Recent Discoveries of Supersoft X-Ray Sources in M 31

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Recent discoveries of supersoft X-ray sources in M 31

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Classical nova (CNe) have recently been reported to represent the major class of supersoft X-ray sources (SSSs) in the central area of our neighbouring galaxy M 31. This paper presents a review of results from recent X-ray observations of M 31 with XM-M-Newton and Chandra. We carried out a dedicated optical and X-ray monitoring program of CNe and SSSs in the central area of M 31. We discovered the first SSSs in M 31 globular clusters (GCs) and their connection to the very first discovered CN in a M 31 GC. This result may have an impact on the CN rate in GCs. Furthermore, in our optical and X-ray monitoring data we discovered the CN M31N 2007-11a, which shows a very short SSS phase of 29 – 52 days. Short SSS states (durations ≤ 100 days) of CNe indicate massive white dwarfs (WDs) that are candidate progenitors of supernovae type Ia. In the case of M31N 2007-11a, the optical and X-ray light curves suggest a binary containing a WD with $M_{WD} > 1.0 \, M_\odot$. Finally, we present the discovery of the SSS counterpart of the CN M31N 2006-04a. The X-ray light curve of M31N 2006-04a shows short-time variability, which might indicate an orbital period of about 2 hours.

1 Introduction

The class of supersoft X-ray sources (SSSs) was first characterised on the basis of ROSAT observations (e.g. Greiner et al. 1991). These sources show extremely soft X-ray spectra, with little or no emission at energies above 1 keV (see e.g. Parmar et al. 1998), that can be described by equivalent black body temperatures of $\sim$15-80 eV (see Kahabka & van den Heuvel 1997, and references therein). Pietsch et al. (2005a) found that classical novae (CNe) represent the major class of SSSs in the central area of M 31. They showed that more than 60% of the SSSs from the XMM-Newton survey of M 31 by Pietsch et al. (2005b) can be identified with novae.

CNe originate in thermonuclear explosions on the surface of white dwarfs (WDs) in cataclysmic binaries. These explosions are resulting from the transfer of matter from the companion star to the WD. The transferred hydrogen-rich matter accumulates on the surface of the WD until hydrogen ignition starts a thermonuclear runaway in the degenerate matter of the WD envelope. The resulting expansion of the hot envelope causes the brightness of the WD to rise by more than nine magnitudes within a few days, and leads to ejection of mass at high velocities (see Hernanz 2005; Warner 1995, and references therein). However, a fraction of the hot envelope can continue burning hydrogen steadily on the surface of the WD (Starrfield et al. 1974; Sala & Hernanz 2005), powering a luminous ($L_x \sim 10^{37} \ldots 38 \text{ erg s}^{-1}$), transient SSS that can be observed directly once the ejected envelope becomes sufficiently transparent for X-rays (Starrfield 1989; Krautter 2002).

The duration of the SSS phase of CNe is related to the amount of H-rich matter that is not ejected during the nova outburst and also depends on the mass of the WD. More massive WDs need to accrete less matter to initiate the thermonuclear runaway, because of their higher surface gravity (José & Hernanz 1998). As a consequence, post-nova WD envelopes are smaller for more massive WDs, although this also depends on the accretion rate. Thus, the duration of the SSS state is inversely related to the mass of the WD (Sala & Hernanz 2005; Tuchman & Truran 1998). In turn, the time...
of appearance of the SSS is determined by the fraction of mass ejected in the outburst (Hachisu & Kato 2006). Typically, SSS states of CNe last from months to several years (Pietsch et al. 2007b).

We carried out a dedicated optical and X-ray monitoring program of CNe and SSSs in the central area of our neighbour galaxy M 31 (distance 780 kpc, Holland 1998; Stanek & Garnavich 1998, used throughout the paper). The X-ray observations were obtained with XMM-Newton and Chandra in three monitoring campaigns from June 2006 till March 2007 (AO5), November 2007 till February 2008 (AO6), and November 2008 till February 2009 (AO7). The AO6 and AO7 monitoring consisted of single observations separated by 10 days, in contrast to AO5 where the separation between the observations was about 50 days. We revised the monitoring strategy to be able to detect the CNe with short SSS phases as found by Pietsch et al. (2007b).

In this work we discuss newly discovered objects from three different, peculiar classes of SSSs: (a) SSSs in globular clusters (GCs) in Sec.2, (b) CNe with very short SSSs phases in Sec.3, and (c) SSSs with indications for light curve periodicity in Sec.4. In Sec.5 we conclude with a brief summary.

