Globular Cluster X-ray Sources in M31

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INTRODUCTION

The giant spiral galaxy M31 is close enough for a detailed study of accreting X-ray sources with luminosities comparable to those in the Milky Way. With the *Einstein* observatory Trinchieri[1] and Fabbiano discovered 108 individual point sources within $\sim$ 100 ksec IPC and $\sim$ 200 ksec HRI observations, which had a limiting sensitivity of approximately 10^{37} erg/s. Long[2] and van Speybroeck detected 117 sources within these observations. A search for optical counterparts of these 117 sources by Crampton[3] et al. revealed 23 candidates for X-ray GC sources. The identifications were done by spatial correlation of the X-ray sources with GC lists of Hodge[4], Sargent[5] et al., Battistini[6] et al., and van den Bergh[7]. Among these 23 possible GC sources 19 were considered as being extremely strong candidates.

From these results Battistini[8] et al. calculated a luminosity distribution of the X-ray GC sources in M31 and compared it to that one of the Milky Way. They found a significant difference between both luminosity distributions and raised the question whether the GC sources in M31 are more luminous and/or more numerous compared with those in the Milky Way. Because these distributions are a function of X-ray GC sources as well as a function of optical GC sources, new X-ray and optical observations were expected to reveal more detailed results about the discrepancy of both luminosity distributions.

Within two ROSAT PSPC deep surveys of M31 563 individual X-ray sources have been discovered. The observations add up to $\sim$ 400 ksec of total exposure with a limited sensitivity of $\sim 10^{35}$ erg/s. Within these observations 38 X-ray GC sources have been identified by spatial correlations to optical GC lists of Battistini[6,9] et al. and Magnier[10]. The last one is the result of a new deep optical survey of M31. In the following the spectral properties of the brightest of these 38 X-ray GC sources will be discussed showing typical spectra for low mass X-ray binaries (LMXB). A new luminosity distribution will be presented and also a comparison to that one of the Milky Way, revealing that both distributions are comparable.

OBSERVATIONS

The first pointed M31 survey with the ROSAT PSPC was performed in July 1991. It consists of 6 contigous pointings covering the whole disk at equidistant positions and with $\sim$ 200 ksec of total observation time. Figure 1 shows an overlay of the central region of the 6 pointings over the D_{25} ellipse of M31 (Tully[11]). Each circle marks the boundary of the inner area of the PSPC with a radius of 20' in which the instrument has it's highest angular resolution, whereas the total field of view of the PSPC is 57' in radius.

The second pointed M31 survey with the ROSAT PSPC was performed in July/August 1992 and a few follow up observations in January 1993. It consists of 80 single pointings, each with 2.5 ksec observation time, covering the disk in 4 paths

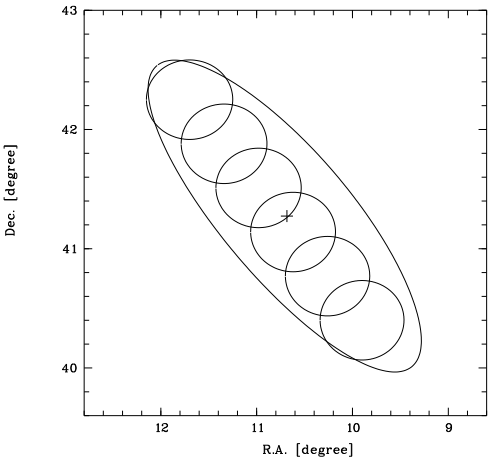

Figure 1: Locations of the central region of the 6 pointings of the first survey plotted over the D_{25} ellipse of M31. The cross marks the optical center of M31.

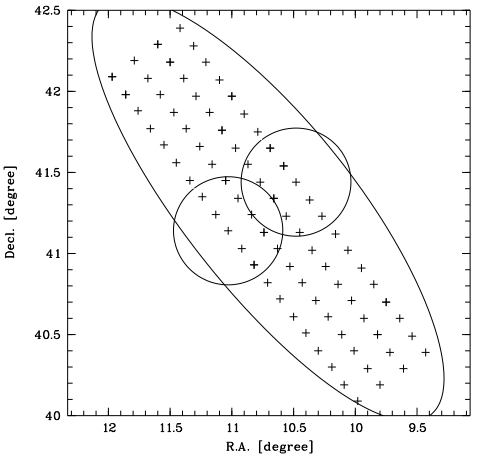

Figure 2: Locations of the on-axes pointing directions of the 80 pointings of the second survey, plotted over the D_{25} ellipse of M31. Two central regions are drawn representatively.

of 20 pointings each. Figure 2 shows the location of these 80 pointings marked with crosses representing the on-axes direction. For two pointings the circle of the inner area of the PSPC (20' radius) is drawn representatively. The D_{25} ellipse of M31 is also drawn for orientation. As can be seen from a comparison with Figure 1, the second survey is more homogenious than the fist one.

SPECTRAL PROPERTIES OF X-RAY GC SOURCES

The process of data preparation and the source detection strategy is explained in detail in Supper[12] et al. for the first survey. A description of the source identification technique can also be found there. For the second survey, the reader should refer to Supper[13]. Within the first survey 396 X-ray sources have been detected from which 29 correlate with GCs. The second survey adds 167 new sources and 9 new correlations with GCs. The main part of new sources in the second survey comes from the outer paths where this survey has a higher sensitivity than the first one.

