AN X-RAY SOURCE POPULATION STUDY OF THE ANDROMEDA GALAXY M 31

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ABSTRACT

Archival *XMM-Newton* EPIC observations reveal the population of X-ray sources of the bright Local Group spiral galaxy M 31, a low-star-formation-rate galaxy like the Milky Way, down to a 0.2-4.5 keV luminosity of 4.4$\times 10^{34}$ erg s^{-1}. With the help of X-ray hardness ratios and optical and radio information different source classes can be distinguished. The survey detected 856 sources in an area of 1.24 square degrees. Sources within M 31 are 44 supernova remnants (SNR) and candidates, 18 super-soft sources (SSS), 16 X-ray binaries (XRBs) and candidates, as well as 37 globular cluster sources (GlC) and candidates, i.e. most likely low mass XRBs within the GlC. 567 hard sources may either be XRBs or Crab-like SNRs in M 31 or background AGN. 22 sources are new SNR candidates in M 31 based on X-ray selection criteria. Time variability information can be used to improve the source classification. Two GlC sources show type I X-ray bursts as known from Galactic neutron star low mass XRBs. Many of the M 31 SSS detected with *XMM-Newton*, *Chandra* and *ROSAT*, could be identified with optical novae. Soft X-ray light curves can be determined in M 31 center observations for several novae at a time opening a new area of nova research.

Key words: galaxies: individual (M 31), novae, cataclysmic variables, supernova remnants, X-rays: galaxies, X-rays: binaries, X-rays: bursts.

1. INTRODUCTION

In the *XMM-Newton* survey of the Local Group Sc galaxy M 33 (Pietsch et al., 2004a, hereafter PMH2004), 408 sources were detected in a 0.8 square degree field combining the counts of all EPIC instruments, which could be identified and classified using X-ray colors and time variability as well as optical and radio information. This proved to be an efficient way to separate super-soft X-ray sources (SSSs) and thermal supernova remnants (SNRs) in M 33 from Galactic stars in the foreground and "hard" sources. These hard sources may be either X-ray binaries (XRBs) or Crab-like SNRs in M 33 or active galactic nuclei (AGN) in the background of the galaxy. The success of this survey inspired us for a similar analysis of all archival *XMM-Newton* observations of M 31.

The Andromeda galaxy M 31 is located at a distance similar to the one of M 33 (780 kpc, Holland, 1998; Stanek & Garnavich, 1998, i.e. $1''$ corresponds to 3.8 pc and the flux to luminosity conversion factor is 7.3$\times 10^{49}$ cm^2) and – compared to the near face-on view of M 33 – is seen under a higher inclination (78°). The optical extent of the massive SA(s)b galaxy can be approximated by an inclination-corrected D_{25} ellipse with a large diameter of 153.3' and axis ratio of 3.09 (de Vaucouleurs et al., 1991; Tully, 1988). With its moderate Galactic foreground absorption ($N_{\rm H}$= 7$\times 10^{20}$ cm^{-2}, Stark et al., 1992), M 31 is well suited to study the X-ray source population and diffuse emission in a nearby spiral similar to the Milky Way. M 31 was a target for many previous imaging X-ray missions. The *Einstein* Observatory detected 108 individual X-ray sources brighter than 5$\times 10^{36}$ erg s^{-1} (see e.g. Trinchieri & Fabbiano, 1991). The sources were identified with young stellar associations, globular clusters (GCs) and SNRs. The *ROSAT* HRI (Primini et al., 1993) detected 86 sources brighter than $\sim 10^{36}$ erg s^{-1} in the central area of M 31. The *ROSAT* PSPC covered the entire galaxy twice in surveys conducted one year apart and detected altogether 560 X-ray sources down to a limit of $\sim$5$\times 10^{35}$ erg s^{-1} and SSS were established as a new class of M 31 X-ray sources (Supper et al., 1997, 2001). The flux of many of the sources varied significantly between the *Einstein* and *ROSAT* observations. Deep *Chandra* ACIS I and HRC observations of the central region (covered areas of 0.08 and 0.27 square degree) resolved 204 and 142 X-ray sources, respectively (Garcia et al., 2000; Kong et al., 2002b; Kaaret, 2002). A synoptic study of M 31 with the *Chandra* HRC covered "most" of the disk (0.9 square degree) in 17 epochs using short observations, and resulted in mean fluxes and long-term light curves for the 166 objects detected (Williams et al., 2004). In these observations, several M 31 SNRs were spatially resolved (Kong et al., 2002a, 2003) and bright XRBs in globular clusters and SSSs and quasi-soft sources (QSSs) could be characterized (Di Stefano et al., 2002, 2004; Greiner et al., 2004).

