

Unresolved X-ray emission in M31 and constraints on progenitors of Classical Novae

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ABSTRACT

We investigate unresolved X-ray emission from M31 based on an extensive set of archival *XMM-Newton* and *Chandra* data. We show that extended emission, found previously in the bulge and thought to be associated with a large number of faint compact sources, extends to the disk of the galaxy with similar X-ray to K-band luminosity ratio. We also detect excess X-ray emission associated with the 10-kpc star-forming ring. The L_X/SFR ratio in the 0.5 – 2 keV band ranges from zero to $\approx 1.8 \cdot 10^{38}$ (erg s⁻¹)/(M_⊙/yr), excluding the regions near the minor axis of the galaxy where it is $\sim 1.5 - 2$ times higher. The latter is likely associated with warm ionized gas of the galactic wind rather than with the star-forming ring itself.

Based on this data, we constrain the nature of Classical Nova (CN) progenitors. We use the fact that hydrogen-rich material, required to trigger the explosion, accumulates on the white dwarf surface via accretion. Depending on the type of the system, the energy of accretion may be radiated at X-ray energies, thus contributing to the unresolved X-ray emission. Based on the CN rate in the bulge of M31 and its X-ray surface brightness, we show that no more than ~ 10 per cent of CNe can be produced in magnetic cataclysmic variables, the upper limit being ~ 3 per cent for parameters typical for CN progenitors. In dwarf novae, $\gtrsim 90 - 95$ per cent of the material must be accreted during outbursts, when the emission spectrum is soft, and only a small fraction in quiescent periods, characterized by rather hard spectra.

Key words: Galaxies: individual: M31 – Galaxies: stellar content – stars: white dwarfs – X-rays: diffuse background – X-rays: galaxies

1 INTRODUCTION

Similarly to other normal galaxies, X-ray emission from the bulge of the Andromeda galaxy is dominated by accreting compact sources (e.g. Voss & Gilfanov 2007). In addition, there is relatively bright extended emission which nature was explored in Li & Wang (2007); Bogdán & Gilfanov (2008) (hereafter Paper I) based on extensive set of *Chandra* observations. In Paper I we revealed the presence of warm ionized ISM in the bulge which most likely forms a galactic-scale outflow and showed that bulk of unresolved emission is associated with old stellar population, similar to the Galactic ridge X-ray emission in the Milky Way (Revnivtsev et al. 2006; Sazonov et al. 2006). Although these studies led to a much better understanding of X-ray emission from the bulge of M31, the disk of the galaxy could not be investigated in similar detail due to insufficient *Chandra* data coverage of the galaxy. The *XMM-Newton* data, available at the time, also did not provide adequate coverage of the galaxy either, with only the northern part of the disk observed with relatively short exposures (Trudolyubov et al. 2005).

Over the last several years *XMM-Newton* completed a survey

of M31, which data has become publicly available now. The numerous pointings with total exposure time of ~ 1.5 Ms give a good coverage of the entire galaxy. With these data it has become possible to study X-ray emission from the disk of the galaxy. In the present paper we concentrate on the unresolved emission component and compare its characteristics in the disk and bulge. We also study the 10-kpc star-forming ring to support our earlier claim that excess unresolved emission is associated with star-forming regions in the galactic disk (Paper I).

Classical Nova explosions are caused by thermonuclear runaway on the surface of a white dwarf (WD) in a binary system (Starrfield et al. 1972). In order for the nuclear runaway to start, a certain amount of hydrogen rich material, $\Delta M \sim 10^{-5} M_{\odot}$, needs to be accumulated on the WD surface (Fujimoto 1982). This material is supplied by the donor star and is accreted onto the WD. Obviously, there is a direct relation between the frequency of CNe and collective accretion rate in their progenitors. The accretion energy is released in the form of electromagnetic radiation which spectrum depends on the type of the progenitor system. In certain types of accreting WDs it peaks in the X-ray band, for example in magnetic systems – polars and intermediate polars. Emission from these systems contributes to the unresolved emission in the galaxy, therefore their number and contribution to the CN rate can be constrained

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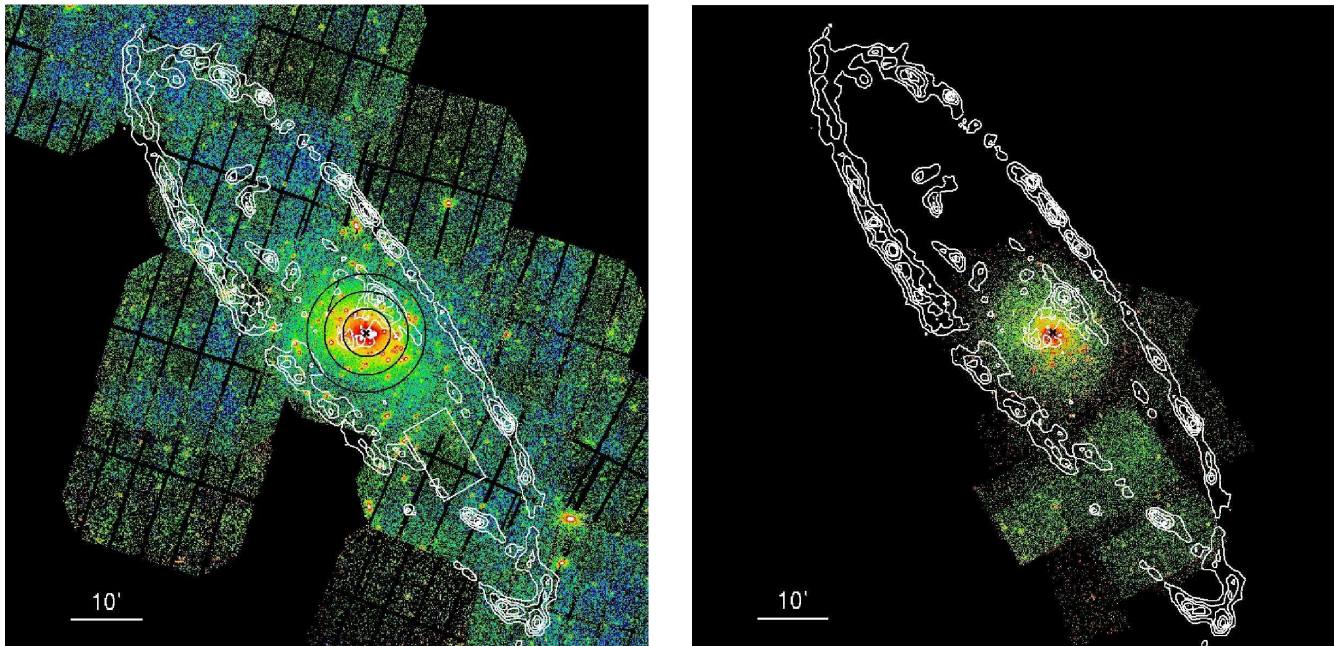


Figure 1. Combined image of *XMM-Newton* (left panel) and *Chandra* (right) observations in the 0.5 – 2 keV energy band. The instrumental background components are subtracted, and the telescope vignetting correction is applied. White contours show the location of the 10-kpc star-forming ring, traced by the 160 μm *Spitzer* image. Overplotted are the regions used for spectral analysis in Section 3.2 and to compute the L_X/L_K ratios in Section 3.3. The center of M31 is marked with the cross. North is up and east is left.

using high resolution X-ray data. This is the subject of the second part of the paper. Note, that a similar line of arguments can be used to constrain the nature of progenitors of Type Ia Supernovae (Gilfanov & Bogdán 2010).

In the following, the distance to M31 is assumed to be 780 kpc (Stanek & Garnavich 1998; Macri 1983) and the Galactic hydrogen column density is $6.7 \times 10^{20} \text{ cm}^{-2}$ (Dickey & Lockman 1990).

