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X-ray source population studies in nearby galaxies

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Abstract. Observations of nearby galaxies are important to enhance our knowledge of the X-ray source population in galaxies. The XMM-Newton and *Chandra* Observatories produced many interesting results. In XMM-Newton surveys of M 31 and M 33 so far more than 850 and 400 X-ray sources were detected, respectively, down to a 0.2-4.5 keV luminosity of less than 10^{35} erg s^{-1}. EPIC hardness ratios, time variability and spectra as well as informations from earlier X-ray, optical, and radio catalogues were used to distinguish between different source classes (SNRs, supersoft sources (SSSs), X-ray binaries (XRBs), globular cluster sources within the galaxies, and foreground stars from the Milky Way or objects in the background). Many of the SSSs in both galaxies were identified as optical novae. *Chandra* and XMM-Newton observations identified the XRB M 33 X−7 as the first eclipsing high mass black hole XRB. However, many sources in both galaxies could only be classified as "hard". These sources may either be XRBs or Crab-like SNRs in the galaxies or background sources. The high energy response of Simbol-X should allow us to differentiate XRBs and Crab-like SNRs in the galaxies and background AGN by their spectrum. Therefore, Simbol-X observations will have the potential to significantly enhance our knowledge of the X-ray source population in nearby galaxies.

Key words. X-rays: Galaxies

1. Introduction

Within the Milky Way several different classes of bright X-ray sources can be observed. The most prominent are low and high mass X-ray binaries (XRBs) and supernova remnants (SNRs). However, there also are very bright supersoft X-ray sources (SSS) which often coincide with optical novae. One ot the largest uncertainties in their study is the distance that is often only known to not better than a factor of two. This may result in an order of magnitude uncertainty in the X-ray luminosity and prevents the determination of the luminosity function of the various types of sources. In addition, due to our location in the outer disk of the Milky Way, absorption within the plane of the Galaxy strongly suppresses soft X-ray emission. Therefore SSS and the hot interstellar medium (ISM) in the plane can only be observed in the solar neighborhood. In this paper we will discuss the different X-ray emission components of nearby galaxies and the possible impact of Simbol-X for their understanding. We leave aside the emission from ultraluminous X-ray sources (ULXs) and ac-

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tive galactic nuclei (AGN) that are discussed in separate contributions.

2. History of X-ray observations of galaxies

Detailed X-ray observations of galaxies started in 1978 with the observations of the *Einstein* Observatory, the first satellite with a focusing X-ray telescope. Its sensitivity and spatial resolution lead to the detection and study of a significant number of normal galaxies. For a review see e.g. Fabbiano (1989) and the catalogues of *Einstein* images and spectra of galaxies (Fabbiano et al. 1992; Kim et al. 1992a,b). The ROSAT observatory provided much higher sensitivity in the soft X-ray band, and slightly better angular resolution, its telescope had a wider field of view and the mission lasted significantly longer compared to the *Einstein* observatory. All these points have led to a better understanding of the spatial morphology of the X-ray emission of galaxies, and to the detection and study of the soft X-ray-emitting ISM of spiral galaxies. ASCA and *Beppo*SAX extended the observable energy band to 10 keV and above. This allowed the study of different spectral components of the X-ray emission. However, the significantly inferior angular resolution of these satellites compared to *Einstein* and ROSAT prohibited in most cases detailed studies of individual galaxies.

The new generation of X-ray observatories, *Chandra* and XMM-Newton, represent a big step forward in sensitivity, imaging capabilities and spectral resolution compared to the previous generation of X-ray observatories and provide a new and much deeper look at galaxies in X-rays.

With the increased sensitivity of the X-ray instrumentation galaxy science has developed to an important topic of X-ray astronomy. This is best demonstrated by the fact that observations of fields in the Large Magellanic Cloud (LMC) were selected as first light targets for ROSAT and XMM-Newton and pointings to nearby galaxies (e.g. LMC, Small Magellanic Cloud SMC, M 31, NGC 253) were used as calibration and performance verification targets for XMM-Newton and *Chandra*.