One of *XMM-Newton*'s most important contributions to galaxy science was a deep survey of the central region around the long axis of M 31 as part of the guaranteed time program. This survey is unique in that it has the greatest depth ($\sim 10^{35}$ erg s^{-1}) and best spatial resolution of any existing large area M 31 survey. It has covered almost 3° (>40 kpc) along the major axis of the galaxy and 30' ($\sim$7 kpc) along the central portion of the minor axis. These deep *XMM-Newton* observations have allowed us for the first time to study the short-term time variability ($\sim$100 s and shorter, see below) and spectra of bright X-ray sources in a galaxy outside the Milky Way and the Magellanic Clouds (e.g. Osborne et al., 2001; Barnard et al., 2003, 2005; Mangano et al., 2004). The observations revealed diffuse emission from the hot ISM in the centre and the northern disk (Shirey et al., 2001; Trudolyubov et al., 2001, 2004), and were used to derive source luminosity distributions (Trudolyubov et al., 2002).

Here, I summarize results of our group mainly based on the archival M 31 *XMM-Newton* observations, including X-ray images and a source catalogue for the archival observations of M 31 (Pietsch et al., 2005b, hereafter PFH2005), the detection of type I X-ray bursts in M 31 (Pietsch & Haberl, 2005, hereafter PH2005) and on the detection of optical novae in M 31 as SSSs (Pietsch et al., 2005a, hereafter PFF2005).

2. XMM-NEWTON SURVEY OF M 31

PFH2005 have created merged medium and thin filter images for the three EPIC instruments, in five energy bands (0.2–0.5 keV, 0.5–1.0 keV, 1.0–2.0 keV, 2.0–4.5 keV, and 4.5–12 keV), using only times of low background from the archival *XMM-Newton* M 31 observations which at the time contained four observations of the centre area of M 31 separated by half a year, two pointings in the southern, three in the northern disk, and one short observation in the halo, which all at least partly cover the optical D_{25} ellipse. In total, the observations in the analysis cover an area of 1.24 square degrees (see Fig. 1) with a limiting sensitivity of 4.4×10^{34} erg s^{-1} in the 0.2–4.5 keV band which is a significant improvement compared to the *Chandra* surveys. However, up to now only about 2/3 of the optical M 31 extent (D_{25} ellipse) are covered with a rather inhomogeneous exposure. There were still significant offsets between the observations that had to be corrected for before merging. For the centre observations these offsets were determined from source lists of the individual observations using the USNO-B1, 2MASS, and *Chandra* catalogues to define an absolute reference frame. This finally resulted in a residual systematic position error of less than 0.5". The source detection procedures revealed 856 sources using simultaneously 5×3 images (5 energy bands and PN, MOS1 and MOS2 camera). For the pointings into the disk and halo of M 31 this procedure was applied to the individual observations. The centre pointings strongly overlap and therefore the images were merged to reach higher detection sensitivity.

Figure 1. Combined XMM-Newton EPIC image in the 0.2–4.5 keV band smoothed with a 20" FWHM Gaussian. Orientation and optical D_{25} ellipse are indicated.