The paper is structured as follows. In Section 2 we describe the analyzed X-ray and near-infrared data and the main steps of its reduction. In Section 3 results of the analysis of unresolved X-ray emission are presented. In Section 4 we derive constraints on the nature of CN progenitors. Our results are summarized in Section 5.

2 DATA REDUCTION

2.1 *XMM-Newton*

We analyzed 24 observations from *XMM-Newton* survey of M31, listed in Table 1. The data was taken between 2000 June 25 and 2007 July 25 and covers nearly the entire disk of M31 and its bulge. The approximate coverage of the galaxy by *XMM-Newton* data is illustrated in the left panel of Fig. 1. We analyzed the data of the European Photon Imaging Camera (EPIC) instruments (Strüder et al. 2001; Turner et al. 2001), for its reduction we used Science Analysis System (SAS) version 7.1.

Main steps of data analysis were performed in the same way as described in Paper I. After applying the double filtering technique (Nevalainen et al. 2005) the exposure time decreased to $T_{\text{filt}} \approx 639$ ks. The out-of-time events were removed using the Oot event list. The exposure maps were calculated with EEXPMAP command of SAS, using a powerlaw model with slope of $\Gamma = 2$. The observations were re-projected and merged in the coordinate system of obs-id 0112570101.

Table 1. The list of *XMM-Newton* observations used for the analysis.

Obs-ID	T_{obs} (ks)	T_{filt} (ks)	Date
0109270101	62.5	16.0	2001 Jun 29
0109270301	54.2	25.2	2002 Jan 26
0109270401	91.6	32.2	2002 Jun 29
0109270701	54.9	53.7	2002 Jan 05
0112570101	61.1	52.6	2002 Jan 06
0112570201	62.8	42.6	2002 Jan 12
0112570301	59.9	15.2	2002 Jan 24
0112570401	31.0	25.0	2000 Jun 25
0202230201	18.3	17.8	2004 Jul 16
0202230401	14.6	9.0	2004 Jul 18
0202230501	21.8	2.0	2004 Jul 19
0402560301	66.7	33.9	2006 Jul 01
0402560401	57.0	5.0	2006 Jul 08
0402560501	57.0	24.0	2006 Jul 20
0402560701	64.4	14.0	2006 Jul 23
0402560801	64.0	41.0	2006 Dec 25
0402560901	60.0	33.6	2006 Dec 26
0402561001	63.6	39.7	2006 Dec 30
0402561101	60.0	32.0	2007 Jan 01
0402561301	52.1	25.1	2007 Jan 03
0402561401	62.0	40.0	2007 Jan 04
0402561501	54.9	36.9	2007 Jan 05
0404060201	40.0	14.0	2006 Jul 03
0410582001	20.1	8.0	2007 Jul 25

In the analysis of extended emission, contribution of resolved point sources needs to be removed. For this, we used the *Chandra* source list, where available. In the disk, not covered by *Chandra*, we ran the SAS source detection tool, which gives a complete list of sources above $\sim 10^{36} \text{ erg s}^{-1}$. The resulting list was used to mask out compact sources in these regions. As before (Paper I), we use

Table 2. The list of *Chandra* observations used for the analysis.

Obs-ID	T_{obs} (ks)	T_{fit} (ks)	Instrument	Date
303	12.0	8.2	ACIS-I	1999 Oct 13
305	4.2	4.0	ACIS-I	1999 Dec 11
306	4.2	4.1	ACIS-I	1999 Dec 27
307	4.2	3.1	ACIS-I	2000 Jan 29
308	4.1	3.7	ACIS-I	2000 Feb 16
311	5.0	3.9	ACIS-I	2000 Jul 29
312	4.7	3.8	ACIS-I	2000 Aug 27
313	6.1	2.6	ACIS-S	2000 Sep 21
314	5.2	5.0	ACIS-S	2000 Oct 21
1575	38.2	38.2	ACIS-S	2001 Oct 05
1577	5.0	4.9	ACIS-I	2001 Aug 31
1580	5.1	4.8	ACIS-S	2000 Nov 17
1583	5.0	4.1	ACIS-I	2001 Jun 10
1585	5.0	4.1	ACIS-I	2001 Nov 19
2049	14.8	11.6	ACIS-S	2000 Nov 05
2050	13.2	10.9	ACIS-S	2001 Mar 08
2051	13.8	12.8	ACIS-S	2001 Jul 03
2895	4.9	3.2	ACIS-I	2001 Dec 07
2896	5.0	3.7	ACIS-I	2002 Feb 06
2897	5.0	4.1	ACIS-I	2002 Jan 08
2898	5.0	3.2	ACIS-I	2002 Jun 02
4360	5.0	3.4	ACIS-I	2002 Aug 11
4536	54.9	30.2	ACIS-S	2005 Mar 07
4678	4.9	2.7	ACIS-I	2003 Nov 09
4679	4.8	2.7	ACIS-I	2003 Nov 26
4680	5.2	3.2	ACIS-I	2003 Dec 27
4681	5.1	3.3	ACIS-I	2004 Jan 31
4682	4.9	1.2	ACIS-I	2004 May 23
7064	29.1	23.2	ACIS-I	2006 Dec 04
7068	9.6	7.7	ACIS-I	2007 Jun 02

enlarged source regions in order to limit the contribution of remaining counts from point sources to less than $\lesssim 10$ per cent.

The particle background components were subtracted as described in Paper I, where their origin is also discussed. By removal of the cosmic X-ray background (CXB) we took into account that the resolved fraction of CXB changes as the exposure time varies. In order to compensate for this effect we assumed that the point source detection sensitivity is proportional to the exposure time, and computed the resolved fraction of CXB for each pixel using $(\log N - \log S)$ distribution from Moretti et al. (2003). We took into account various systematic errors in the background subtraction procedure, which include the scatter in the determination of the “flat” internal background (caused by the interaction of cosmic rays with the detector material), the uncertainty in the $(\log N - \log S)$ distribution, and the uncertainty in the determination of the solar proton component. The combined effect of these uncertainties is indicated by grey shaded area in the surface brightness profiles analyzed in Section 3.1. Due to limitations of the background subtraction procedure, data can be analyzed and interpreted reliably only out to $\sim 1^\circ$ central distance along the major axis of M31 in the 0.5–2 keV energy range. We found that in harder energy band only the bulge of the galaxy can be studied with XMM-Newton data.

2.2 Chandra

We combined an extensive set of *Chandra* data taken between 1999 October 13 and 2007 June 2, listed in Table 2. The data was

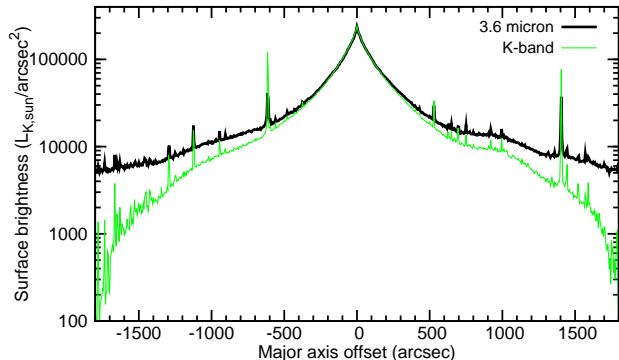


Figure 2. Near-infrared light distribution along the major axis of M31 based on 3.6 μm data of *Spitzer Space Telescope* (black thick line) and the 2MASS K-band (thin green line) data. The normalization of *Spitzer* profile was adjusted to match the K-band light in the center of M31. The x-coordinate increases from south-west to north-east.

processed with CIAO¹ software package tools (CIAO version 4.0; CALDB version 3.4.5). The 29 observations allowed us to study the bulge and the southern disk of M31, the exact data coverage is shown in the right panel of Fig. 1. In case of ACIS-S observations we used the data from S1, S2, S3, I2, I3 CCDs, except for Obs-ID 1575 where we extracted data only from the S3 chip. The peak value of the exposure time reaches $T_{\text{fit}} \approx 144$ ks in the center of the galaxy.

