

The central region of M 31 observed with *XMM-Newton*^{*}

II. Variability of the individual sources

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Abstract. We present the results of a study of the variability of X-ray sources in the central 30′ of the nearby Andromeda Galaxy (M 31) based on *XMM-Newton* Performance Verification observations. Two observations of this field, with a total exposure time of about 50 ks, were performed in June and December of 2000. We found 116 sources brighter than a limiting luminosity of 6×10^{35} erg s⁻¹ (0.3–12 keV, $d = 760$ kpc). For the ~ 60 brightest sources, we searched for periodic and non-periodic variability; at least 15% of these sources appear to be variable on a time scale of several months. We discovered a new bright transient source $\sim 2.9'$ from the nucleus in the June observation; this source faded significantly and was no longer detected in December. The behaviour of the object is similar to a handful of Galactic LMXB transients, most of which are supposed to harbor black holes. We detected pulsations with a period of ~ 865 s from a source with a supersoft spectrum. The flux of this source decreased significantly between the two *XMM* observations. The detected period is unusually short and points to a rapidly spinning magnetized white dwarf. The high luminosity and transient nature of the source suggest its possible identification with classical or symbiotic nova, some of which were observed earlier as supersoft sources.

Key words. galaxies: individual: M 31 – galaxies: spiral – galaxies: general – X-rays: galaxies

1. Introduction

At a distance of 760 kpc (van den Bergh 2000; adopted throughout this paper), M 31 is close enough to allow detailed study of individual sources within the galaxy using modern X-ray telescopes. Over 100 discrete X-ray sources in M 31 were detected with the *Einstein* observatory (Trinchieri & Fabbiano 1991, hereafter TF; van Speybroeck et al. 1979). Primini et al. (1993, hereafter PFJ) reported on the detection of 86 X-ray sources in the central 34′ of M 31 with the *ROSAT* HRI. Supper et al. (2001, hereafter Su01) recently published the complete catalog of 560 sources detected in a ~ 10.7 deg²

survey of M 31 with the *ROSAT*/PSPC¹. From the extrapolation of the luminosity distribution, PFJ concluded that the detected population of X-ray sources could account for only ~ 15 – 26% of the unresolved X-ray emission in M 31, suggesting that the remaining emission is truly diffuse or due to a new class of X-ray sources. Spectral analysis of *ROSAT* data performed by Borozdin & Priedhorsky (2000) and observations with *XMM* (Shirey et al. 2001, hereafter Paper I) and *Chandra* (Garcia et al. 2001) showed that the unresolved X-ray emission in the bulge of M 31 is significantly softer than most of the point sources and can be approximated with an optically-thin thermal plasma model ($kT \sim 0.3$ keV) as expected from truly diffuse emission.

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¹ This is an extension of the previously published catalog of 396 sources (Supper et al. 1997, Su97).