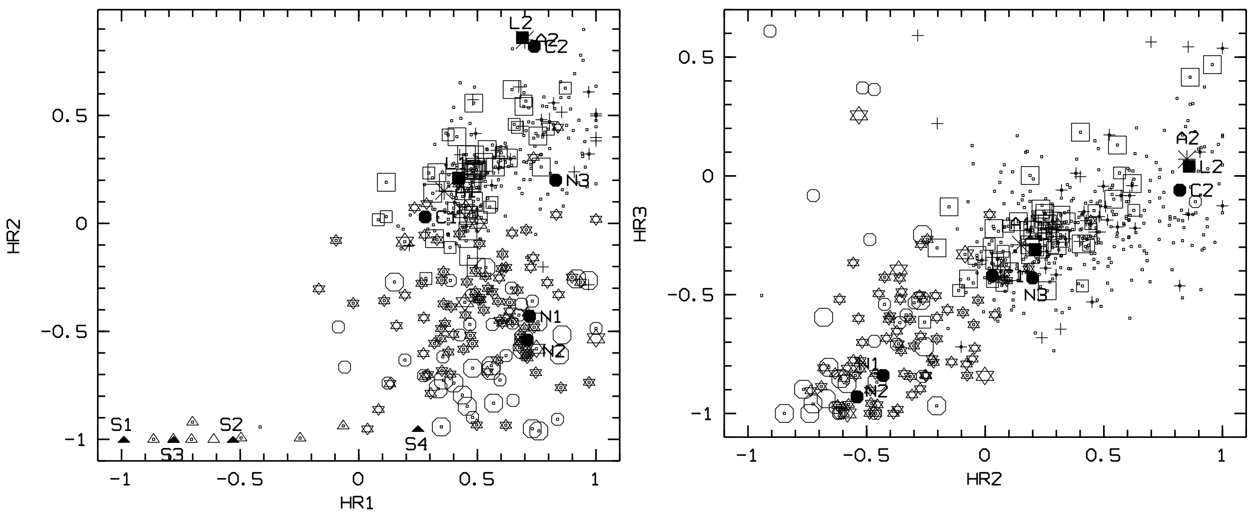

Figure 2. Hardness ratios (HR) detected by XMM-Newton EPIC. Shown as dots are only sources with HR errors smaller than 0.2 on both HRi and $HRi + 1$. Foreground stars and candidate are marked as big and small stars, AGN and candidates as big and small crosses, SSS candidates as triangles, SNR and candidates as big and small hexagons, GlCs and XRBs and candidates as big and small squares. In addition, we mark positions derived from measured XMM-Newton EPIC spectra and models for SSSs (S1 to S4) as filled triangles, low mass XRBs (L1 and L2) as filled squares, SNRs (N132D as N1, 1E 0102.2–7219 as N2, N157B as N3, Crab spectra as C1 and C2) as filled hexagons, AGN (A1 and A2) as asterisk (extracted from Fig. 5 of PFH2005).

Table 1. Summary of identifications and classifications of XMM-Newton X-ray sources in the M 31 and M 33 fields (see PFH2005 and PMH2004).

	M 31		M 33	
Source type	ident.	class.	ident.	class.
fg Star	6	90	5	30
AGN	1	36		12
Gal	1		1	1
GalCl	1	1		
SSS		18		5
SNR	21	23	21+2	23-2
GlC	27	10		
XRB	7	9	2	
hard		567		267

Hardness ratios were calculated only for sources for which at least one of the two band count rates had a significance greater than 2σ (Fig. 2). In search for identifications, the X-ray source positions were correlated with sources in the SIMBAD and NED archives and within several catalogues. The cataloged X-ray sources are “identified” or “classified” based on properties in X-rays (hardness ratios (HR), variability, extent) and of correlated objects in other wavelength regimes. A source is counted as identified, if at least two criteria secure the identification. Otherwise, it is only counted as classified.

Table 1 summarizes identifications and classifications according to the *XMM-Newton* catalogues of M 31 and M 33. For the SNRs in M 33 two new optical counterparts for soft X-ray SNR candidates from the *XMM-Newton* list are indicated (see Ghavamian et al., 2005). Detection of strong time variability in follow-up analysis will certainly move many objects from the “hard” to “XRB” classification. Comparison to earlier X-ray surveys revealed transients not detected with *XMM-Newton*, which add to the number of M 31 XRBs. Up to to now, only low mass X-ray binaries have been identified in M 31, mostly by correlations with globular cluster sources. In M 33, however, besides the ultra-luminous X-ray source close to the nucleus (X–8, most likely a black hole XRB) the only other XRB identified is the eclipsing high mass XRB X–7 with an orbital period of 3.45 d that has been confirmed by the ellipsoidal heating light curve of its optical companion (Pietsch et al., 2004b).