For the brightest GC sources with more than 200 counts spectral fits have been carried out using a power law as spectral model. Since a detailed discussion of all spectra is beyond the scope of this paper, only a summary of the results can be given here:

For the mean power index $\Gamma = -1.6 \pm 0.3$ was found, which is at the hard end of the mean power index range of $\Gamma = -2.0 \pm 1.1$ for all bright sources independentely of any identification. The fitted N_H column densities correspond with the expected values from HI radio measurements. The spectrum of the brightest GC source is shown in Figure 3. Its spectrum is relatively hard ($\Gamma = 1.27 \pm 0.1$). In addition, this source shows variability on a time scale of $\sim$ 16 hours, which can be seen from its light curve in Figure 4. The hard spectra and the variability of the light curves is expected for LMXBs. Their calculated X-ray luminosities lie between $\sim 10^{36}$ and $\sim 10^{38}$ erg/s.

For the fainter sources hardness ratio colors have been calculated. The hardness

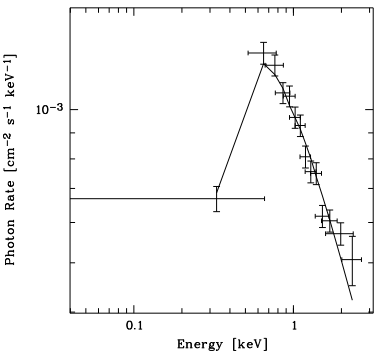

Figure 3: Spectrum and power law fit of the brightest GC source in M31.

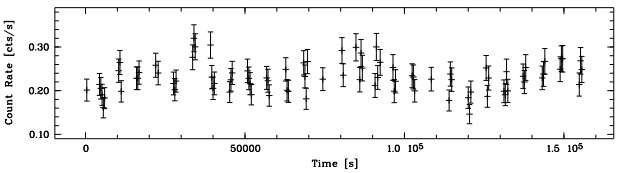

Figure 4: Light curve of the brightest GC source in M31. It shows variability on a time scale of $\sim$ 16 hours.

ratio is defined as $HR_1 = (H - S)/(H + S)$, where H and S represent the count rates in the hard (0.5 - 2.0 keV) and soft (0.1 - 0.4 keV) energy band respectively. For all GC sources $0.0 \leq HR_1 \leq 1.0$ have been found which underlines their hard spectral properties (for comparison, foreground stars have hardness ratios between -0.85 and 0.7). A more detailed description of the spectral properties of all GC sources and fits with different spectral models can be found in Supper[12] et al. and Supper[13].

THE GC LUMINOSITY DISTRIBUTION

The spectral properties of the GC sources described above allow the discrimination against accidental correlations of X-ray sources with optical GCs and therefore to obtain a 'clean' sample of GC sources. As a result, 38 strong candidates for X-ray GC sources have been found with an error of ± 7. The error is the 1σ error level of accidentals comming out of the correlation process and having GC-like spectral properties.

27 of these GC sources are situated in the most sensitive region of the surveys. From the optical lists 473 uncorrelated GCs also lie within this region, for which an upper limit in count rate of 1.36×10^{-3} cts/s can be given from the ROSAT detection threshold within this area. With the number of detected and non-detected X-ray GC sources a luminosity distribution for GC sources in M31 can be determined by using the Kaplan Meier estimator to obtain a nonparametric estimate of the cumulative distribution function $\Phi(L)$ (Schmitt[14]). This distribution function $\Phi(L)$ gives the fraction of detected sources among all detectable sources at a given luminosity. To allow a straight foreward comparison with the results of Hertz[15] and Grindlay for the galactic GC sources, luminosities have been calculated by using an exponential spectral model with kT = 5 keV in the 0.5 - 4.5 keV energy band and assuming 690 kpc for M31 distance. The resulting distribution is shown in Figure 5 (thick line), where also the galactic distribution is shown (thin line), calculated in the same manner. Both distributions are consistent with being from the same parent distribution: a Kolmogorov-Smirnov test yields a probability of 86% for this hypothesis. Furthermore, the maximum luminosities are comparable.

This result suggests that the fraction of X-ray bright clusters among the total cluster population in both galaxies is similar and also their maximum luminosity is comparable, both against earlier reports. This is the result of the more complete detection of X-ray luminous GCs with ROSAT and the also more complete list of

the optical detected GC population in M31. Applying a single power law $N(>L) = N_0 \cdot L^{\alpha}$ to the integral luminosity distribution of GCs in M31, yields $\alpha = -0.63 \pm 0.04$ including all data points or $\alpha = -1.02 \pm 0.05$ when only considering luminosities $\geq 1 \times 10^{37}$ erg/s. The difference indicates a flattening of the distribution, quite comparable to the result of the Milky Way.

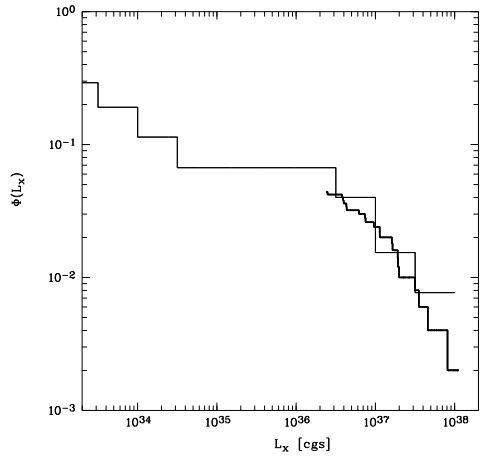

Figure 5: The integral luminosity distribution of the GC sources in M31 (thick line) together with the distribution in our own galaxy (thin line) reported by Hertz and Grindlay. Both presentations are normalized by the parameter-free estimator $\Phi(L)$ described by Schmitt.

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