The main steps of the data analysis are similar to those outlined in Paper I. After excluding the flare-contaminated time intervals the total exposure time decreased by ~ 25 per cent. The instrumental background was subtracted following Hickox & Markevitch (2006) and using the stowed data set². By subtraction of CXB we followed the same procedure as described for XMM-Newton, to correct for the varying fraction of resolved CXB sources.

2.3 Near-infrared data

In order to compare the unresolved X-ray emission with the stellar mass distribution, a stellar mass tracer is needed. The K-band image from the *Two-Micron All Sky Survey* (2MASS) Large Galaxy Atlas (LGA) (Jarrett et al. 2003) image is commonly used for this purpose. Alternatively, one could use data of the Infrared Array Camera (IRAC) on the *Spitzer Space Telescope* (SST), which provides images at near-infrared wavelengths, among others at 3.6 μm .

Due to the large angular extent of M31 the background on the 2MASS K-band image provided by LGA is somewhat over-subtracted (T. Jarrett, private communication), therefore the disk of M31 appears to be too faint. In Fig. 2 we compare the K-band surface brightness distribution with the *Spitzer* 3.6 μm data. The profiles were extracted along the major axis of M31, with bin width of 5'' and the bins were averaged on 500'' in the transverse direction. The background level of *Spitzer* image was estimated using nearby fields to M31. There is a good agreement in the central $\sim 300''$, where the background subtraction is nearly negligible, but at large

¹ <http://cxc.harvard.edu/ciao/>

² <http://cxc.harvard.edu/contrib/maxim/stowed/>

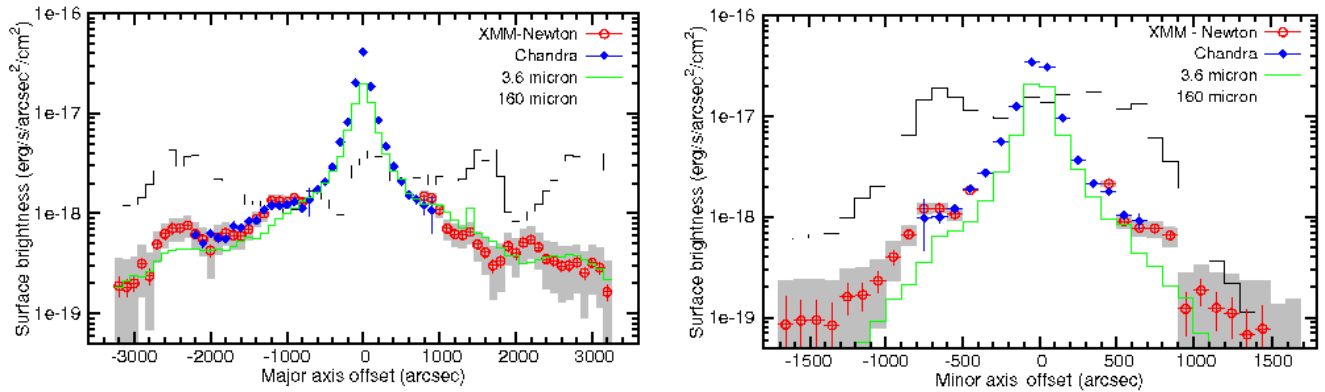


Figure 3. X-ray surface brightness distribution along the major (left panel) and minor axes (right) in the 0.5 – 2 keV energy band. The filled (blue in the color version) symbols show the *Chandra* data, open (red) symbols represent the *XMM-Newton* data, the solid (green) histogram is the surface brightness of 3.6 μm *Spitzer* data, the thin solid (black) line is 160 μm *Spitzer* data. The shaded area shows the systematic uncertainty in the background subtraction for the *XMM-Newton* data. The normalization of near- and far-infrared profiles are the same on both panels. The x-coordinate increases from south-west to north-east for the major axis and from south-east to north-west for the minor axis profile.

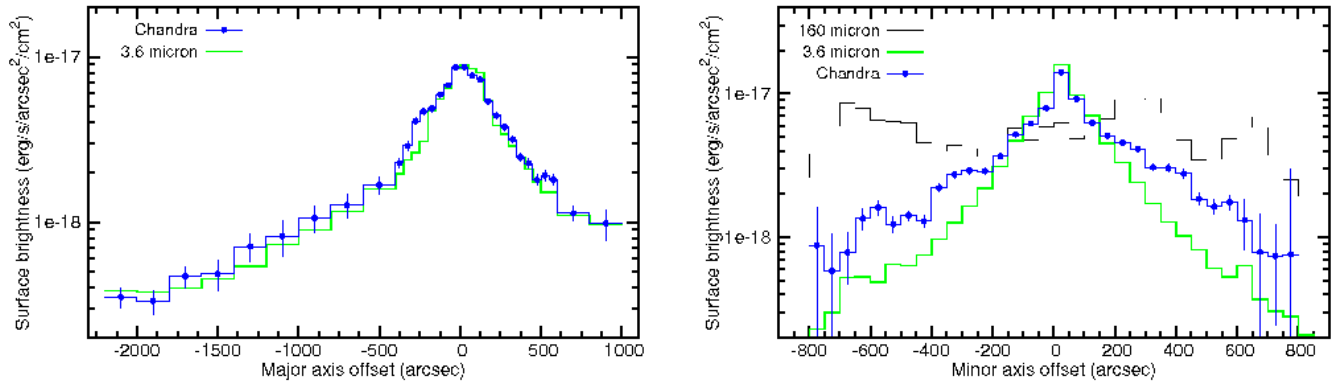


Figure 4. Same as Fig. 3 but in the 2 – 7 keV energy band, based on *Chandra* data. The normalization of the near-infrared profiles is the same on both panels.

offsets an increasing deviation appears. Therefore in the present study we use the 3.6 μm image of *Spitzer* to trace the stellar mass. In order to facilitate the comparison of results with other studies we converted *Spitzer* near-infrared luminosities to K-band values using the central regions of the galaxy. The obtained conversion factor between pixel values is $C_K/C_{3.6\mu\text{m}} \approx 10.4$.

In Paper I we used 2MASS image to compute K-band luminosities and stellar masses of different parts of the galaxy. As the analysis of the Paper I did not extend beyond $\approx 1000''$ from the center, the underestimated disk brightness on the 2MASS image at large offset angles has not affected our results in any significant or qualitative way. It resulted, however, in small quantitative difference in X/K ratios between this paper and Paper I.

3 UNRESOLVED X-RAY EMISSION IN M31

3.1 Surface brightness distribution

We study the brightness distribution of unresolved X-ray emission in M31 in the 0.5 – 2 keV and in the 2 – 7 keV energy range (Fig.3, 4). In all cases profiles were averaged over 500'' in the

transverse direction. The contribution of resolved point sources is removed. The profiles are corrected for vignetting, furthermore all instrumental and sky background components are subtracted. We found good agreement at all studied distances between *Chandra* and *XMM-Newton* data. In the inner bulge region, which is most crowded with point sources we consider only *Chandra* data. X-ray light distributions are compared with the 3.6 μm *Spitzer* data.