Many foreground stars, SSSs and SNRs can be classified or identified. The number of 44 SNRs and candidates more than doubles the X-ray-detected SNRs. 22 sources are new SNR candidates in M 31 based on X-ray selection criteria. Another SNR candidate may be the first plerion detected outside the Galaxy and the Magellanic Clouds. Additional SNR candidates can be identified by comparing cataloged X-ray sources with optical narrow filter images of the Local Group survey of Massey et al. (2001). Figure 3 gives two examples for two new optical SNR candidates proposed by X-ray source position and a [S II]/Hα ratio of the optical emission characteristic for optical SNRs.

However, besides a few clearly identified XRBs and AGN, and SNR candidates from positions in other wavelengths, we have no clear hardness ratio criteria to se-

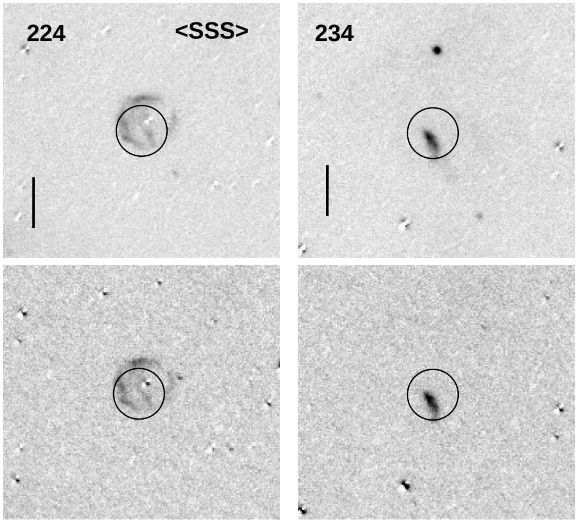

Figure 3. SNR candidates from overlay of Local Group survey images (Hα above, [SII] below): [PFH2005] 224 was classified as SSS candidate, [PFH2005] 234 was unclassified.

lect XRBs, Crab-like SNR or AGN. They are all "hard" sources (567 sources classified as hard in total). Only additional criteria like short or long term X-ray variability or detailed spectral modeling will reveal their nature. Such methods can be used in the M 31 center area with four overlapping observations in the *XMM-Newton* archive (separated by half a year) and additional observations of the area taken 2.5 yr later (see Fig. 4 and 5).

3. DETECTION OF TYPE I X-RAY BURST SOURCES IN M 31

Within the Milky Way, bright globular cluster X-ray sources were identified as low mass XRBs. Many of them show type I X-ray bursts identifying them as neutron star systems. PH2005 searched for X-ray bursts in *XMM-Newton* archival data of M 31 sources which were identified or classified as globular cluster sources in the PFH2005 catalogue (Fig. 5). Two bursts were detected simultaneously in EPIC pn and MOS detectors and some more candidates in EPIC pn. The energy distribution of the burst photons and the intrinsic luminosity during the peak of the bursts indicate that at least the strongest events were type I radius expansion burst radiating during maximum at the Eddington limit of a 1.4 $M_{\odot}$ neutron star for hydrogen-poor matter (Fig. 6). Standard type I bursts would show harder spectra and would not be bright enough to be detected by *XMM-Newton*EPIC. The bursts identify the sources as neutron star low mass XRBs in M 31. These type I X-ray bursts are the first detected outside the Milky Way and show that, with the large collecting area of *XMM-Newton*, X-ray bursts can be used to classify neutron star low mass XRBs in Local Group galaxies.

