Populations of High Energy Sources in Galaxies
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The Luminosity Function of X-ray Point Sources in Centaurus A

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Abstract. We studied the population of X-ray point sources in the elliptical galaxy Centaurus A, using archival Chandra data. Within a radius of 10 arcmin from the centre we detected 272 sources. Of these approximately half are LMXBs with the rest being CXB sources. The spatial distribution of the LMXBs is found to be consistent with the distribution of K-band light. We constrain the luminosity function (LF) of the X-ray sources down to $\sim 2 \times 10^{36}$ erg s^{-1}. The X-ray LF of the LMXBs flattens significantly below $L_X \sim 5 \times 10^{37}$ erg s^{-1} and follows the $dN/dL \propto L^{-1}$ law in agreement with results from the bulges of spiral galaxies.

Keywords. galaxies: individual (Centaurus A), X-rays: binaries, X-rays: galaxies.

1. Introduction

The faint end of the low-mass X-ray binary (LMXB) X-ray luminosity function (XLF) was studied by Gilfanov (2004), using observations of the bulges of two spiral galaxies, the Milky Way and M31. This study showed a broken powerlaw with a break at a few times 10^{37} erg s^{-1}, a power law index of ∼1 below and ∼1.8 above. It is important to extend the study of the low end of the XLF of LMXBs to also include the populations in elliptical galaxies as these have evolutionary histories that are different from the bulges of spiral galaxies.

Centaurus A (Cen A) is the primary candidate for such a study. It is massive enough to contain sufficient number of LMXBs and, on the other hand, is sufficiently nearby to reach luminosities below $\sim 10^{37}$ erg s^{-1} with moderate observing time. Details can be found in Voss & Gilfanov (2005). The analysis in this paper is based on 4 Chandra observations, two of them made with the ACIS-I array (OBS-ID 316 and 962), and the other two with the ACIS-S array (OBS-ID 2978 and 3965). Together these four observations cover most of Cen A within a 10 arcmin radius from the centre. The data preparation was done following the standard CIAO† threads (CIAO version 3.1; CALDB version 2.28), and limiting the energy range to 0.5–8.0 keV. The observations were merged and sources were detected in the merged image using `wavdetect`. To avoid crowding and strong diffuse emission, we excluded the area within a radius of 30 pixels (∼15 arcsec) from the centre of the galaxy, as well as the region covering an X-ray jet emanating from the galaxy nucleus. Finally we end up with a sample of 272 point-like sources.

2. Optical identifications

For the identification of Chandra sources we used the results of the optical studies of the Cen A region by Peng *et al.* (2004), Minniti *et al.* (2003), Woodley *et al.* (2005) and Graham & Fasset (2002). In total we identified 6 X-ray sources as foreground stars,

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† http://cxc.harvard.edu/ciao/

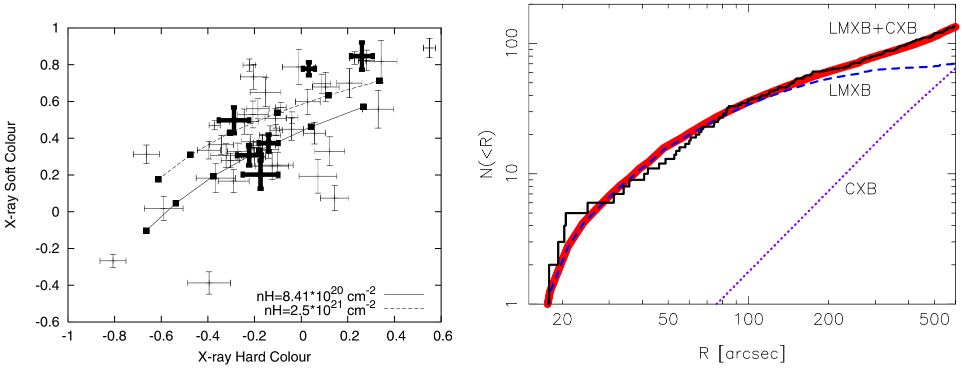

Figure 1. Left: The colour–colour diagram of the brightest, >200 counts, sources within 5 armin from the centre of Cen A. The sources coinciding with H_α-emitting regions are shown in bold. For reference, the two lines show the hardness ratios of power law spectra for two different values of absorption. Right: The radial distribution of observed sources (solid, black), compared to the best fit model (thick, grey) and the contributions of LMXBs (dashed) and CXBs (dotted).

leaving 266 sources of presumably extragalactic origin – either intrinsic Cen A sources or background AGNs. Of these, 37 were identified with the globular clusters in Cen A. Eight sources within 4 arcmin from the centre of Cen A coincide with Hα-emitting regions found in Minniti *et al.* (2003). The optical magnitudes of the Hα sources indicate that they may be young star clusters as well as individual X-ray binaries. In order to search for further indications of the high-mass X-ray binary (HMXB) nature of these sources we have compared their spectral properties with other sources and searched for periodic variability in their X-ray emission. The results of these attempts to find the nature of the objects were inconclusive, as no periodic variability was found, and the colour distribution does not deviate from the distribution of the rest of the sources (Fig. 1, left).