3. Sources of X-rays in nearby galaxy fields

A systematic analysis of all *Einstein* galaxy observations (Fabbiano 1989; Fabbiano et al. 1992; Kim et al. 1992b,a) showed normal galaxies of all morphological types as spatially extended sources of X-ray emission with luminosities in the (0.2–3.4) keV band in the range of 10^{38} erg s^{-1} to 10^{42} erg s^{-1}. Spiral galaxies only reach a few 10^{41} erg s^{-1}. On average the X-ray spectra for spiral galaxies are harder than for elliptical galaxies. This is explained by the commonly accepted view that X-rays from bright elliptical galaxies originate mainly from a hot interstellar medium while the emission of spiral galaxies is dominated by point-like sources with a harder spectrum (XRBs and SNRs). Also nuclear sources may be present and contribute significantly to the total X-ray emission. These sources may either be connected to star forming or Seyfert-like activity. Some spiral galaxies showed in addition to the expected hard component a soft component in their spectra indicating that an extended gaseous component can also be present in spirals.

Many of these galaxies have been investigated in greater detail in the (0.1–2.4) keV band with ROSAT and are targets of XMM-Newton and *Chandra* observations. The good spatial and spectral resolution of present X-ray observatories allows us to separate the emission from distinct sources from that arising from surrounding gas within the galaxies. The emission from the hot gas in galaxies mostly shows temperatures below 1 keV and therefore most likely is too soft to be investigated in detail with Simbol-X.

The bright point-like emission components in nearby galaxies include X-ray binaries (XRBs), supersoft sources (SSS), supernovae (SN) and supernova remnants (SNRs), nuclear sources (AGN), and a number of very luminous sources, so-called ultra-luminous X-ray sources (ULXs). ULXs are radiating at lumi-