2 First supersoft X-ray sources in M 31 globular clusters

In our AO6 monitoring data we discovered the very first SSSs in M 31 globular clusters (GCs) (Henze et al. 2009b). The sources were found in the GCs Bol 111 (source SS1) and Bol 194 (source SS2) in a Chandra observation starting at 2007-11-07.64 UT (ObsID 8526). Table 1 summarises the source properties. The X-ray positions of both SSSs are in good agreement with the optical positions of the two GCs. Since both sources were at large off-axis angles in the HRC-I field of view, we computed their positions using XMM-Newton observations for SS1 and Swift observations for SS2.

To perform spectral analysis of SS1 we used XMM-Newton observations obtained at 2008-01-05.99 UT and at 2008-02-09.31 UT (ObsIDs 0511380201 and 0511380601). Since SS2 faded before the start of the XMM-Newton observations, we used a Swift follow-up observation (ObsID 00031027001) to constrain the spectrum. Source parameters derived from XSPEC black body fits to the spectra are shown in Table 1. The table also shows SS1 parameters derived from Swift observation 00031017002 for comparison. Note, that this observation was performed on 2007-11-19.27 UT, about 50 days before the XMM-Newton observations, and therefore indicates a trend for some parameters. Despite the errors for the black body temperature of SS2 are large, due to the few counts in the Swift XRT spectrum, this source only emits photons with energies below 750 eV. Therefore, we classify both sources as SSSs.

SSSs in GCs are extremely rare. There was just one previously known object: the transient 1E 1339.8+2837 in the Galactic GC M 3 (NGC 5272; Dotani et al. 1999; Verbunt et al. 1995). Dotani et al. (1999) measured for this source a black body temperature of \( kT \sim 36 \text{ eV} \) and a luminosity of \( \sim 10^{35} \text{ erg s}^{-1} \), which is significantly lower than the observed peak luminosities of other SSSs, including the two sources discussed here. Dotani et al. (1999) discuss 1E 1339.8+2837 as a cataclysmic variable (CV) system that may be a dwarf nova involving a massive WD.

### Table 1 Features of the SSSs in GCs. X-ray parameters of SS1 are based on XMM-Newton (Swift) observations, X-ray parameters of SS2 are based on Swift.

<table>
<thead>
<tr>
<th>Source</th>
<th>SS1 (ObsID 111)</th>
<th>SS2 (ObsID 194)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RA (J2000)</td>
<td>00:42:33.21</td>
<td>00:43:45.30</td>
</tr>
<tr>
<td>Dec (J2000)</td>
<td>+41:00:26.1</td>
<td>+41:06:08.2</td>
</tr>
<tr>
<td>Position error (3(\sigma))</td>
<td>1&quot;6</td>
<td>13&quot;8</td>
</tr>
<tr>
<td>GC RA (J2000)</td>
<td>00:42:33.16</td>
<td>00:42:45.0</td>
</tr>
<tr>
<td>GC Dec (J2000)</td>
<td>+41:00:26.1</td>
<td>+41:06:08.3</td>
</tr>
<tr>
<td>Distance to GC</td>
<td>0&quot;5</td>
<td>1&quot;1</td>
</tr>
<tr>
<td>kT [eV]</td>
<td>48 (\pm) 2</td>
<td>74 (\pm) 23</td>
</tr>
<tr>
<td>(N_E [10^{23} \text{ cm}^{-2}])</td>
<td>2.3 (\pm) 0.1 (2.3 (\pm) 0.3)</td>
<td>1.0 (\pm) 1.0</td>
</tr>
<tr>
<td>(L_x [10^{38} \text{ erg s}^{-1}])</td>
<td>10.6 (\pm) 0.2 (20 (\pm) 4)</td>
<td>0.6 (\pm) 0.1</td>
</tr>
<tr>
<td>(L_{bol} [10^{38} \text{ erg s}^{-1}])</td>
<td>28.7 (\pm) 0.5 (85 (\pm) 18)</td>
<td>1.0 (\pm) 0.4</td>
</tr>
<tr>
<td>(R [10^3 \text{ cm}])</td>
<td>7.0 (\pm) 1.0 (15 (\pm) 3)</td>
<td>0.5 (\pm) 0.3</td>
</tr>
</tbody>
</table>

Notes: 
- a: GC positions from Galletti et al. (2004)
- b: Unabsorbed; range 0.2 – 1.0 keV.

