High resolution Chandra X-ray imaging of the nucleus of M33

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Abstract. We show with a short Chandra HRC-S exposure that the powerful X-ray source coincident with the nucleus of M33 is unresolved at the highest spatial resolution available to date (0.′4). The source flux is variable, doubling during the 5 ks exposure. The combination of properties exhibited by M33 X-8 establishes the source as the nearest example of the ultraluminous X-ray sources that have been uncovered in other nearby galaxies. On short timescales, we set limits of 9% r.m.s. variability for pulsations in the 0.01–1000 Hz range.

Key words. galaxies: individual (M33) — galaxies: nuclei — Local Group — X-rays: galaxies.

1. Introduction

The nearby galaxy M33 (\(d \approx 795 \text{ kpc};\) van den Bergh 1991) hosts the most luminous steady X-ray source in the Local Group: M33 X-8 has a 1-10 keV luminosity of \(1.2 \times 10^{39} \text{ erg s}^{-1}\). The source has been detected at this level ever since the first X-ray observations of M33 (Long, D’Odorico, Charles, & Dopita 1981; Markert & Rallis 1983). Chandra observations established that M33 X-8 is coincident with the optical position of the nucleus to the 0′.6 uncertainty of the astrometric solution (Dubus & Rutledge 2002). However, the 1500 M\(_{\odot}\) upper limit on the mass of a central black hole placed by the measured velocity dispersion (Gebhardt et al. 2001) and the lack of activity at other wavelengths (Long et al. 2002 and references therein) rule out a low luminosity active galactic nucleus.

Ultra-luminous X-ray sources (ULXs) are defined as point sources having X-ray luminosities in excess of the Eddington limit for a 10 M\(_{\odot}\) object (\(10^{39} \text{ erg s}^{-1}\); Fabbiano & White 2003). ULXs could be due to beamed emission from stellar mass-sized neutron stars (NS) / black holes (BH) or truly isotropic emission from 100-1000 M\(_{\odot}\) intermediate mass BHs (King et al. 2001). If M33 X-8 is a single object, then it is the nearest example of a ULX. The detection of a 106 day \(\sim 20\%\) modulation in the X-ray flux from M33 X-8 in a 5 year span of ROSAT data (Dubus et al. 1997) and the resemblance of the spectrum to that of black hole binaries (La Parola et al. 2003) support this picture.

ROSAT images show M33 X-8 to be point-like at 5′′ resolution (Schulman & Bregman 1995). But diffuse emission from the compact optical nucleus (3′′ wide, see Fig. 3 in Kormendy & McClure 1993) or contributions from close, faint sources would not have been resolved using any pre-Chandra instrument. With its superior angular resolution, Chandra has been able to reduce the possibility that ULXs in nearby galaxies are chance superpositions of lower luminosity sources. Unfortunately, in the case of M33 X-8, the existing Chandra observations of M33 X-8 had the nuclear source either off-axis or heavily piled-up in ACIS CCD. As a result, the Chandra data could not be used to study the radial extent below a few arc seconds.

Here we report a new observation of M33 X-8 with Chandra, an on axis observation obtained with the High Resolution Camera (HRC) on board Chandra that fully exploits the spatial resolution of Chandra in an attempt to resolve the nuclear source in M33. The observation, spatial and timing analysis are described in §2-4. The results are discussed in §5.

2. Observation

M33 was observed with the Chandra/HRC-S instrument (Murray et al. 1998) on July 29, 2003 from 19:53:12 UT for a total exposure time of 5355 s. The HRC is unaffected by pile-up and provides the best achievable spatial resolution (0′.4 FWHM) to date. We decided to use the HRC-S which has the capability to study the poorly known timing properties of M33 X-8 at frequencies above 1 Hz. We performed the analysis with CIAO version 3.0.1\textsuperscript{1}.

There is only one point source, M33 X-8, with signal-to-noise greater than 5 in the field-of-view. In the 6 × 8′′ central region surrounding M33 X-8 where the background is

\textsuperscript{1} http://asc.harvard.edu/ciao
spatially uniform, we estimated the average background rate per 2” circular region, and found that 28 counts would be needed for a 3σ detection (taking into account the 13750 separate trials). This translates into a 0.6-9 keV luminosity upper limit for point source detection in this observation of \(< 9 \times 10^{38} (d/795 \text{ kpc})^2 \text{ erg s}^{-1}\) (assuming a photon power-law of \(\alpha = 2\), \(N_H = 1.9 \times 10^{21} \text{ cm}^{-2}\)). There are 43 sources within 8’ of M33 X-8 in the X-ray \textit{ROSAT} catalogue of Haberl & Pietsch (2001) but the brightest of these (excluding X-5 which is at the very edge of the field-of-view) have count rates a factor \(\leq 1\)% that of M33 X-8. Hence, it is not surprising that we failed to detect any other sources in this short exposure.