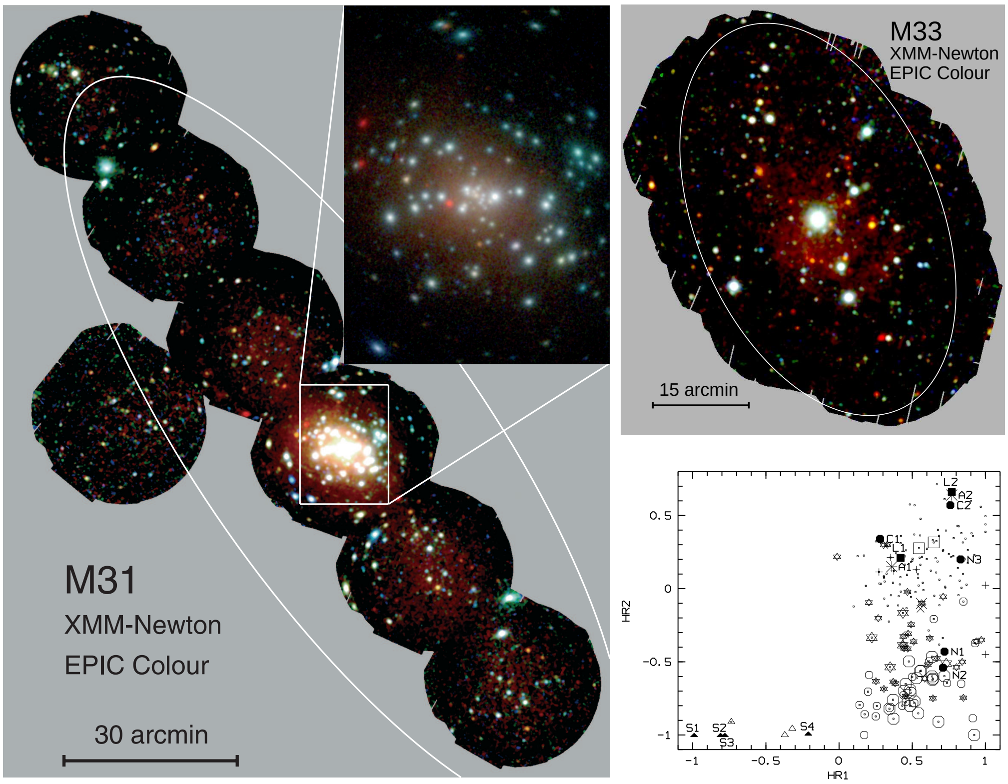

Fig. 1. Three color XMM-Newton EPIC images of the Andromeda galaxy M 31 (**left** together with a zoom-in on the M 31 bulge area, Pietsch et al. (2005b)) and M 33 (**upper right**, Pietsch et al. (2004a)). Red, green and blue show respectively the (0.2–1.0) keV, (1–2) keV and (2–12) keV bands. The ellipses indicate the optical extent of the galaxies. The X-ray color/color plot (**lower right**, Pietsch et al. (2004a)) using energy bands (0.2–0.5) keV, (0.5–1) keV and (1–2) keV can be used – together with informations from other wavelength regimes – to classify the detected X-ray sources as SSS, SNRs, foreground stars or hard sources (XRBs, Crab-like SNRs, background sources).

nosities above the Eddington limit for a 1 $M_\odot$ object and their nature is not fully understood. But at least part of them could belong to the classes of objects mentioned above. AGN and ULX show hard X-ray components in their spectra. They will be discussed in detail in other contributions and certainly are interesting targets for detailed studies with Simbol-X.

Often, the X-ray source population of a target galaxy is confused by foreground stars in the Milky Way and background objects (galaxies, galaxy clusters and AGN) observed in the same field. For fainter X-ray sources, the fraction of these spurious objects rise in number and in Local Group galaxies it can dominate the detected sources. One therefore has to find ways to separate the different galactic and extragalactic source classes. This can be achieved by identifying detected X-ray sources with the help of their position and/or time variability with counterparts that were categorized in surveys in other wavelength regimes (e.g. as SNR, globular clusters, SN). Due to the high source density in the fields, good X-ray positions are of utmost importance for this approach. Classification can also be based on X-ray properties like time variability, extent, hardness ratios or energy spectra. Classification schemes including X-ray hardness and extent were successfully applied to ROSAT PSPC sources in the LMC (758 sources cataloged), SMC (517) and M 33 (184) fields (Haberl & Pietsch 1999; Haberl et al. 2000; Haberl & Pietsch 2001).

4. The X-ray source population of M 31 and M 33

Figure 1 shows X-ray color images of deep XMM-Newton EPIC surveys of the bright Local Group spirals M 31 and M 33 together with a hardness ratio diagram for M 33. More than 850 respectively 400 point-like sources were detected in these surveys (Pietsch et al. 2005b, 2004a). The X-ray sources have been classified using similar schemes as developed for the ROSAT observations. Many foreground stars, SSS, SNRs and candidates can be identified by these procedures. However, even with the broader energy band of XMM-Newton and the better energy resolution, Crab-like SNRs, XRBs and AGN do not separate in the hardness ratio diagrams and mostly can only by classified as "hard" (see Table 1). XRBs may be separated if they show strong time variability (for M 33 see e.g. Misanovic et al. 2006), or as sources correlating with an optically identified globular cluster in the galaxy. A source may be classified as AGN or Crab-like SNR if additional optical or radio indicators are available.

Luminous SSSs were recognized as an important new class of intrinsically bright X-ray sources by ROSAT which can be described by blackbody spectra with temperatures of (10^5–10^6) K and luminosities of 10^{36} erg s^{-1} to 10^{38} erg s^{-1}. Several have been detected in M 31 and M 33. Pietsch et al. (2005a, 2007) demonstrated that the majority of SSS in M 31 are novae in their SSS state and even M 33 where the optical nova catalogues are much less complete than for M 31, revealed two X-ray source/optical nova correlations. Also thermal SNRs and foreground stars mainly radiate at energies below 2 keV. Therefore these source classes will not be prime targets for Simbol-X studies.