Recently, Shafter & Quimby (2007) reported the very first nova found in a M 31 GC (M31N 2007-06b). CNe in GCs are scarce, with just two sources known before 2007 that fit this definition. One was detected in the Galactic GC M 80 whereas the second nova was found in a GC of the galaxy M 87 (see Shara et al. 2004, and references therein). According to Shara et al. (2004) a third candidate (nova 1938 in the galactic GC M14) is less likely to be a CN. For all of this CNe there is no X-ray counterpart known.

M31N 2007-06b was found in Bol 111 on 2007 June 19.38, i.e. 141 days before our discovery of the SSS SS1 in Bol 111. Supersoft spectra like the one of SS1 are typical for X-ray counterparts of optical novae. Time lags of \~150 days between an optical nova outburst and the first detection of the SSS counterpart have been observed before for other CNe (Pietsch et al. 2007b). Therefore, we identify the supersoft X-ray transient in the globular cluster Bol 111 with the CN M31N 2007-06b.

No optical counterpart has been reported for SS2 in Bol 194. Therefore, we searched our optical monitoring data for indications of a nova outburst in the GC. These data are based on observations with the 45 cm ROTSE-IIIb telescope (Akerlof et al. 2003) at the Turkish National Observatory (Bakırtepe, Turkey), the robotic 60 cm telescope Livernoise Optical Transient Imaging System (Super-LOTIS, Williams et al. 2008) located at Steward Observatory (Kitt Peak National Observatory, Arizona).
Peak, Arizona, USA), supplemented by archival data from K. Hornoch obtained at telescopes in Lelekovice (35 cm telescope) and Ondřejov (65 cm telescope).

Unfortunately, we did not discover a CN counterpart of SS2. However, due to seasonal gaps in the observation this does not rule out a CN in Bol 194. We conducted simulations of optical nova outbursts with different peak magnitudes and corresponding light curve decay times on any day between October 2004 and November 2007. These simulations took into account the intrinsic magnitude of the underlying GC. We find that most CN would have remained undetected in our optical data if they occurred during the periods 2005-02-15 – 2005-05-12, 2006-02-19 – 2006-05-09, or 2007-02-18 – 2007-05-20, which is 990 – 904, 621 – 542, and 257 – 166 days before the first detection of SS2 in X-rays. These detection gaps account for 23% of the optical monitoring time. On the other hand, our coverage for 77% of the time is almost complete, down to nova peak magnitudes of about 18.5 – 19.0 mag in the R band.

If we assume that both SSSs are post-CNe and that the SSS phase lasts on average one year we find a nova rate of 0.015 yr$^{-1}$ GC$^{-1}$ for M 31. This is significantly larger than previous upper limits based on optical non-detections (e.g. 0.005 novae yr$^{-1}$ GC$^{-1}$; Tomaney et al. 1992). The connection of SSSs and CNe may therefore help to study the CN population in GCs.

3 Very short SSS phase of M31N 2007-11a

Our AO6 monitoring also led to the discovery of the very short SSS phase of the CN M31N 2007-11a (Henze et al. 2009c). We discovered M31N 2007-11a in the optical as a candidate nova in our Super-LOTIS monitoring data of 2007 Nov 2.28 UT (Pietsch et al. 2007a) at RA = 00h42m37.29s, Dec = +41°17’10”3” (J2000, accuracy of 0.2”). The outburst date is well-constrained, since M31N 2007-11a was not detected on the night before the discovery. In the second HRC-I observation of the M 31 X-ray monitoring campaign (starting 2007 Nov 17.76), we detected M31N 2007-11a as a X-ray source. The X-ray position is in excellent agreement with the optical data. Thanks to our AO6 monitoring strategy, M31N 2007-11a was visible in four consecutive Chandra observations before it faded and was not detected in the following XMM-Newton observations. We computed HRC-I hardness ratios, as described in “The Chandra Proposers Observatory Guide”¹, from count rates in the bands S, M, and H (channels 1:100, 100:140, and 140:255). The ratios S/M = −0.10 ± 0.15 and M/H = 0.09 ± 0.15 indicate a SSS spectrum with a $kT \lesssim 40$ eV. This assumes an absorbed black body spectrum with an $N_H \geq 6.7 \times 10^{20}$ cm$^{-2}$, the Galactic foreground absorption towards M 31 (Stark et al. 1992). Based on the indication of a SSS counterpart and the optical and X-ray light curves we classify M31N 2007-11a as a CN.