3. Populations of X-ray sources in the field of Centaurus A

LMXBs are related to the population of old stars, and there is therefore a correlation between their number and the stellar mass of a galaxy (Gilfanov 2004). In order to estimate the expected number and luminosity distribution of LMXBs we used a K-band image from 2MASS Large Galaxy Atlas (Jarret *et al.* 2003) and integrated the flux emitted in the parts of Cen A analyzed in this paper. Using the results of Gilfanov (2004) we predict ≈81 LMXBs with $L_X > 10^{37}$ erg s^{-1}.

Being young objects, HMXBs are associated with star formation. We used calibration of Grimm *et al.* (2003) to calculate the expected number of HMXBs (see comments in Shtykovskiy & Gilfanov 2005, regarding the normalization), from the FIR luminosity of Cen A (Marston & Dickens 1988). From this we get the expectation of ≈10 HMXBs brighter than 10^{37} erg s^{-1}.

To estimate the number of background sources we used results of the cosmic X-ray background (CXB) $\log(N) - \log(S)$ determination by Moretti *et al.* (2003). For the total area of our survey of 0.079 deg^2 we obtain from the source counts in the soft band ≈34 CXB sources above the flux corresponding to 10^{37} erg s^{-1}. From the hard band counts the predicted number is ≈47 sources.

We detected 136 sources with a luminosity above 10^{37} erg s^{-1}, fitting well the expectations above.

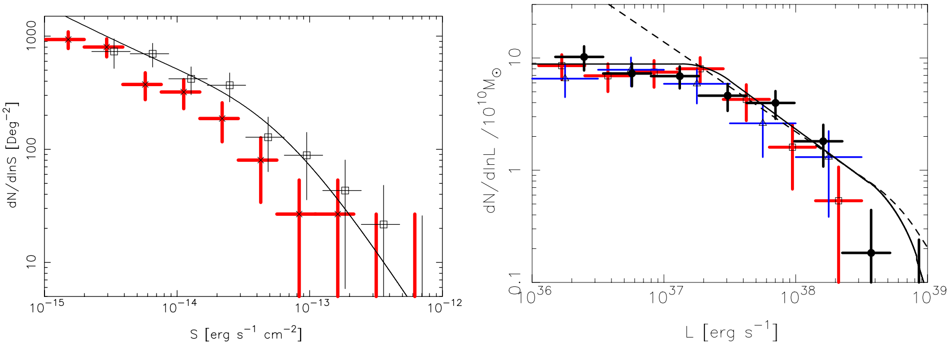

Figure 2. Left: The source counts (open squares) in the outer region (5 arcmin<r<10 arcmin). Thick solid line: CXB $\log(N)-\log(S)$ from Moretti *et al.* (2003) with best fit normalization from this paper. For comparison the source counts in the CDF-N Obs-ID 1671 are shown (crosses). Right: The LF of LMXBs in the inner $r \leqslant 5$ arcmin of Cen A (the CXB contribution subtracted) in comparison with LMXB XLFs in the Milky Way (triangles) and M31 (squares) in Gilfanov (2004). The latter two are multiplied by constant factors of 1.7 and 0.6, respectively. Solid line: average LMXB XLF in the nearby galaxies as determined by Gilfanov (2004). Dashed line: average LMXB XLF from Kim & Fabbiano (2004) and its extrapolation towards low luminosities.

4. Spatial distribution of point sources

The spatial distribution of the LMXBs has been shown (Gilfanov 2004) to follow, to the first order approximation, the distribution of the stellar mass. This can be represented by the distribution of the K-band light and was computed using the K-band image of Cen A from 2MASS. The density of the CXB sources can be assumed flat on the angular scales under consideration. Therefore the CXB growth curve is proportional to the enclosed solid angle. The (unknown) distribution of HMXBs has not been included as it is unlikely to exceed 10 per cent in the total number of sources.