### 3. Timing Analysis

We extracted 3756 counts from a 16 pixel radius region around M33 X-8, giving an average of 0.70\(\pm\)0.01 counts s\(^{-1}\). Using an annulus with inner and outer radii of 20 and 30 pixels, we estimate the background contribution to be only 6 counts (and hence negligible). Surprisingly, the count rate from M33 X-8 varied significantly during our observation, increasing from 0.36\(\pm\)0.03 to 0.92\(\pm\)0.04 counts s\(^{-1}\), on a timescale of 2400 s (Fig. 1). Previous results have consistently shown that the X-ray spectrum of M33 X-8 is well fitted by a \(kT = 3.5 \text{ keV}\) thermal bremsstrahlung spectrum with \(N_H = 1.9 \times 10^{21} \text{ cm}^{-2}\) (Takano et al., 1994; Parmar et al., 2001; Dubus & Rutledge, 2002; La Parola et al., 2003). Assuming this spectrum (for which 1 HRC-S count corresponds to \(2.6 \times 10^{-11} \text{ erg cm}^{-2}\) of unabsorbed flux in the 0.6-9 keV band), the maximum count rate is equivalent to \(L_X = 1.8 \times 10^{39} (d/795 \text{ kpc})^2 \text{ erg s}^{-1}\).

We applied barycenter corrections to the photon arrival times and computed their power density spectrum (PDS), with a Nyquist frequency of 1000 Hz. We find no excess power above 0.01 Hz, with a 99.9\% upper limit of \(< 8.8\%\) root-mean-squared (r.m.s.) variability from a sinusoidal signal. Logarithmically rebinning the PDS to 100 bins, we do not find any excess from broad timing features above >0.01 Hz. The 90\% upper limit to a quasi-periodic oscillation (QPO) is 24\% r.m.s. where we have modeled the QPO as a 0.25 Hz FWHM gaussian at 6 Hz. There is significant power at low frequencies with a measured 30\(\pm\)6\% r.m.s. variability below 0.01 Hz. Further rebinning to 20 frequency bins (Fig. 2), we find that the data are well described \((\chi^2 = 0.7, 18 \text{ degrees of freedom})\) by a fit to a constant plus a power-law low frequency noise (LFN) with a steep slope \(\alpha = -2.65 \pm 0.15\) (90\% confidence error). The constant is taken equal to the high frequency average, 1.98 (close to the expected level from a pure Poisson flux). However, the LFN power must turn over between 0.02 and 0.19 mHz in order for it not to diverge (i.e. exceed 100\%). To constrain any additional high frequency, flatter timing feature, we fixed the power-law slope at -2.65 and added a second component with \(\alpha = 1\). The 90\% confidence upper limit to the r.m.s. variability below 10 Hz is \(< 3.2\%\), corresponding to a change in the minimum \(\chi^2\) of 4.61 (Lampton, Margon, & Bowyer, 1976).

In spite of the lack of photon energy sensitivity in the HRC detectors, we can still search for spectral variability by exploiting the fact that the photon energy to pulse-invariant (PI) energy channel calibration is stable during an observation. We therefore investigated the data in two ways: firstly by comparing counts in the first 2000 s interval (cf. Fig. 1 with those detected afterwards (a total of 907 and 2829 counts respectively); secondly by dividing in time so as to produce an equal number
of counts in each group (which occurs 3172 s into the observation). The distributions of the PI channels between groups are statistically identical (respectively a probability of 0.30 and 0.19 of being drawn from the same distribution for a two-sided Kolmogorov-Smirnov test). Hence, within the constraints of the HRC, there is no evidence for spectral variability during our observation.

4. Spatial Analysis

Our main purpose in undertaking this observation was to determine whether the nuclear source in M33 is point-like. We therefore used ChaRT and Marx to simulate how the PSF of M33 X-8 would appear on the HRC-S detector if it were point-like. In carrying out this simulation (of 28861 counts in total), we assumed the same spectrum as in §3. This simulation accounts for all known telescope and detector effects. It also shows why the spectrum is important, as the ChaRT PSF is significantly broader than a monochromatic PSF (at 1 keV) calculated with mkpsf.