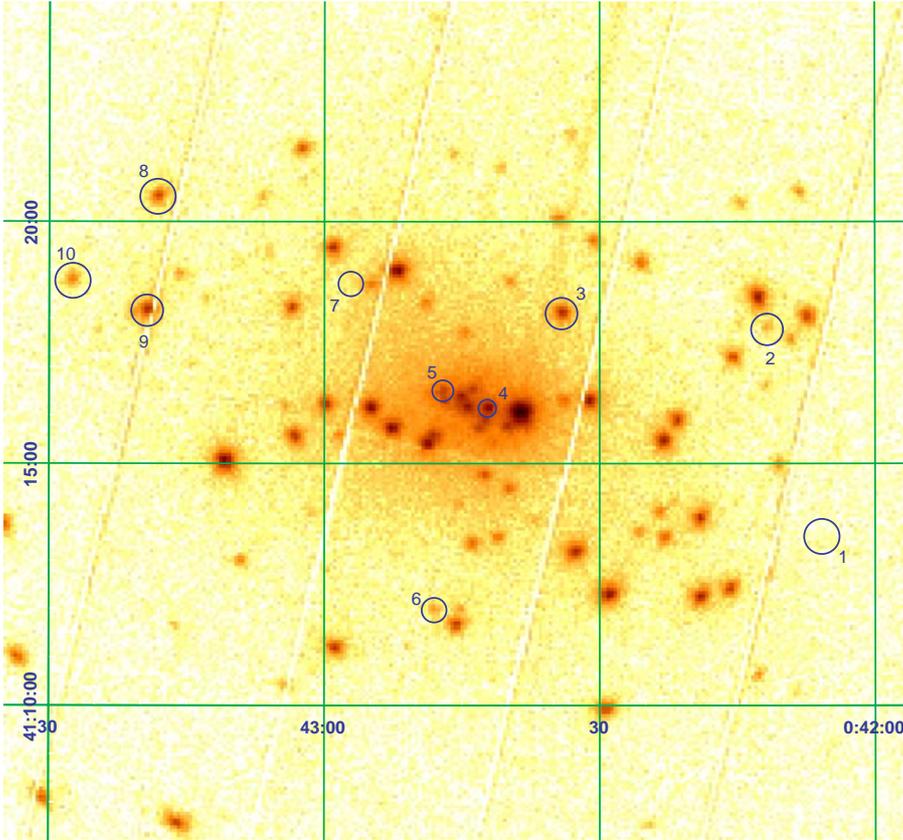


Fig. 1. The 0.3–10 keV EPIC PN image of the central region of M 31. The data are from the 31-ks exposure taken on June 25, 2000. The intensity of the color is proportional to the logarithm of the number of counts collected (with a maximum of 5000 counts). PN chip boundaries are clearly visible. The positions of ten variable sources are encircled and labelled with the numbers listed in Table 2.

Table 1. *XMM-Newton* PV observations of the core of M 31.

Date & Time (UTC)	Rev	Obs. ID	Exp. (ks)
25/6/2000 (10:44–20:25)	100	0112570401	34.8 ^a /30.7 ^b
28/12/2000 (0:10–3:34)	193	0112570601	12.2 ^a /9.8 ^b

^a For EPIC-MOS.

^b For EPIC-PN.

In the first *Chandra* observation of M 31, the nuclear source seen with *Einstein* and *ROSAT* was resolved into five sources (Garcia et al. 2000, hereafter G2000). One of these sources is located within 1'' of the radio nucleus of M 31 and exhibits an unusually soft X-ray spectrum, suggesting that it may be associated with the central supermassive black hole. A few more pairs of previously unresolved sources and a new transient were also detected within 30'' of the nucleus.

We report on observations of the Andromeda Galaxy (M 31) carried out with *XMM-Newton* (Jansen et al. 2001) during its Performance Verification (PV) phase. M 31 was selected as an *XMM* PV target in order to demonstrate the capabilities of the mission in performing spectral and timing studies in a field of point sources and extended emission. In Paper I we focused on the group properties of the X-ray point sources and on the diffuse emission. The spectral properties of discrete X-ray sources in the *XMM-Newton* exposures will be discussed in Trudolyubov et al. (2001, Paper III). In this present

paper we discuss the variability of individual X-ray sources in M 31. In Sect. 2, we summarize the *XMM-Newton* observations and our data-reduction process. In Sect. 3, we discuss our detections of transient and periodic variability in individual sources. Finally, we present our conclusions.

2. observations

The bulge of M 31 was observed with *XMM-Newton* on June 25, 2000 and again on Dec. 28, 2000 (see Table 1). The observations were centered on the core of M 31 ($\alpha = 00^{\text{h}}42^{\text{m}}43^{\text{s}}.0$, $\delta = +41^{\circ}15'46.0''$ J2000), with a field of view of 30' in diameter for the three European Photon Imaging Camera (EPIC) instruments. The two EPIC MOS instruments (Turner et al. 2001) and the EPIC PN (Strüder et al. 2001) operated in full-window mode with the medium optical blocking filter. The Optical/UV Monitor Telescope (OM; Mason et al. 2001) filter wheel was set to the blocked position during the June observation. During the December observation, exposures were obtained with the *B* and *UVW1* filter of the OM; results of these observations will be presented elsewhere.