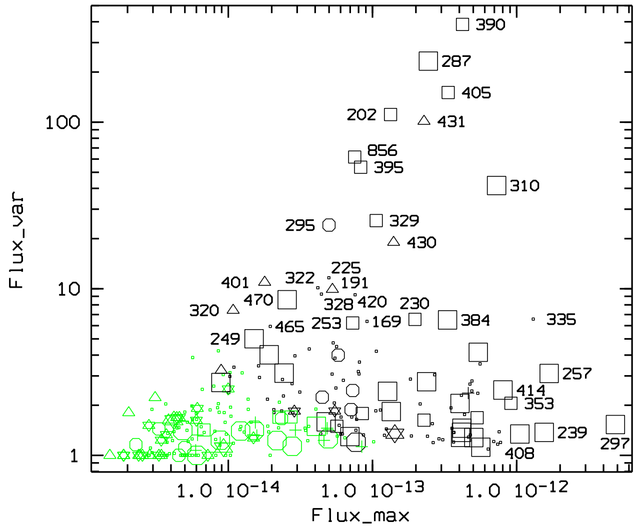

Figure 4. Variability of X-ray sources within four overlapping XMM-Newton observations to the M 31 centre performed from June 2000 to January 2002.

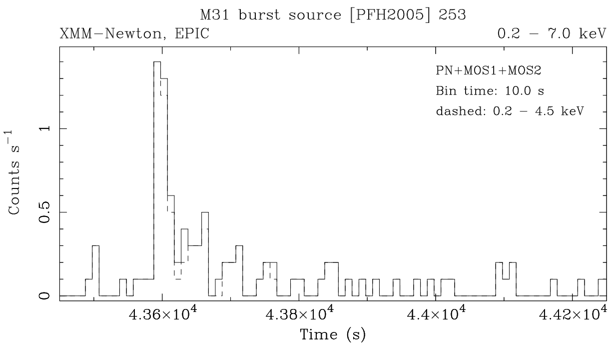

Figure 6. Combined XMM-Newton EPIC light curve of a type I X-ray burst of source [PFH2005] 253 in M31 (Fig. 3 from Pietsch & Haberl, 2005).

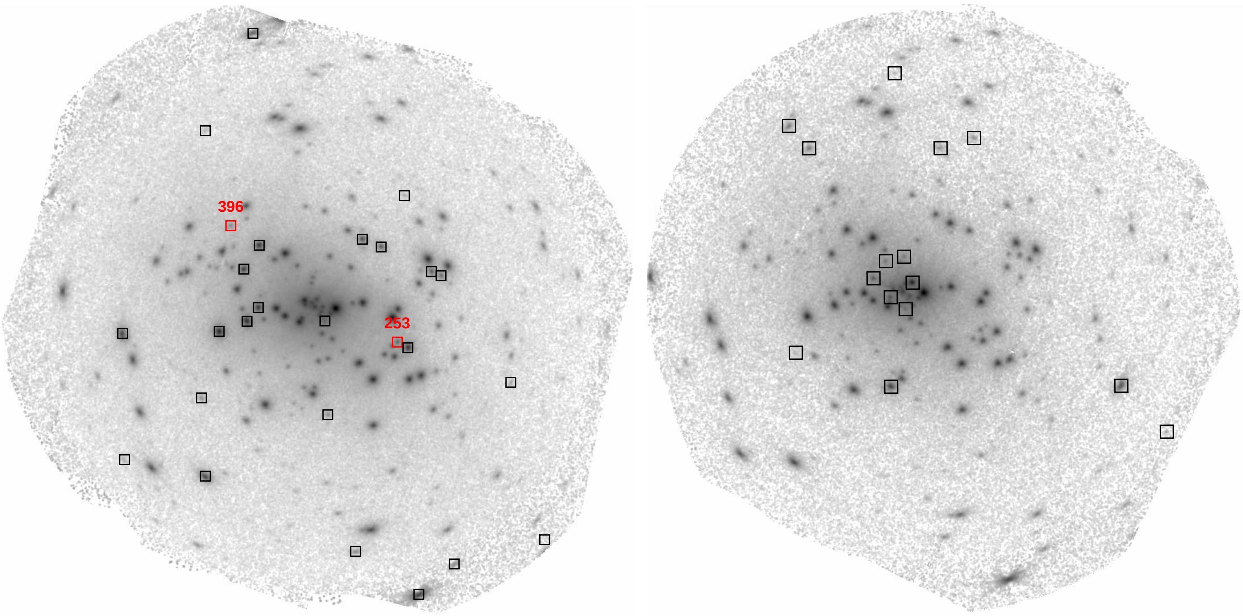

Figure 5. *Variability of X-ray sources between combined XMM-Newton M 31 center observations of June 2000 to January 2002 (left, globular cluster sources and candidates marked, burst sources numbered) and observations 2.5 yr later (right). New transients are marked. However, many bright sources from left image are missing.*