M31N 2007-11a was a very fast CN in the optical, exhibiting a very short SSS state in the X-ray with an appearance time of 6–16 days and a turn-off time of 45–58 days after the optical outburst. The appearance timescale implies an ejected mass of $(0.4 – 3) \times 10^{-7} M_\odot$. To compute the ejected mass range we assume a typical value for the envelope expansion velocity of 2000 km s$^{-1}$, since we do not have an optical spectrum of M31N 2007-11a, and that the SSS turns on when the absorbing hydrogen column density decreases to $\sim 10^{21}$ cm$^{-2}$. This mass range is about two orders of magnitude lower than the ejected envelope masses of most M 31 novae discussed in Pietsch et al. (2007b). The SSS turn off time constrains the burned mass to the range $(8 – 10) \times 10^{-8} M_\odot$, according to Sala & Hernanz (2005, their Equation (5)). Here we assume a bolometric luminosity of $3 \times 10^4 L_\odot$ and a hydrogen mass fraction $X_H = 0.5$.

It is noteworthy that the burned mass is comparable to the ejected mass, within a factor of 2 – 3. The extremely short SSS phase could have been caused either by a WD with $M_{WD} > 1.1 M_\odot$ for a standard hydrogen fraction in the envelope or by a very hydrogen-poor envelope in a WD with $M_{WD} \sim 1.0 M_\odot$.

4 Short time variations in the X-ray light curve of M31N 2006-04a

A comprehensive analysis of our AO5 – AO7 monitoring will be given in Henze et al. (2009a). Here we present the short-time variability in the X-ray light curve of the CN M31N 2006-04a.

M31N 2006-04a was independently discovered in our optical M 31 monitoring (with the Bradford Robotic Telescope Galaxy at the Tenerife Observatory; see Pietsch et al. 2006) and by K. Itagaki. The CN showed up as an X-ray source in only one XMM-Newton observation on 2006-08-09 (ObsID 0405320601), which is 103 days after the first optical detection. The source is not detected on 2006-07-02 (XMM-Newton ObsID 0405320501) and on 2006-09-30 (Chandra ObsID 7284), which are about 67 and 157 days after the optical discovery, respectively. M31N 2006-04a only shows photons with energies $< 0.7$ keV and is therefore classified as a SSS. The EPIC PN light curve (see Fig. 1) indicates significant variability with a period of about 2 hours.

In M 31, there were just three SSSs known previously which show periodicities in their X-ray light curves: the persistent SSS XMMU J004252.5+411540 (217.7s period; Trudolyubov & Priedhorsky 2008), the transient supersoft source XMMU J004319.4+411758 (865.5s period; Osborne et al. 2001), and the CN M31N 2007-12b (1100s period; contribution of W. Pietsch in this volume). We want to mention that also in the Galaxy there are just a few novae known with periodicities in their light curves: RS Oph (Ness et al.

¹ http://cxc.harvard.edu/proposer/POG/html/index.html; chapter 7.6

² see http://www.cfa.harvard.edu/iau/CBAT_M31.html#2006-04a
the operation of Super-LOTIS.

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The orbital periods of CVs in general are typically in the range of 1 – 10 hours (Ritter & Kolb 2003). CNe have similar orbital periods (Warner 2002). The pulsation and spin periods of WDs in CNe are typically shorter than 1 hour (see e.g. Drake et al. 2003, 2500s pulsation period in nova V1494 Aql). The light curve variability of M31N 2006-04a might therefore be interpreted as the orbital period of the binary system.

5 Summary

In this paper we review recent discoveries of SSSs in M 31. The discovery and good light curve coverage of fast transients like SS2 in Bol 194 or M31N 2007-11a shows that our XMM-Newton AO6/AO7 monitoring strategy was successful. Also for the AO5 source M31N 2006-04a a denser X-ray monitoring would have been useful for the study of light curve variability. In agreement with Pietsch et al. (2007b) we find that short supersoft states could play an important role in the SSS population of M 31.

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Fig. 1 Exposure and barycentre corrected XMM-Newton EPIC PN light curve of M31N 2006-04a (0.2 – 1.0 keV, 100s bins).

2007), V4743 Sgr (Leibowitz et al. 2006), and V1494 Aql (Drake et al. 2003).

The discovery and good light curve coverage of fast transients like SS2 in Bol 194 or M31N 2007-11a shows that our XMM-Newton AO6/AO7 monitoring strategy was successful. Also for the AO5 source M31N 2006-04a a denser X-ray monitoring would have been useful for the study of light curve variability. In agreement with Pietsch et al. (2007b) we find that short supersoft states could play an important role in the SSS population of M 31.

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