A background flare occurred during the final 5 ks of the EPIC exposures from the June observation. Data obtained during this background flare were excluded from the variability studies.

We used the *XMM-Newton* Science Analysis System (versions 4.1 and 5.0.1) to reduce the EPIC data to calibrated event lists, produce images, and extract light

Table 2. Bright variable X-ray sources detected in M 31 with *XMM-Newton* in 2000.

#	Source name ^a	$\alpha(2000)$	$\delta(2000)$	F_{Jun}^b	F_{Dec}^b	Comments ^c
1	XR J004205.9+411329	00:42:05.9	41:13:29	<2.7	12.6 ± 2.6	PFJ#3
2	XR J004212.3+411800	00:42:12.3	41:18:00	1.8 ± 1.3^d	17.5 ± 4.1	TF#14, PFJ#8
3	XMMU J004234.1+411808	00:42:34.1	41:18:08	27.9 ± 1.7	<6.4	<i>XMM</i> X-ray nova (Sect. 3.1)
4	CXO J004242.0+411608	00:42:42.2	41:16:09	58.1 ± 2.1	45.6 ± 3.0	<i>Chandra</i> transient (G2000 and Sect. 3.2)
5	RX J0042.7+4116	00:42:47.2	41:16:28	9.5 ± 1.3	94.0 ± 3.6	TF#59, PFJ#50, Su97#198, Su01#195
6	XMMU J004247.5+411158	00:42:47.5	41:11:58	4.0 ± 1.3	<3.0	
7	CXOU J004257.1+411843	00:42:57.1	41:18:43	<2.0	6.3 ± 2.2	seen on Oct. 13, 1999 with <i>Chandra</i>
8	RX J0043.3+4120	00:43:18.9	41:20:19	23.4 ± 1.3^e	2.5 ± 1.4^e	SSS ^f , TF#87, Su97#235, Su01#235
9	XMMU J004319.4+411759	00:43:19.4	41:17:59	$43.6 \pm 1.7^{e,g}$	<5.1 ^{e,h}	SSS ^f , 865-s pulsations (Sect. 3.3)
10	RX J0043.4+4118	00:43:27.9	41:18:35	8.6 ± 0.8^e	6.5 ± 1.5^e	SSS ^f , TF#89, PFJ#80, Su97#240, Su01#241, SNR

^a The names for *ROSAT* and *Einstein* sources were adopted from Su01. If the source had not been found in Su01, we used the acronym XR followed with truncated *XMM* coordinates. The sources seen first with *Chandra* or *XMM* are named according to the naming conventions for these missions.

^b Source count rates for the *XMM-Newton* observations in June and December of 2000 are given in units of 10^{-3} counts/s (MOS1) and are corrected for vignetting. Quoted count rates are measured in the 0.3–10 keV energy range, except for supersoft sources (SSS), which are measured in the 0.3–1.5 keV band. In cases when sources are not detected, 2σ upper limits are listed.

^c References to the earlier observations: TF = Trinchieri & Fabbiano (1991); PFJ = Primini et al. (1993); Su97 = Supper et al. (1997); Su01 = Supper et al. (2001); G2000 = Garcia et al. (2000).

^d Source near the chip edge; the detected count rate might be an underestimation of real count rate.

^e Source count rates for 0.3–1.5 keV band.

^f Supersoft source.

^g With contribution from a nearby faint source.

^h Upper limit is defined by the contribution of a nearby source.

curves. A combination of SAS programs and external software was applied to further analyze the data. The data from MOS1, MOS2 and PN were extensively compared to confirm the consistency of our results. The variability of individual sources within the longest (June) observation was studied by Fourier analysis. The value of the pulsation period detected in one of the supersoft sources (see below) was refined by the epoch-folding method.