4. OPTICAL NOVAE AS MAJOR CLASS OF SSS IN M 31

PFF2005 searched for X-ray counterparts to optical novae detected in M 31 and M 33. They combined an M 31 optical nova catalogue from the WeCAPP survey with optical novae reported in the literature and correlated them with the most recent X-ray catalogues from *ROSAT*, *XMM-Newton* and *Chandra*, and – in addition – searched for nova correlations in archival data. They report 21 X-ray counterparts for novae in M 31 (mostly SSS). Their sample more than triples the number of known optical novae with super-soft phase. Most of the counterparts are covered in several observations which allows to constrain X-ray light curves of optical novae (see Fig. 7). Selected brighter sources were classified by their *XMM-Newton* EPIC spectra. Six counterparts are only detected in *Chandra* HRC I (3) or ROSAT HRI (3) observations, i.e. X-ray detectors with no energy resolution, and therefore can not be classified as super-soft. From the well-determined start time of the SSS state in two novae one can estimate the hydrogen mass ejected in the outburst to $\sim 10^{-5} M_\odot$ and $\sim 10^{-6} M_\odot$, respectively. The super-soft X-ray phase of at least 15% of the novae starts within a year. At least one of the novae shows a SSS state lasting 6.1 years after the optical outburst. Six of the SSSs turned on between 3 and 9 years after the optical discovery of the outburst and may be interpreted as recurrent novae. If confirmed, the detection of a delayed SSS phase turn-on may be used as a new method to classify novae as recurrent. At the moment, the new method yields a ratio of recurrent novae to classical novae of 0.3. Ongoing optical and X-ray monitoring of the central region of M 31, where most of the novae are detected, should allow

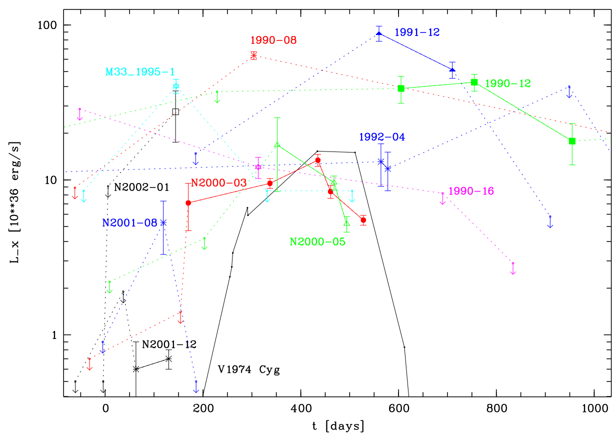

Figure 7. *Light curves for M 31 and M 33 novae that were detected within 1000 d after outburst. Detections of individual novae are connected by solid lines, and connections to upper limits are marked by dashed lines (Fig. 3 from Pietsch et al., 2005a).*

us to determine the length of the plateau phase of several novae and, together with the nova temperature development, give a handle on the masses of the white dwarfs involved.

5. CONCLUSIONS

The sensitivity of *XMM-Newton* and *Chandra* observations of M 31 combined with the wealth of multi-wavelength data for the galaxy allows a detailed study of the point source population. Many more interesting results can be expected from further monitoring of M 31 with *XMM-Newton* and *Chandra* specifically also in the energy band below 0.5 keV. The first light curves of the SSS state of optical novae proved that these kind of studies can be more efficiently achieved by observing many candidates at the same time in one field in M 31 than by monitoring individual novae in the Milky Way or the Magellanic Clouds. The results of the *Chandra* and *XMM-Newton* observations of M 31 demonstrate the importance of arcsec spatial resolution, broad energy coverage, good energy resolution, and high collecting power – used together with deep images and catalogues at other wavelengths – also for future X-ray source population studies in nearby galaxies.