The left panel of Fig. 3 presents the surface brightness distribution along the major axis of M31 in the 0.5 – 2 keV band. The shaded area shows the background subtraction uncertainties (see Section 2.1). The profile confirms the presence of the additional soft emission in the central bulge, which was shown to originate from hot ionized gas (see Paper I). Outside few central bins X-ray flux follows the near infrared profile – unresolved emission associated with the bulge of the galaxy continues into the disk with approximately the same X-ray to K-band ratio. Although overall correlation between X-ray and near infrared brightness is quite good, there are several deviations, of which the most prominent is the excess X-ray emission at the central distance of $-2500''$. This excess approximately coincides with the broad hump on the 160 μm profile corresponding to the southern end of the 10-kpc star-forming

ring (Fig. 1). Similar excess emission (“shoulders” at $\sim \pm 700''$) coinciding with the peaks on the $160 \mu\text{m}$ profiles is present in the distribution along the minor axis. (Note that overall normalization of the X-ray flux is larger on the minor axis profile due to contribution of the gas emission.) A possible association of excess X-ray emission with the star-forming activity in the 10-kpc star-forming ring is further discussed in Section 3.4.

In Fig. 4 we show the brightness distribution in the 2 – 7 keV energy band based on *Chandra* data. No contribution of the hot gas emission with $kT \sim 300 - 400$ eV is expected in this energy range. Accordingly, there is a good agreement between the X-ray and near-infrared distribution along the major axis (Fig. 4). However, along the minor axis the unresolved X-ray emission traces the stellar light only in the inner region. Outside $\sim 200 - 300''$ the X-ray brightness becomes systematically larger than the normalized $3.6 \mu\text{m}$ distribution. The origin of this enhancement is not clear. It may be associated with the star-formation activity in the disk and 10-kpc star-forming ring, as suggested in Paper I, or may be related to the galactic scale wind.

3.2 Spectra

In order to extract spectra of the bulge and the disk of M31 we used only *Chandra* data. The background was subtracted using the ACIS “blank-sky” files as described in Paper I. We extracted the spectrum of the inner bulge, outer bulge, and disk of M31. The inner bulge region is represented by a circle with 200 arcsec radius, the outer bulge spectrum is extracted from a circular annuli with radii of 350 – 500 arcsec, and the disk spectrum is computed from a rectangular region at the southern part of the disk. The applied regions are also depicted in Fig 1. As a comparison we also added M32, the extraction region is same as described in Paper I. In order to compare the spectra we normalized them to the same level of near-infrared luminosity.

Fig. 5 reveals that all spectra are consistent above ~ 1.5 keV. Below this energy the inner bulge region is strikingly different, it has a factor of ~ 4 times stronger soft component than all other spectra. Also the outer bulge has a weak excess below ~ 1 keV compared to the disk and M32 spectra, which show very similar spectral characteristics at all energies. The remarkable soft component is the consequence of the hot ionized gas, located in the bulge of M31 (see Paper I). The somewhat increased soft emission in the outer bulge is presumably due to the contribution from gas emission, lacking completely in the disk of the galaxy. A relatively weak soft component is also present in the spectra of the disk region and M32, which presumably originates from the population of unresolved sources. Indeed, the different nature of the soft components in the inner bulge and in the disk of M31 is also supported by difference in their best-fit temperatures. Using a simple two component spectral model, consisting of an optically-thin thermal plasma emission spectrum and a power-law model (MEKAL in XSPEC), we find a best-fit temperature of $kT = 0.36 \pm 0.01$ keV for the inner bulge, whereas we obtain $kT = 0.62 \pm 0.10$ keV in the disk and $kT = 0.54 \pm 0.15$ keV in M32.

3.3 L_X/L_K ratios

The X-ray to K-band luminosity ratios (L_X/L_K) were computed for the same regions as used for spectral analysis. As before, we use *Chandra* data only. The L_X/L_K ratios are obtained in the 0.5 – 2 keV and in the 2 – 10 keV energy range to facilitate comparison with previous studies. The X-ray luminosities in the 0.5 – 2

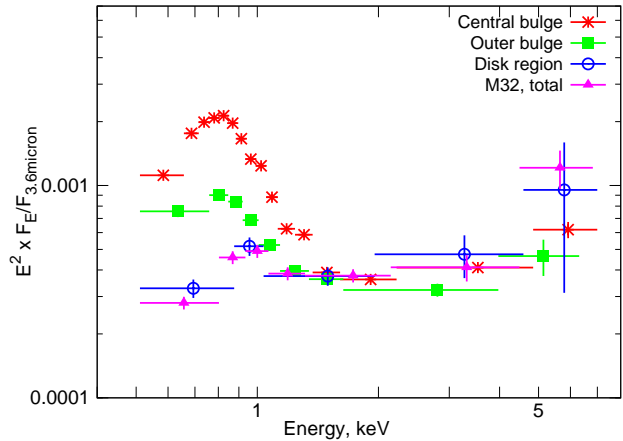


Figure 5. X-ray spectra of different regions in M31 and in M32: stars (red) show the spectrum of the central 200'' region; filled boxes (green) are the spectrum of the 350 – 500'' annulus; open circles (blue) are the spectrum of the disk; filled triangles (purple) show the spectrum of M32. All spectra were extracted using *Chandra* data. The spectra are normalized to the same level of near-infrared brightness.

keV energy range were computed using the best fit spectral models. For the outer bulge and disk we assumed a “power law + MEKAL” model, whereas for the inner bulge a second MEKAL component was added to obtain a better fit. In the 2 – 10 keV band the X-ray luminosities were computed from the count rate using the count-to-erg conversion factor for a power law spectrum with a photon index of $\Gamma = 2$. The conversion factor depends weakly on the assumed slope, changing by $\lesssim 10$ per cent when Γ varied by ± 0.4 . The luminosities and their ratios are listed in Table 3, errors correspond to statistical uncertainties in the X-ray count rates.

The L_X/L_K ratios for the bulge regions are consistent with those given in Paper I, albeit somewhat smaller, due to the increased K-band luminosity for some of the regions (Section 2.3). In agreement with spectra, the L_X/L_K ratio in the soft band is highest in the inner bulge, and smallest in the disk of the galaxy, where it is consistent with M32 value (Paper I). In the outer bulge the obtained L_X/L_K ratio is in-between due to residual contribution from gas emission. In the hard band all L_X/L_K ratios are similar to each other, in the range of $(3.4 - 4.5) \cdot 10^{27} \text{ erg s}^{-1} L_{K,\odot}^{-1}$. There is a statistically significant scatter in their values, which origin is not clear. It can not be explained by the varying residual contribution of LMXBs due to different point source detection sensitivity in different region. Indeed, the latter varies from $\sim 2 \cdot 10^{35} \text{ erg s}^{-1}$ in the outer bulge to $\sim 6 \cdot 10^{35} \text{ erg s}^{-1}$ in the disk. If we use the luminosity function of LMXBs of Gilfanov (2004) and assume a power-law spectrum with slope of $\Gamma = 1.56$ as average LMXB spectrum (Irwin et al. 2003), we find that LMXBs in the luminosity range of $(2 - 6) \cdot 10^{35} \text{ erg s}^{-1}$ contribute $L_X/L_K \sim 3 \cdot 10^{26} \text{ erg s}^{-1} L_{K,\odot}^{-1}$, which may account only for $\sim 1/4$ of the scatter. Further contribution to the observed difference in L_X/L_K ratios may be made by the difference in star-formation history of different regions. This may be an interesting topic on its own, but it is beyond the scope of this paper.

3.4 Emission from the 10-kpc star-forming ring

Surface brightness profiles suggest that there may be additional emission component associated with spiral arms and the 10-kpc star-forming ring. In order to study this further, we consider X-ray emission along the 10-kpc star-forming ring of the galaxy and

Table 3. X-ray to K-band luminosity ratios for different regions of M31 and for M32.