3. Individual X-ray sources

The EPIC images of the central 30' of M 31 (Fig. 1 represents part of EPIC PN image) contain more than 100 discrete X-ray sources as well as unresolved emission near the centre (see Paper I for more details). The detections include sources seen with *Einstein*, *ROSAT*, or *Chandra* (TF, PFJ, Su97, Su01, G2000) as well as new sources. The transient source discovered by *Chandra* (G2000) is clearly seen in both *XMM-Newton* observations (Sect. 3.2). In the June observation, there is a bright new transient which was not seen previously (Sect. 3.1). Several other bright sources demonstrated significant variability on half of a year time scale, so that uncertainties of count rate measurements do not overlap for the two observations. We have analyzed 66 sources with limiting

count rate² 4 counts/ks and found 10 variables. These sources are listed in Table 2 along with their *XMM* positions, June and December count rates in MOS1, and any relevant identifications (though only count rates in MOS1 are cited, we selected the sources based on the data from all three *XMM-Newton* instruments). The source positions were derived from comparison with *Chandra* calibrated images of the central region of M 31. The estimated positional error of 1''–3'' (in diameter) depends on the distance of the source from the boresight axis, its intensity and nearby sources. We estimate 3'' as a conservative error limit for the *XMM* positions presented in this paper.

Taking into account the total number of sufficiently bright detected sources, we conclude that at least $\sim 15\%$ of all sources in the central field of M 31 are variable on a time scale of several months. We believe, however, that this value should be considered a lower limit, because the sensitivity of our analysis was a function of the source flux, and the variability of many of the fainter sources would not be detected. Below we discuss in more detail several individual variable sources in M 31.

² Some of the sufficiently bright sources were excluded from our analysis because of the confusion with nearby sources or because they were too close to the chip edge.

3.1. X-ray Nova in M 31

We found a new bright X-ray source in EPIC PN and EPIC MOS images from the June observation. The coordinates of the new source are presented in Table 2. The source was neither detected in previous *Einstein* and *ROSAT* observations nor has been reported from *Chandra* observations. During the June observations the flux from the source was $(1.57 \pm 0.09) \times 10^{-13}$ erg s $^{-1}$ cm $^{-2}$ (0.3–10 keV), which corresponds to a luminosity of $\sim 1.1 \times 10^{37}$ erg s $^{-1}$ in the cited energy band assuming a power-law spectrum (see Paper III). The source flux faded to below the background level before the next *XMM-Newton* observation of the same field on Dec. 28, 2000. The upper limit for the count rate for this second observation was less than 6.4 counts/ks (2σ upper limit for MOS1). The detected luminosity of the source during the June 25 observation, as well as its several-month time scale to fade to quiescence, is typical for bright X-ray transients in our Galaxy (see reviews by Tanaka & Shibazaki 1996; Chen et al. 1997).

3.2. Chandra transient

A bright transient source designated CXO J004242.0+411608 was discovered with *Chandra* during a 17.5 ks observation of the core of M 31 on Oct. 13, 1999 (G2000). We detected an X-ray source at the same location during both our *XMM-Newton* PV observations. The flux of the source measured on June 25, 2000 was equal to $(5.5 \pm 0.5) \times 10^{-13}$ erg s $^{-1}$ cm $^{-2}$ ($L_x \sim 3.8 \times 10^{37}$ erg s $^{-1}$). The source was detected again on Dec. 28, 2000 with flux of $(4.2 \pm 1.0) \times 10^{-13}$ erg s $^{-1}$ cm $^{-2}$. Including both the *Chandra* and *XMM* detections, the source has remained bright for more than 14 months, with only slight possible fading ($\sim 25\%$) between the two *XMM-Newton* observations separated by half of a year. The X-ray luminosity and spectral shape detected by *XMM-Newton* (Paper III) correspond to those of the hard/low state of Galactic black hole transients (e.g., Tanaka & Lewin 1995). Typically Galactic X-ray transients fade significantly in less than ~ 100 days (see Chen et al. 1997 for a review); however, a long plateau in a hard spectral state was observed from the X-ray transient GRS 1716-249 (Sunyaev et al. 1994; Revnitsev et al. 1998). We should mention that our sampling does not allow us to distinguish reliably between single and repeated outbursts. It will be interesting to follow the evolution of CXO J004242.0+411608 during future planned observations with *XMM-Newton*.

