray 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, simultaneous observations are required.

5 And more ..

Of the few hundred X-ray point sources detected by *Chandra* and *XMM-Newton*, only a fraction have been identified with individual sources. More work is needed to identify the remainder with sources in or behind M31. The combination of the radio and X-ray data have already yielded valuable identifications. Currently we are comparing the sensitive 4.9 GHz VLA radio image with the 8.4 GHz VLA image obtained from the Crane et al. (1992, 1993) data. Since these sources are both unresolved and bright, it is likely they are ultracompact H II regions. They may reveal how environmental differences in e.g., electron densities and number of ionizing photons influence the formation of massive stars.

While Very Long Baseline Interferometric observations are difficult on sources as faint as M31*, recently phase referencing has made these observations possible. These would provide micro-arcsecond resolution images of M31*, perhaps revealing a core-jet structure. Additionally these observations would provide highly accurate astrometry, tracking proper motions of sources within M31.

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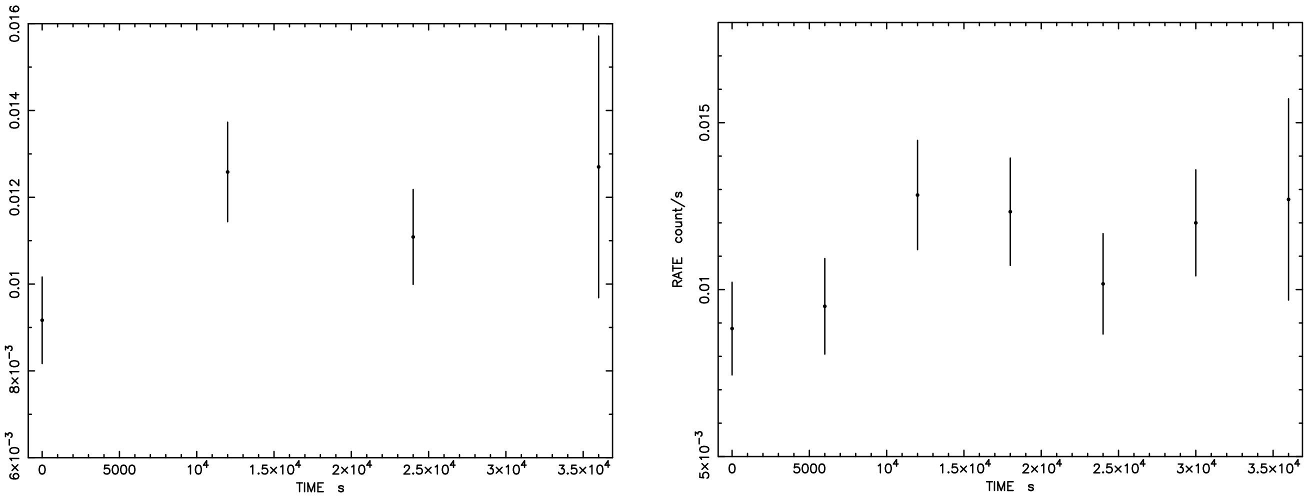

Figure 3: These figures show the result of splitting up the only long archival *Chandra* ACIS observation (40 ks) of M31* as in the radio (Fig. 2). Left: four-hour intervals. Right: two-hour intervals. The error bars are the formal errors to the fit.

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