ACKNOWLEDGMENTS

Based on observations obtained with XMM-Newton, an ESA science mission with instruments and contributions directly funded by ESA Member States and NASA. The *XMM-Newton* project is supported by the Bundesministerium für Bildung und Forschung / Deutsches Zentrum für Luft- und Raumfahrt (BMBF/DLR), the Max-Planck Society and the Heidenhain-Stiftung.

REFERENCES

Barnard, R., Kolb, U., & Osborne, J. P. 2003, A&A, 411, 553

Barnard, R., Kolb, U., & Osborne, J. P. 2005, A&A, submitted (astro-ph/0508284)

de Vaucouleurs, G., de Vaucouleurs, A., Corwin, H. G., et al. 1991, Third Reference Catalogue of Bright Galaxies (Volume 1-3, XII, 2069 pp. 7 figs.. Springer-Verlag Berlin Heidelberg New York)

Di Stefano, R., Kong, A. K. H., Garcia, M. R., et al. 2002, ApJ, 570, 618

Di Stefano, R., Kong, A. K. H., Greiner, J., et al. 2004, ApJ, 610, 247

Garcia, M. R., Murray, S. S., Primini, F. A., et al. 2000, ApJ, 537, L23

Ghavamian, P., Blair, W. P., Long, K. S., et al. 2005, AJ, 130, 539

Greiner, J., Di Stefano, R., Kong, A., & Primini, F. 2004, ApJ, 610, 261

Holland, S. 1998, AJ, 115, 1916

Kaaret, P. 2002, ApJ, 578, 114

Kong, A. K. H., Garcia, M. R., Primini, F. A., & Murray, S. S. 2002a, ApJ, 580, L125

Kong, A. K. H., Garcia, M. R., Primini, F. A., et al. 2002b, ApJ, 577, 738

Kong, A. K. H., Sjouwerman, L. O., Williams, B. F., Garcia, M. R., & Dickel, J. R. 2003, ApJ, 590, L21

Mangano, V., Israel, G. L., & Stella, L. 2004, A&A, 419, 1045

Massey, P., Hodge, P. W., Holmes, S., et al. 2001, Bulletin of the American Astronomical Society, 33, 1496

Osborne, J. P., Borozdin, K. N., Trudolyubov, S. P., et al. 2001, A&A, 378, 800

Pietsch, W., Fliri, J., Freyberg, M. J., et al. 2005a, A&A, 442, 879

Pietsch, W., Freyberg, M., & Haberl, F. 2005b, A&A, 434, 483

Pietsch, W. & Haberl, F. 2005, A&A, 430, L45

Pietsch, W., Misanovic, Z., Haberl, F., et al. 2004a, A&A, 426, 11

Pietsch, W., Mochejska, B. J., Misanovic, Z., et al. 2004b, A&A, 413, 879

Primini, F. A., Forman, W., & Jones, C. 1993, ApJ, 410, 615

Shirey, R., Soria, R., Borozdin, K., et al. 2001, A&A, 365, L195

Stanek, K. Z. & Garnavich, P. M. 1998, ApJ, 503, L131

Stark, A. A., Gammie, C. F., Wilson, R. W., et al. 1992, ApJS, 79, 77

Supper, R., Hasinger, G., Lewin, W. H. G., et al. 2001, A&A, 373, 63

Supper, R., Hasinger, G., Pietsch, W., et al. 1997, A&A, 317, 328

Trinchieri, G. & Fabbiano, G. 1991, ApJ, 382, 82

Trudolyubov, S., Kotov, O., Priedhorsky, W., Cordova, F., & Mason, K. 2004, ApJ, submitted (astro-ph/0401227)

Trudolyubov, S. P., Borozdin, K. N., & Priedhorsky, W. C. 2001, ApJ, 563, L119

Trudolyubov, S. P., Borozdin, K. N., Priedhorsky, W. C., Mason, K. O., & Cordova, F. A. 2002, ApJ, 571, L17

Tully, R. B. 1988, Nearby galaxies catalog (Cambridge and New York, Cambridge University Press)

Williams, B. F., Garcia, M. R., Kong, A. K. H., et al. 2004, ApJ, 609, 735