3.3. Supersoft 865-s pulsator

We detected significant oscillations in the X-ray flux from one of the bright variable sources in our field (source #9 in Table 2). The Fourier power density spectra (PDS) from each of the three independent EPIC instruments (Fig. 2)

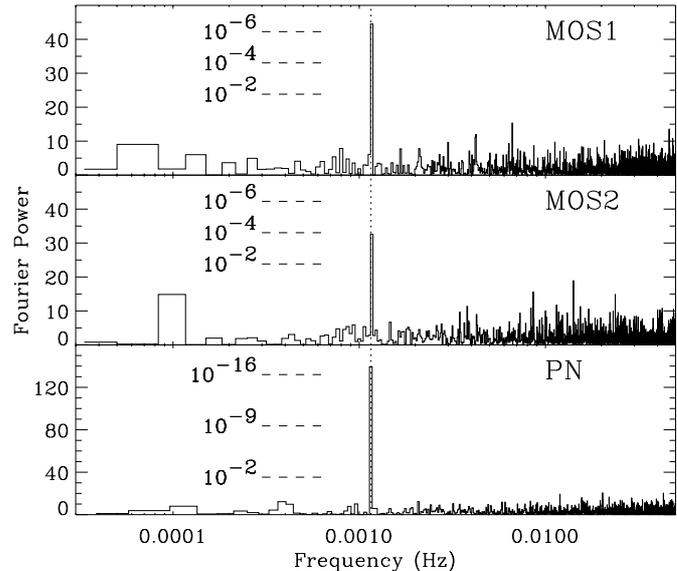


Fig. 2. Power density spectra for a supersoft source in M 31 obtained from each of the three EPIC instruments during the observation on June 25, 2000. The peak power from each of the three instruments occurs at a frequency corresponding to a period of ~ 865 s. The vertical dotted line denotes the best fit value of the period found by the epoch-folding method. Detection thresholds are indicated by horizontal dashed lines labelled with the approximate probability that any of the 1500 or 1300 frequency bins in each PDS (for MOSs and PN respectively; no averaging applied) would have a noise value exceeding the indicated power level (Vaughan et al. 1994).

show a highly significant periodic signal from this source during the June observation, with a best-fit period of 865.5 ± 0.5 s. The folded light curve for this source (Fig. 3) is quasi-sinusoidal with an amplitude of about 40%.

In June 2000 this 865-s pulsator had a spectrum similar to the three sources in the *XMM* field previously identified by Kahabka (1999) as supersoft source (SSS) candidates based on their *ROSAT*/PSPC hardness ratios and luminosities (one was identified with a supernova remnant). The temperature of the blackbody spectral fit was $kT_{\text{bb}} = 61 \pm 2$ eV with reduced $\chi^2 = 1.5$ (for EPIC-MOS data). All four SSSs exhibit blackbody-like spectra with effective temperatures in the range $kT \sim 50$ –150 eV and no detectable X-ray emission above ~ 1.5 keV (see Paper III for more detailed discussion of spectral parameters). Such sources are typically interpreted as accreting white dwarfs in binary systems, powered by nuclear burning of the accreted matter on their surfaces (see Kahabka & van den Heuvel 1997 for a review).

The source count rate during the June 25 observation was equal to 44 counts/ks in the 0.3–1.5 keV energy range (MOS1, see Table 2). By Dec. 28 the source count rate had faded down to a level below 5 counts/ks (MOS1); thus, it was not possible to detect pulsations during the second observation. All three supersoft sources in the NE portion of our field (sources ## 8, 9 and 10) faded between the June and December observations (see Table 2). We are

aware of a possible sensitivity degradation in this region of MOS1; however, the result is confirmed by MOS2 and PN data. In particular, the count rate of the supersoft pulsator as detected by MOS2 dropped down from 41 ± 1.5 counts/ks in June to 3 ± 1.5 counts/ks in December, while many other sources in the field showed no significant variability or became brighter in December.