The model has been compared with the observed distribution of sources more luminous than 10^{37}erg s^{-1}. The model adequately describes the data (Fig. 1, right) as confirmed with the KS-test, which gave the probability of 96 per cent. A Maximum Likelihood (M-L) fit to the radial distribution of the unbinned data gave 70.3 ± 10.0 LMXBs and 65.7 ± 9.8 CXB sources ($>10^{37}$ erg s^{-1}). The abundance of LMXBs is surprisingly close to the expectation value. The number of CXB sources, on the other hand, is higher than the expectation.

5. Source counts and the CXB source density

In analysing the LFs and $\log(N)-\log(S)$ distributions, we corrected for incompleteness effects as described in Voss & Gilfanov (2005). We estimated the normalization of the CXB $\log(N)-\log(S)$ distribution from the source counts in the outer region. This region is far enough from the inner parts of the Cen A to keep the number of sources related to the galaxy low, while close enough to the aimpoints of the observations to have a reasonable sensitivity. In this region the incompleteness corrected (Voss & Gilfanov 2005) number of sources with the 0.5–8 keV flux exceeding 2.7×10^{-15} erg s^{-1} cm^{-2} (luminosity 4.0×10^{36} erg s^{-1}) is 101.3 from which 13.4 are expected to be LMXBs. The implied number of CXB sources is therefore ≈88. This is consistent with the normalization obtained from the radial distribution of sources, and higher than the expectation from Moretti *et al.* (2003). To confirm that the difference is not due to different analysis methods, we analyzed one CDF-N observation Obs-ID 1671, using the same method as for Cen A. As can be seen from Fig. 2, left, the difference remains, although it is smaller ∼50%.

6. LMXB XLF

The LMXB XLF based on the combined data of $r \leqslant 5$ arcmin is plotted in Fig. 2, right, along with luminosity distributions of LMXBs in the Milky Way and M31. This is the first study to extend the LMXB XLF in elliptical galaxies below a few times 10^{37} erg s^{-1}. We find that the XLF of the LMXBs is consistent with the results from the bulges of spiral galaxies (Gilfanov 2004). The bright end is consistent with the slope found by Kim & Fabbiano (2004). The faint end is, however, inconsistent with an extrapolation of their XLF.

The plot illustrates qualitative and quantitative similarity of the LMXB luminosity distributions in Cen A and bulges of spiral galaxies. Spiral and elliptical galaxies have different evolutionary histories and could differ in the properties of their LMXB populations. As demonstrated here, the LFs nevertheless seem very similar.

7. Summary and conclusions

We have used archival data of Chandra observations to study statistical properties of the point source population of Cen A. About half of the detected sources are expected to be X-ray binaries in Cen A, mostly LMXBs, and the vast majority of the remaining sources are background galaxies constituting the resolved part of the CXB.

The spatial distribution of the detected sources can be well described by a sum of two components. One follows the K- band light, representing LMXBs in Cen A, while the other is uniform over the field, representing the resolved part of the CXB. The normalization of the LMXB component agrees well with the average value derived for the local galaxies by Gilfanov (2004). The normalization of the uniform component and source counts in the exteriors of the galaxy appears to indicate an overabundance of the CXB sources in the direction of Cen A by a factor of ~1.5 or, possibly, more.

We were able to recover the the LMXB LF in the inner $r \leqslant 5$ arcmin down to $L_X \sim 2 \times 10^{36}$ erg s^{-1}. This is by a factor of ~5–10 better than achieved previously for any elliptical galaxy (Kraft *et al.* 2001; Kim & Fabbiano 2004). The shape of the luminosity distribution is consistent with the average LMXB XLF in nearby galaxies derived by Gilfanov (2004) and of the bright end by Kim & Fabbiano (2004). In particular, we demonstrate that the LMXB XLF in Cen A flattens at the faint end and is inconsistent with extrapolation of the steep power law with differential slope of ≈1.8–1.9 observed above $\log(L_X) \sim 37.5$–38 in the previous studies of elliptical galaxies.

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Discussion

Kim: But Cen A is a complex system, with a large amount of different X-ray emission (with considerable sub-structures), dust lanes, jets etc. The complete correction is therefore very critical, likely more at the central region.

Voss: Since Kim & Fabbiano (2004) results are based on X-ray sources with $L_X > \sim$ a few * 10^{37}, the XLF flattening which you have found is not really consistent.

Maccarone: A comment: we would expect to see breaks in the luminosity function to state transitions between low/hard and high/soft states, since the bolometric corrections to the Chandra band change substantially there. These will be at a few percent of the Eddington limit – about 3 * 10^{37} erg/sec for BHs and 3 * 10^{36} erg/sec for NSs.

Voss: That's an interesting point and I plan to look into it when I get home.