Region	L_K ($L_{K,\odot}$)	$L_{0.5-2keV}$ (erg s^{-1})	$L_{2-10keV}$ (erg s^{-1})	$L_{0.5-2keV}/L_K$ ($\text{erg s}^{-1} L_{K,\odot}^{-1}$)	$L_{2-10keV}/L_K$ ($\text{erg s}^{-1} L_{K,\odot}^{-1}$)
Inner bulge	$1.9 \cdot 10^{10}$	$1.7 \cdot 10^{38}$	$8.0 \cdot 10^{37}$	$(8.9 \pm 0.1) \cdot 10^{27}$	$(4.2 \pm 0.1) \cdot 10^{27}$
Outer bulge	$8.2 \cdot 10^9$	$4.1 \cdot 10^{37}$	$2.9 \cdot 10^{37}$	$(5.0 \pm 0.1) \cdot 10^{27}$	$(3.4 \pm 0.1) \cdot 10^{27}$
Disk	$2.1 \cdot 10^9$	$7.6 \cdot 10^{36}$	$9.4 \cdot 10^{36}$	$(3.6 \pm 0.1) \cdot 10^{27}$	$(4.5 \pm 0.2) \cdot 10^{27}$
M32	$8.5 \cdot 10^8$	$3.0 \cdot 10^{36}$	$3.4 \cdot 10^{36}$	$(3.5 \pm 0.1) \cdot 10^{36}$	$(4.0 \pm 0.2) \cdot 10^{36}$

investigate the behavior of the L_X/SFR (star formation rate) ratio. We use *XMM-Newton* data since only they provide good coverage of the star-forming ring with adequate sensitivity. Due to uncertainties in the background subtraction procedure in the hard energy band, we restrict this study to 0.5 – 2 keV range. The X-ray luminosity was computed in the same way as described in Section 3.1. The contribution of unresolved emission associated with old stellar population was removed based on the near-infrared luminosity of studied regions and using the L_X/L_K ratio of the disk of M31. The remaining X-ray emission is 25 – 50 per cent of of the original value. The star-formation rate was determined based from 160 μm image of the galaxy provided by *Spitzer*. The background level for the latter was determined from a combination of nearby blank sky fields. The star-formation rate was computed from the 160 μm flux using the infrared spectral fits from Gordon et al. (2006) and calibration of Kennicutt (1998). This resulted to a conversion coefficient of $\text{SFR} = 9.5 \cdot 10^{-5} F_{160\mu\text{m}}/Jy M_{\odot}\text{yr}^{-1}$ for the distance of M31.

The behavior of X/SFR ratio along the 10-kpc star-forming ring is shown in Fig. 6. It is the largest in the bins centered at the position angle of $\approx 90^\circ$ and $\approx 270^\circ$ corresponding to the minor axis of the galaxy. These bins are contaminated by the gas emission as it is obvious from the minor axis soft band profile shown in Fig.3. On the other hand, no excess X-ray emission above the level corresponding to the L_X/L_K ratio for the disk was detected in the northern (the position angle of $\sim 10^\circ$) and southern ($\sim 215^\circ$) parts of the ring. In order to indicate the level of possible systematic uncertainties (the statistical errors are much smaller) we show the level corresponding to 20 per cent of X-ray emission associated with the old stellar population by upper limit signs. Apart from these bins, Fig. 6 clearly demonstrates presence of the excess unresolved emission approximately correlated with the far-infrared luminosity with X/SFR values in the range $(0.9 - 1.8) \cdot 10^{38}$ (erg s^{-1})/(M_{\odot}/yr). This emission presumably arises from a multitude of unresolved sources associated with star-formation, such as young stellar objects (protostars and pre-main-sequence stars), young stars (e.g. Koyama et al. 1996), low luminosity Be X-ray binaries. Contribution of supernova remnants and hot X-ray emitting gas may also play a role. The origin of observed variations in the X/SFR ratio is not entirely clear. They may be intrinsic, due to the different star-formation history and population age in different parts of the 10-kpc star-forming ring (Shtykovskiy & Gilfanov 2007), or may be caused by varying column density which can be as large as few times 10^{21} cm^{-2} (Nieten et al. 2006). The latter possibility may play particular role in disappearing of the X-ray emission at the position angle of $\sim 10^\circ$ and $\sim 215^\circ$. Data in the hard band, unaffected by absorption, could discriminate between these two possibilities. To this end, extensive Chandra observations of the 10-kpc star-forming ring would be instrumental.

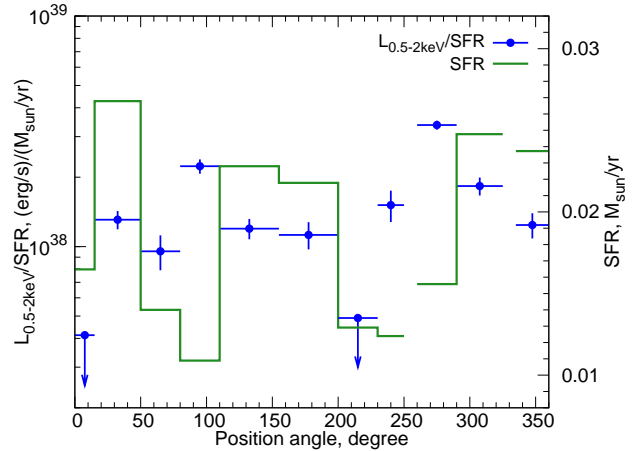


Figure 6. The X/SFR ratio along the 10-kpc star-forming (filled circles with error bars). The position angle increases clockwise and its zero point is at the northern side of the galaxy along its major axis. The bins centered at $\approx 90^\circ$ and $\approx 270^\circ$ approximately correspond to the minor axis of the galaxy. The solid histogram shows the star formation rate in the same regions (right hand y-axis). No X-ray emission above the level defined by the X/K luminosity ratio of the disk was detected in the bins located at $\approx 10^\circ$ and $\approx 215^\circ$. In order to illustrate the amplitude of possible systematic uncertainties, we show by upper limit signs the level, corresponding to 20% of the emission from old population. No X-ray data with sufficient exposure time was available at position angles of $\approx 250^\circ$ and $\approx 330^\circ$.

4 PROGENITORS OF CLASSICAL NOVAE IN M31

4.1 X-ray emission from progenitors of Classical Novae

Classical Novae (CNe) are nuclear explosions occurring upon accumulation of critical mass of hydrogen-rich material on the surface of an accreting white dwarf. The frequency of these events in a galaxy depends on the rate at which matter accretes onto white dwarfs, hence it can be related to their luminosity. Indeed, the accretion energy (bolometric) released between two successive CN outbursts is:

$$\Delta E_{\text{accr}} = \frac{GM_{\text{WD}}\Delta M}{R_{\text{WD}}} \quad (1)$$

where ΔM (M_{WD} , \dot{M}) is the mass of hydrogen-rich material needed to trigger a CN explosion (Yaron et al. 2005), M_{WD} and R_{WD} are the mass and radius of the white dwarf. For parameters believed to be typical for CN progenitors ($M_{\text{WD}} = 1 M_{\odot}$ and $\dot{M} = 10^{-9} M_{\odot}/\text{yr}$) $\Delta M \approx 4.7 \cdot 10^{-5} M_{\odot}$ and total accretion energy released by an accreting WD between two CN explosions is $\Delta E_{\text{accr}} \sim 2 \cdot 10^{46}$ ergs. If the frequency of CN events in a galaxy is ν_{CN} , the total accretion luminosity due to CN progenitors is

$$L_{\text{accr}} = \Delta E_{\text{accr}} \times \nu_{\text{CN}}. \quad (2)$$

Dependence of the accretion luminosity on the mass of the WD and accretion rate is shown in Fig. 7. In computing this curve we used the WD mass-radius relation of Panei et al. (2000) for a zero temperature carbon white dwarf and $\Delta M(M_{WD}, \dot{M})$ dependence from Yaron et al. (2005).