We logarithmically re-binned the data into a 1-D radial distribution (between $r = 0$ and 40″) for comparison with a ChaRT simulation (Fig. 3). We determined the source centre by rebinning the PSF and performing a radial fit to the data, minimising $\chi^2$ against the 2-D offset. The best-fit to the PSF model has $\chi^2_\nu=1.72$ (18 degrees of freedom), and the simulated PSF is a good description of the data. We find no evidence for any additional component to the emission profile.

Extended emission associated with the nucleus is not statistically required by the data. To place an upper limit on its contribution, we convolved the PSF with the radial profile derived from Hubble Space Telescope visible data (Dubus et al., 1999). The 90% confidence upper limit is <3.7% of the average flux from M33 X-8 during the observation or $4.7 \times 10^{37}$ erg s$^{-1}$.

We also examined the residuals obtained by subtracting the best-fit PSF from the data using an image bin size of 3 pixels (0′:4), equal to the resolution of the HRC-S. There is no apparent structure in the residuals, which have amplitudes smaller than <7% of the peak flux. We derive an upper limit of $9.1\times10^{37}$ erg s$^{-1}$ to the contribution from a point source between 0′:4–1″ from the nucleus.

5. Discussion

Dubus & Rutledge (2002) established to a high degree of precision that M33 X-8 is coincident with the nucleus. The present ChaRT HRC-S observation shows that M33 X-8 is also unresolved at 0′:4 resolution, improving on earlier ROSAT HRI upper limits by a factor $\sim 10$ (Schulman & Bremer, 1995). This rules out contributions from nearby sources but does not rule out multiple sources within the compact nucleus core (Dubus et al., 1999). However, the substantial (50%) variability we observe during this short 5 ks observation shows that a single source dominates. We conclude M33 X-8 is most likely a single source and, as has been claimed previously, the nearest example of a ULX source.

A possible key to uncovering the nature of this source is its variability. The short timescale doubling that we observe is unprecedented: within single pointed observations M33 X-8 is usually seen to be constant. Variability at a level of 10% has been observed within hours to days in only two ROSAT visits (Dubus et al., 1997). More recently, 10% variability on a timescale of 5000 s was seen in a continuous 93 ks Chandra off-axis observation (La Parola et al., 2003; see also Peres, Reale, Collura, & Fabbiano, 1989 for an earlier report).

Although the timescale of the variation we observe is similar, the amplitude in our observation is much larger than the 10% variation observed by La Parola et al. (2003).

Using the doubling timescale of 2400 s, we can set an upper limit to the emission region of 7⋅10$^{13}$ cm which hints at a compact object. Recently, it has been proposed that the break frequency at which the PDS of active galactic nuclei and X-ray binaries switch from a -2 to a -1 power-law slope depends on the black hole mass (McHardy et al., 2004). Using the fact that the PDS of M33 X-8 must turn over between 0.02 and 0.19 mHz, and interpreting this break as the high frequency turnover (e.g. NGC 4051, McHardy et al., 2004), we find the black hole mass would be in the range 10$^{5.6}$ M$_\odot$. This is inconsistent with velocity dispersion upper limits (Gebhardt et al., 2001). Hence, it is unlikely the variability is associated with the high frequency noise phenomenon described by McHardy et al. (2004). Much longer exposures are needed to establish the timing properties of M33 X-8 and investigate its nature.

The X-ray spectrum, long timescale variability and lack of an optical counterpart suggest an X-ray binary. The $\sim$1 hour
doubling, but lack of fast variability, are consistent with a low mass X-ray binary in the high or very high state. On long timescales, Markert & Rallis (1983) observed a 50% count rate drop between two Einstein HRI observations separated by six months. Later ROSAT observations confirmed variations of \( \geq 20\% \) on a timescale of 106 days (Dubus et al., 1997).

La Parola et al. (2003) have emphasized the similarity between M33 X-8 and LMC X-3. LMC X-3 has long term variations on a 99 day (or 199 day) timescale (Wilms et al., 2001). We note that the present observation would correspond to phase \( \phi = 0.87 \) in Fig. 3 of Dubus et al. (1997), very close to the minimum of the cycle where the folded ROSAT data shows the most scatter.

\textit{Chandra} results indicate that ULXs are more frequently found in association with recent star formation (Fabbiano & White, 2003). There is evidence for a 40 Myr old starburst in the nucleus of M33 (O’Connell, 1983; Long et al., 2002). The presence of M33 X-8 could be linked to this episode of star formation, suggesting perhaps a source comprised of a high mass companion orbiting a stellar-mass black hole. At present, the source in the nucleus of M33 appears to have all of the characteristics of a canonical ULX. As such, a better understanding of the nearest ULX should remain a priority.

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