The situation is different for Crab-like SNRs, XRBs and AGN. As mentioned above these sources show hard spectra and with the limited high energy response of XMM-Newton and *Chandra* often can not be separated. This situation should change with the help of the high energy response of Simbol-X. Also detailed investigations of individual XRBs in nearby galaxies will be possible. In this way one can learn about rare X-ray source classes for which no easily accessible example is present in the Milky Way. This I want to demonstrate in the following section for the case of the XRB M 33 X−7.

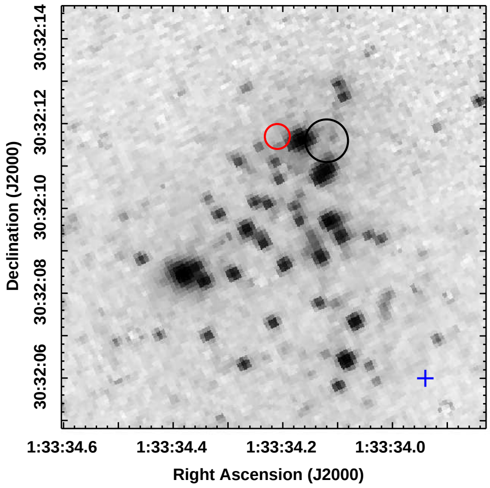

Fig. 3. Hubble Space Telescope 10" x 10" image of the OB star association HS 13. The *Chandra* positions (the two circles) are overlaid. The optical counterpart is the source between the circles (Pietsch et al. 2006).

5. The eclipsing black hole high mass X-ray binary M 33 X−7

The high mass XRB M 33 X−7 with 3.45 d orbital period was the first eclipsing XRB detected outside the Milky Way and the Magellanic Clouds. In 1989 it was suggested as an eclipsing XRB with 1.7 d orbital period based on *Einstein* observations. Adding ROSAT observations revealed that the orbital period is twice as long and allowed to refine the shape of the eclipsing light curve and binary ephemeris. The position of M 33 X−7 was covered in several observations of the XMM-Newton survey of M 33. The collecting power of the instruments not only led to a much clearer orbital light curve (resolution

Table 1. Summary of identifications (id.) and classifications (cl.) for XMM-Newton sources.

Source type	Selection criteria	M 31 id.	M 31 cl.	M 33 id.	M 33 cl.
fg Star	$\log(\frac{f_x}{f_{opt}}) < -1.0$ and $HR2 - EHR2 < 0.3$ and $HR3 - EHR3 < -0.4$ or not defined	6	90	5	30
AGN	Radio source and not classification as SNR from $HR2$ or optical/radio	1	36		12
Gal	optical id with galaxy	1		1	1
GCl	X-ray extent and/or spectrum	1	1		
SSS	$HR1 < 0.0$, $HR2 - EHR2 < -0.99$ or $HR2$ not defined, $HR3$, $HR4$ not defined		18		5
SNR	$HR1 > -0.1$ and $HR2 < -0.2$ and not a fg Star, or id with optical/radio SNR	21	23	21	23
GlC	optical id	27	10		
XRB	optical id or X-ray variability	7	9	2	
hard	$HR2 - EHR2 > -0.2$ or only $HR3$ and/or $HR4$ defined, and no other classification		567		267