The energy of accretion is radiated in the optical, ultraviolet or X-ray bands, depending on the type of the progenitor system. In magnetic systems (polars and intermediate polars) and dwarf novae in quiescence it is emitted predominantly in the X-ray band. Moreover, their X-ray spectra are relatively hard and their emission is therefore essentially unaffected by the interstellar absorption. X-ray radiation from these objects will contribute to unresolved emission from a galaxy. Therefore, comparing theoretical predictions with the surface brightness of unresolved emission one can constrain their contribution to the observed CN rate in galaxies. Derivation of such upper limits based on M31 data is the goal of this section.

4.2 Classical Novae, resolved X-ray sources and unresolved emission in the bulge of M31

The CN frequency in the bulge of M31 is 25 ± 4 (Shafer & Irby 2001) (see also Arp 1956). The number of progenitors required to maintain this rate is:

$$N \sim \frac{\Delta M}{\dot{M}} \nu_{CN}$$

Typical CN progenitors have accretion rate in the range of $\sim 10^{-10} - 10^{-8} M_{\odot}/\text{yr}$ (Puebla et al. 2007) and WD masses of $0.65 - 1 M_{\odot}$ (Ritter & Kolb 2003). Correspondingly, the number of CN progenitors is in the range of $\sim 2 \cdot 10^3 - 2 \cdot 10^6$, where the smaller number corresponds to the more massive white dwarfs and larger accretion rates. This exceeds significantly the number of bright resolved sources in the bulge of M31, ~ 300 . The latter is dominated by low-mass X-ray binaries – these being excluded, the number of potential bright CN progenitors is yet smaller. We therefore conclude that the majority of CN progenitors can not be among bright point sources; rather, they are a part of the unresolved X-ray emission.

To measure the latter, we define the bulge as an elliptical region with $12'$ major axis, with axis ratio of 0.47 and with position angle of 45° . The total K-band luminosity of the studied region is $L_K = 4.2 \cdot 10^{10} L_{\odot}$. We use *Chandra* data, described in the previous sections, to obtain the unresolved X-ray luminosity in the 2–10 keV energy range. The advantage of this energy band is that it is not polluted by hot ionized gas (Section 3.2). We find a total luminosity of the unresolved component of $L_{2-10\text{keV}} = (1.6 \pm 0.1) \cdot 10^{38} \text{ erg s}^{-1}$ in this region. Obviously, this value presents only an upper limit on the luminosity from the population of accreting white dwarfs, as other type of X-ray emitting sources may also contribute. To this end we use results of Sazonov et al. (2006), who studied the population of faint X-ray sources in the Solar neighborhood and found that accreting WDs contribute $\sim 1/3$ of the total luminosity in the 2–10 keV band. As M31 demonstrates similar X/K ratio, we extrapolate this result to the bulge of M31 and estimate the luminosity of CVs of $L_{CV,2-10\text{keV}} = (5.7 \pm 0.3) \cdot 10^{37} \text{ erg s}^{-1}$.

4.3 Magnetic cataclysmic variables

4.3.1 Upper limit on the contribution of magnetic systems to the CN rate

Polars (AM Her systems) and intermediate polars (IPs) are accreting binary systems in which the accretion disk is partly (IPs)

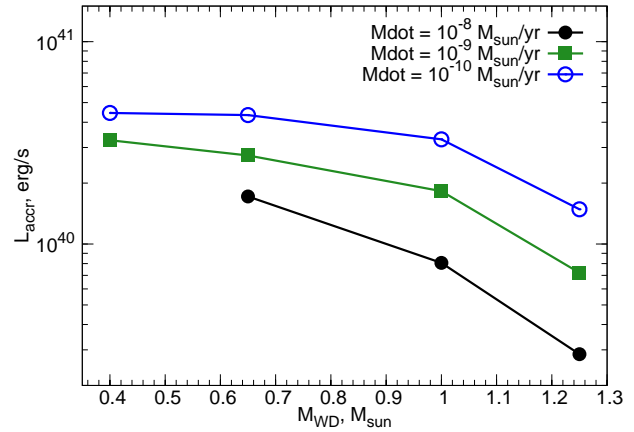


Figure 7. The bolometric luminosity of accreting WDs – progenitors of Classical Novae in a galaxy with CN rate of $\nu_{CN} = 25$ per year. The curves show dependence of L_{accr} on the WD mass for several values of the mass accretion rate.

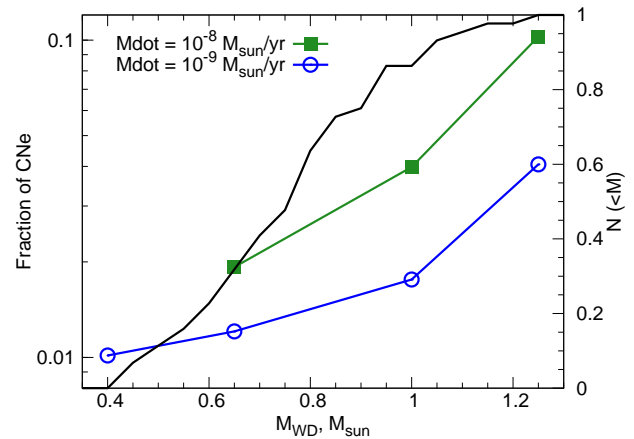


Figure 8. The upper limit of the contribution of magnetic systems to the CN frequency. The filled squares (green in the color version of this plot) correspond to an accretion rate of $10^{-8} M_{\odot}/\text{yr}$, while the empty circles (blue) assumes an accretion rate of $10^{-9} M_{\odot}/\text{yr}$. The solid line (black) shows the cumulative distribution of white dwarf masses in magnetic CVs (right hand y-axis), see text for references. Note, that 85 per cent of white dwarfs are less massive than $1 M_{\odot}$.

or entirely (AM Her systems) disrupted by magnetic field of the white dwarf. These systems are sources of relatively hard X-ray emission produced via optically-thin bremsstrahlung in an accretion shock near the WD surface. They also may have a prominent soft component generated by the WD surface illuminated by hard X-rays. Theory predicts (Lamb & Masters 1979; King & Lasota 1979) and observations confirm (Ramsay & Cropper 2004) that the soft component account for $\sim 1/2$ of the total accretion luminosity of polars. Intermediate polars may also have a soft component in their spectra of somewhat smaller luminosity, $\sim 1/3$ of the total (Evans & Hellier 2007). Correspondingly, we assume in the following calculations, that $1/2$ of the accretion luminosity of magnetic CVs is emitted in the hard X-ray component. To the first approximation, the bremsstrahlung temperature of this component is defined by the depth of the gravitational component on the WD surface, the observed values showing considerable dispersion. For a large sample of magnetic WDs (Landi et al.

Table 4. The list of magnetic and non-magnetic Galactic CNe, classification is taken from Ritter & Kolb (2003) unless otherwise noted.

Name	CV classification	Distance, pc
V603 Aql	SH	400 ^a
V1425 Aql	NL	2700 ^b
OY Ara	SW	1500 ^a
RS Car	SH	2100 ^a
V842 Cen	NL	500 ^a
RR Cha	SH	6100 ^a
V1500 Cyg	AM*	1300 ^a
V1974 Cyg	SH	1700 ^a
V2275 Cyg	IP	5500 ^c
V2467 Cyg	NL	3100 ^d
DM Gem	SW	4700 ^a
DQ Her	DQ	525 ^e
V446 Her	DN	1300 ^a
V533 Her	DQ	1300 ^a
DK Lac	VY	3900 ^a
BT Mon	SW	1000 ^a
GI Mon	IP	4600 ^a
GQ Mus	AM	5100 ^a
GK Per	DN	500 ^a
V Per	NL	1000 ^a
RR Pic	SW	500 ^a
CP Pup	SH	900 ^a
HZ Pup	NL	5800 ^a
V597 Pup	IP*	10300 ^f
T Pyx	SS	2500 ^a
V697 Sco	IP	16100 ^a
V373 Sct	IP	4600 ^a
WY Sge	DN	2000 ^a
V630 Sgr	SH	600 ^a
V1017 Sgr	DN	2600 ^a
V4633 Sgr	AM*	9000 ^g
V4745 Sgr	IP	14000 ^h

* The classification for V1500 Cyg, V597 Pup and V4633 Sgr was taken from Stockman et al. (1988) Warner & Woudt (2009) and Lipkin et al. (2001), respectively.

References are from: ^a Shafter (1997) – ^b Kamath et al. (1997) – ^c Kiss et al. (2002) – ^d Poggiani (2009) – ^e Vaytet et al. (2007) – ^f Naik et al. (2009) – ^g Lipkin et al. (2001) – ^h Csák et al. (2005)

2009; Brunschweiler et al. 2009) we calculate the average value of $kT \approx 23$ keV with the standard deviation of ≈ 9 keV. In the following calculations we assume $kT = 23$ keV and ignore the dependence of the temperature on the WD mass. As demonstrated below this particular choice does not influence our results significantly.

In order to constrain the contribution of magnetic CVs to the CN frequency we compute their predicted X-ray luminosity assuming that CNe are exclusively produced in such systems. In this calculation we assume that the presence of strong magnetic fields does not influence the characteristics of nuclear burning and results of Yaron et al. (2005) for the mass of the hydrogen layer $\Delta M(\dot{M}, M_{WD})$ apply. In particular, we used the $\Delta M(\dot{M}, M_{WD})$ values for the WD temperature of $T_{WD} = 10^7$ K (Townsend & Bildsten 2004). The total accretion luminosity predicted by equation (2) is halved (see above), corrected for interstellar absorption, and converted into the 2–10 keV energy band. The obtained value is then compared with the observed luminosity of the unresolved emission, corrected for the contribution of accreting WDs, as described before. The upper limit on the contribution of magnetic systems in the CN rate in M31 is shown in Fig.8. It shows that allowing all possible values of the WD mass, no more than ≈ 10 per cent of CNe

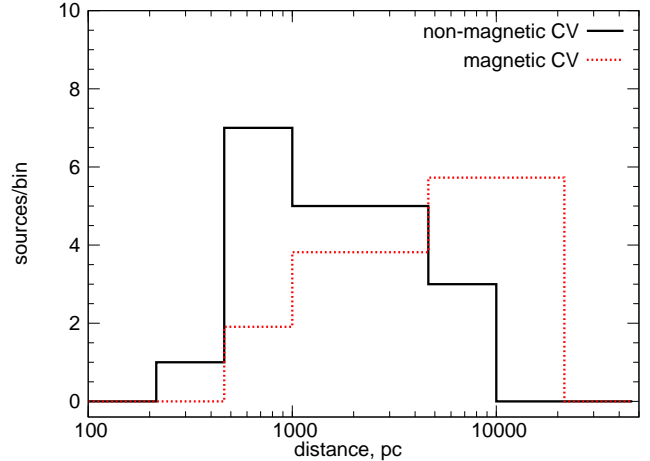


Figure 9. The distance distribution for CNe arising from magnetic and non-magnetic CVs. The total number of magnetic systems is normalized by 1.9 to match the number of non-magnetic ones. The data, used to produce this plot, is given in Table 4.

can be produced in magnetic systems. The less constraining value of the upper limit corresponds to the largest accretion rate and most massive WDs. However, the combination of these extreme parameters is not typical for magnetic CVs as illustrated by the cumulative distribution of the WD mass in magnetic systems (Ritter & Kolb 2003; Suleimanov et al. 2005; Brunschweiler et al. 2009). The distribution shows that ≈ 85 per cent of white dwarfs are less massive than $1 M_{\odot}$. Furthermore the average accretion rate in these systems is fairly low, $\dot{M} \sim 1.8 \cdot 10^{-9} M_{\odot}/\text{yr}$ (Suleimanov et al. 2005). We conclude therefore that a more realistic upper limit should be ≈ 3 per cent, corresponding to $M_{WD} = 1 M_{\odot}$ and $\dot{M} = 10^{-9} M_{\odot}/\text{yr}$.

This result weakly depends on the assumed temperature of bremsstrahlung spectrum. If $kT = 40$ keV is assumed, the upper limit becomes ≈ 4 per cent. Only unrealistically large temperature of $kT = 75$ keV would lead to a two times larger upper limit.

4.3.2 Comparison with statistics of observed CNe from magnetic systems

Ritter & Kolb (2003) find that $\sim 1/3$ of CNe, with known progenitors, are produced in CVs possessing a magnetic white dwarf (Table 4). Although this catalogue is not complete neither in the volume nor in the brightness limited sense, the ~ 10 times discrepancy appears to be too large to be consistent with our upper limit of ≈ 3 per cent. In another study, Araujo-Betancor (2005) investigated the space density of magnetic and non-magnetic CVs, and obtained that ~ 22 per cent of all CVs are magnetic. This number also seems to be in conflict with our upper limits. As demonstrated below, these two discrepancies are caused by the single reason – by an order of magnitude difference in mass accretion rate between magnetic and non-magnetic system.

Indeed, the average accretion rate in magnetic CVs is $\sim 1.8 \cdot 10^{-9} M_{\odot}/\text{yr}$ (Suleimanov et al. 2005), whereas for non-magnetic CNe it is $\sim 1.3 \cdot 10^{-8} M_{\odot}/\text{yr}$ (Puebla et al. 2007). The obvious consequence of this difference is that in magnetic systems it takes longer to accrete the same amount of material needed to trigger the nova explosion. Moreover, at lower accretion rates ΔM is larger by a factor of $\sim 1.5 - 2$ (Yaron et al. 2005). The consequence of these effects is that magnetic CVs undergo CN outburst $\sim 10 - 20$ times less frequently. This explains the second discrepancy – be-

tween the observed fraction of magnetic CVs and our upper limit on their contribution to the CN frequency.

Another consequence of the smaller accretion rate is that CN explosions are brighter in magnetic systems, therefore they can be observed at larger distances and are sampled from larger volume than CNe from non-magnetic progenitors. This explains the first discrepancy – seemingly too large fraction of CN events which progenitors are magnetic systems. To verify this, we selected CNe with known progenitors from the catalogue of Ritter & Kolb (2003) and searched for distances in the literature. In total, we collected 32 CNe, of which 11 are from magnetic progenitors (Table 4). Their distance distributions are shown in Fig. 9. Obviously, magnetic systems are located at larger distances: the average distance is ≈ 6.6 kpc and ≈ 2.2 kpc for magnetic and non-magnetic CNe. Below 1 kpc almost four times more non-magnetic CNe are observed (the normalized number of magnetic systems is ≈ 1.9 and 8 for non-magnetic), whereas above ≈ 5 kpc there are more magnetic CVs (≈ 11.4 vs 3). The difference between two distributions is statistically significant, with the K-S probability of ≈ 0.008 .

The difference in the distance can be compared with the prediction based on the expected brightness at the maximum of the lightcurve. Calculations of Yaron et al. (2005) show that for $0.65 M_{\odot}$ WD the maximum brightness achieved during the CN explosion will differ by ≈ 1 magnitude, the difference being smaller for a more massive WD. Taken at the face value, this would suggest the distance difference of ~ 1.6 which is smaller than the observed difference in average distance by a factor of ~ 3 . Given the crudeness of this calculation, we conclude that these two numbers are broadly consistent with each other.