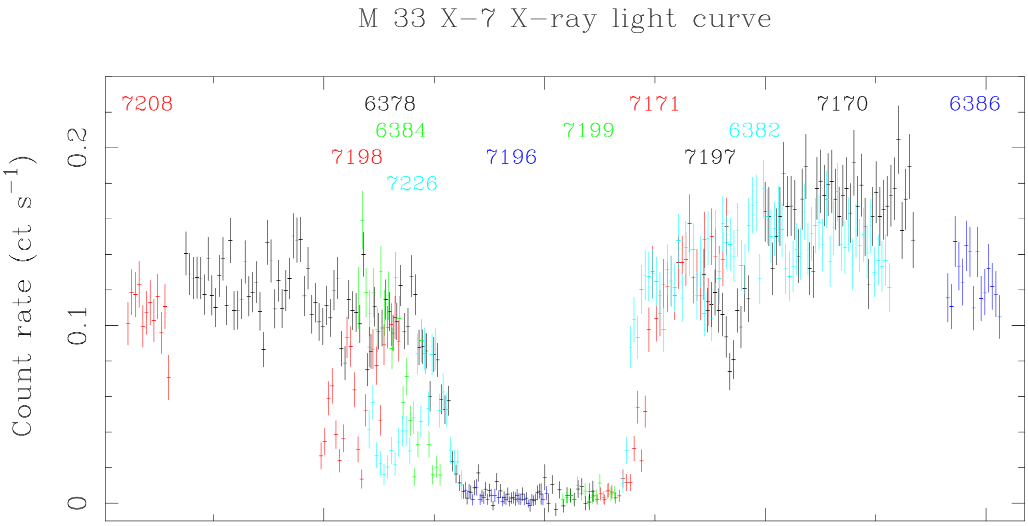

Fig. 2. *Chandra* ACIS light curve of the XRB M 33 X−7 in the (0.5–5.0) keV band (Pietsch et al. 2006).

of 1000 s) but also allowed detailed modeling of the source spectrum with a disk blackbody or bremsstrahlung spectrum. With the improved X-ray position of the source (including *Chandra* observations) a B0I to O7I star could be identified as optical counterpart that showed an optical heating light curve of a high mass XRB with the M 33 X−7 period. The X-ray spectrum together with the lack of an X-ray pulsation period proposed M 33 X−7 as the first eclipsing black hole XRB (see detailed references in Pietsch et al. 2004b). The *Chandra* X-ray survey of M 33 (ChASeM33) started in Sept. 2005 and sampled M 33 X−7 over a large part of the orbital period. Eclipse ingress and egress were resolved for the first time. The occurrence of the X-ray eclipse allowed us to determine an improved ephemeris of mid-eclipse and binary period, and to constrain the eclipse half-angle (see Fig. 2). Hubble Space telescope images identified the optical counterpart as an O6 III star (Fig. 3). Based on the optical light curve, the mass of the compact object in the system most likely exceeds 9 $M_{\odot}$ (Pietsch et al. 2006). Optical spectroscopy of the counterpart of M 33 X−7 with the GMOS instrument on the Gemini-North Telescope allowed us to derive a radial velocity curve which resulted in a optical mass function f(M) of 0.46 $M_{\odot}$. For the lowest plausible secondary mass of 20 $M_{\odot}$, the mass of the compact object exceeds 6.9 $M_{\odot}$ (Orosz et al. 2007). The mass, the shape of the X-ray spectrum and the short term X-ray time variability identify M 33 X−7 as the first eclipsing black hole high mass XRB. No such system is known in the Milky Way.

6. Conclusions

XMM-Newton and *Chandra* observations of nearby galaxies have demonstrated the importance of high collecting power for time variability and high spectral resolution investigations and of sub-arcsecond spatial resolution to separate different emission components, respectively. The high energy response of Simbol-X is essential to gain further insight into the X-ray emission properties of nearby galaxies. It should allow us to separate Crab-like SNRs from XRBs and background sources. Of specific importance for these aims are – besides the good sensitivity of Simbol-X at high energy – to aim for a field of view as large as possible and for a good spatial resolution. One also has to keep in mind that the unexplored energy band for nearby galaxy studies of Simbol-X is not only important for extending the knowledge on known sources but it also opens up discovery space for the unpredicted.

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