4.4 Dwarf novae

Dwarf novae (DNe) are a subclass of CVs showing frequent quasi-periodic outbursts due to thermal-viscous instability of the accretion disk (Osaki 1974; Hoshi 1979). In quiescence they become sources of relatively hard X-ray emission from the optically thin boundary layer, whereas in outburst state the optically thick accretion disk emits predominantly in the ultraviolet and soft X-ray bands. One of the models used to describe the emission spectra in quiescence states is a cooling flow model (e.g. Mukai et al. 2003). Spectral analysis of a large number of quiescence spectra showed a relatively large dispersion in the value of the initial temperature $kT_{max} \sim 8 - 55$ keV with the average value of 23 keV (Pandel et al. 2005). This value is assumed in the calculations performed in this section. It is also assumed, that only half of the accretion energy is emitted in the boundary layer.

Dwarf Novae give rise to CNe. On the other hand, in the quiescence state they may contribute to the unresolved emission. In the outburst state, to the opposite, soft emission is largely hidden because of the interstellar absorption. Therefore the bimodal spectral behavior of dwarf novae can be used to constrain the fraction of mass which is accreted in quiescence, similar to how the upper limit on the contribution of magnetic systems was obtained. Using same approach we calculate the X-ray luminosity in the quiescence state assuming that dwarf novae are responsible for a $\sim 1/2$ of CN events (the other half is due to nova-like variables, Ritter & Kolb (2003)). With this value one can put an upper limit on the fraction of mass, accreted during quiescence. The result of this calculation is shown in Fig. 10. As in the case of magnetic systems, the absolute upper limit is ~ 10 per cent. However, the WD mass in DNe typically does not exceed $\approx 0.9 M_{\odot}$ and the mass accretion rate is not much larger than $\approx 10^{-8} M_{\odot}/\text{yr}$, therefore the realistic upper

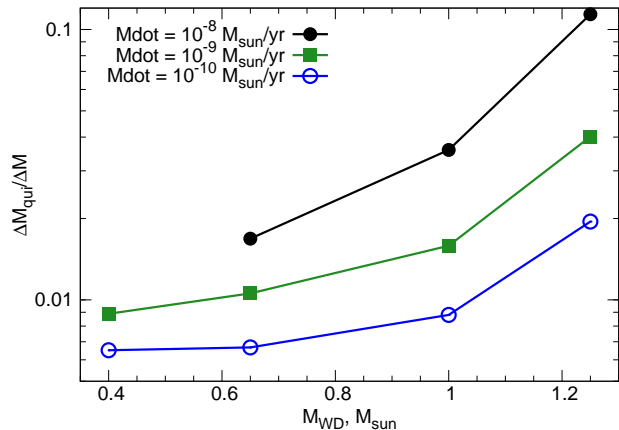


Figure 10. The fraction of mass accreted in quiescence as a function of white dwarf mass. Different mass accretion rates were assumed, the filled circles (black) correspond to $10^{-8} M_{\odot}/\text{yr}$, the filled boxes (green) represent $10^{-9} M_{\odot}/\text{yr}$, whereas the empty circles (blue) stand for $10^{-10} M_{\odot}/\text{yr}$.

limit is ≈ 3 per cent. As before, this result is not strongly sensitive to the choice of kT_{max} parameter of the cooling flow model. Assuming $kT_{max} = 55$ keV our upper limits would increase by $\approx 1/7$ of their value.

Using this upper limit, the enhancement factor of the accretion rate in outburst state can be inferred. Obviously, this quantity depends on the fraction of time spent in the outburst. Since for majority of DNe it is smaller than $\sim 1/5$ (Wils et al. 2009), the accretion rate increases by $\sim 30 - 1000$ during outburst. This conclusion is consistent with observations of dwarf nova. Indeed, one of the best studied dwarf nova, SS Cyg, spends ~ 75 per cent of the time in quiescence (Cannizzo & Mattei 1992). The accretion rate varies from $5 \cdot 10^{-11} M_{\odot}/\text{yr}$ in quiescence (Urban & Sion 2006) to $3.2 \cdot 10^{-9} M_{\odot}/\text{yr}$ in outburst (Hamilton et al. 2007), hence the enhancement factor is 64 and ≈ 95 per cent of the material is accreted in outburst periods, in good agreement with our results.

4.5 Generalization of the results

Although we considered only the bulge of M31, our results can be generalized to other early-type galaxies.

The X-ray to K-band luminosity ratio in early-type galaxies, galaxy bulges, and in the Milky is in good agreement in the 2 – 10 keV band (Revnivtsev et al. 2006; Sazonov et al. 2006; Revnivtsev et al. 2007, present work). On the other hand, for a sample of early type galaxies, including M31, Williams & Shafer (2004). obtained fairly uniform values of the luminosity specific nova rate (ν_K), in the range of $(1.8-2.7) \cdot 10^{-10} L_{\odot,K} \text{ yr}^{-1}$. In apparent contradiction with this, we obtain $\nu_K = (6.0 \pm 1.0) \cdot 10^{-10} L_{\odot,K} \text{ yr}^{-1}$ for the bulge of M31, based on its CN frequency and K-band luminosity. However, Williams & Shafer (2004) computed the K-band luminosity from (B–K) colour and B-band luminosity of the galaxy, which in case of M31 results in by a factor of ~ 3 larger K-band luminosity than the 2MASS value, and by a factor of ~ 2 larger than deduced from the Spitzer data (Williams & Shafer 2004). With this correction, our value for the K-band specific CN rate for the bulge of M31 corresponds to $\nu_K = (3.0 \pm 0.5) \cdot 10^{-10} L_{\odot,K} \text{ yr}^{-1}$, which is in a good agreement with other galaxies.

As both X/K ratio and ν_K are similar, our conclusions hold for other early type galaxies.

5 CONCLUSION

We studied unresolved X-ray emission from the bulge and disk of M31 using publicly available *XMM-Newton* and *Chandra* data. The *XMM-Newton* survey of M31 covered the entire galaxy with the total exposure time of ≈ 639 ks after filtering. *Chandra* data covered the bulge and the southern part of the disk, with the exposure time of the filtered data of ≈ 222 ks.

We demonstrated that unresolved X-ray emission, associated with the bulge of the galaxy, extends into the disk with similar X-ray to K-band luminosity ratio. We obtained $L_X/L_K = (3.4 - 4.5) \cdot 10^{27} \text{ erg s}^{-1} L_\odot^{-1}$ in the 2 – 10 keV band for all studied regions in the bulge and the disk of M31, which is in good agreement with those obtained for the Milky Way and for M32. This suggests that the unresolved X-ray emission in M31 may have similar origin to the Galactic ridge X-ray emission, namely it is a superposition of a large number of faint compact sources, such as accreting white dwarfs and coronally active binaries.

We investigated X-ray emission associated with the 10-kpc star-forming ring based on *XMM-Newton* data. We characterized this emission with L_X/SFR ratio, where L_X is calculated for the 0.5 – 2 keV energy range. We found that its value is spatially variable. After excluding the two regions along the minor axis of the galaxy, which are likely contaminated by the hot gas outflow, we obtained values ranging from zero to $L_X/\text{SFR} = 1.8 \cdot 10^{38} \text{ (erg s}^{-1}\text{)}/(M_\odot/\text{yr})$. The origin of these variations remains unclear.

We derived constraints on the nature of Classical Nova progenitors based on the brightness of unresolved emission. We demonstrated that magnetic CVs – polars and intermediate polars, do not contribute more than ~ 3 per cent to the observed CN frequency, assuming values of parameters most likely for the CN progenitors, the absolute upper limit being ≈ 10 per cent. We also showed that in dwarf novae $\gtrsim 90 - 95$ per cent of the material is accreted during outbursts, and only a small fraction during quiescent periods.

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