We note that there is a nearby source ($\alpha = 00^{\text{h}}43^{\text{m}}21^{\text{s}}.2$, $\delta = +41^{\circ}17'52''$, J2000) with a harder spectrum which is much fainter than the supersoft pulsator in the June observation but dominates this region of the sky for the December observation. The distance between two sources is about $10''$, so that they are spatially resolved with *XMM-Newton*, but their counts are not completely spatially separated on the detector. Because the relative flux of the harder source was much lower during the June observation, it did not significantly affect our timing and spectral analysis of the SSS. The *ROSAT*/PSPC would barely be able to resolve the two sources, so *ROSAT*'s RX J0043.3+4117 (Su01#236) may include contributions from both of them, although its position coincides with that of the harder source rather than the SSS pulsator.

The 865.5-s period is the shortest among all known SSSs (Greiner 2000). Interpreted as the binary orbital period, it would be too short to accommodate a main-sequence companion and would suggest a degenerate secondary. It may be more plausible to assume that the pulsations indicate that the white dwarf possesses a magnetic field large enough to modulate the X-ray emission yet not so large that the spin and orbital periods are locked, e.g., as in intermediate polars or DQ Her stars (see review by Cordova 1995). However, the absorbed luminosity of the object $\sim 1.7 \times 10^{37}$ erg s $^{-1}$ (0.3–1.5 keV) is several orders of magnitude higher than typical for intermediate polars luminosity range $L_{\text{X}} = 10^{31}$ – 10^{34} (see e.g. Patterson 1994). The high luminosity and transient nature of the pulsator may indicate steady burning in a post-nova stage, as has been observed in a few classical and symbiotic novae (Kahabka & van den Heuvel 1997). An alternative explanation for the nature of the SSS could be a double degenerate polar similar to RX J1914.4+2456 (Haberl & Motch 1995; Ramsay et al. 2000). An interpretation of the source as a foreground object is unlikely due to the lack of an optical counterpart in Dec. 2000 *XMM* OM images up to the limiting magnitude of ~ 19 in the *B* filter.

3.4. Variability of other sources within a single observation

We have searched for coherent periodic modulation on time scales from ~ 10 to ~ 1000 s for about 60 of the brightest sources in the *XMM-Newton* field of view; however, only in one case (see previous subsection) was significant variability detected. The 90% upper limits to periodic modulation fractions, calculated as the ratio of the sine amplitude to the constant flux level for periods of 10 000,

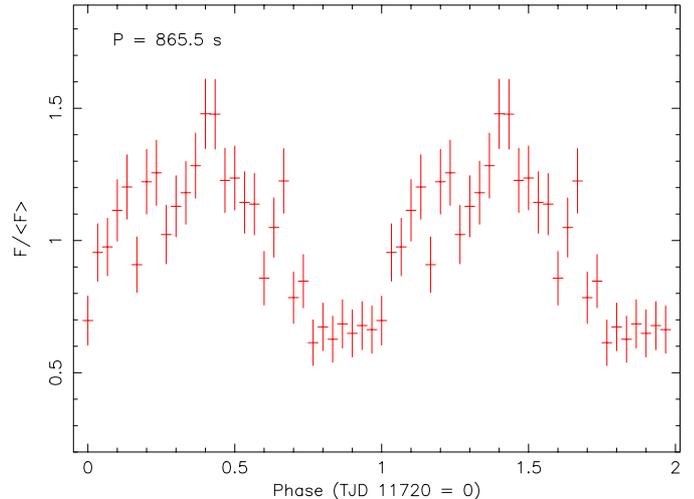


Fig. 3. Light curve of the pulsating supersoft source in M 31, folded using a period of 865.5 s. The data is from the June 25, 2000 observation, and counts from all three EPIC instruments have been used. Contribution of the background is within the error bars.

300, and 10 s were obtained in all other cases. These upper limits vary from 3.6% for the brightest source to $\sim 30\%$ for the faintest sources of the sample.

The lack of detectable variability for many of the individual sources in M 31 may seem surprising compared with rich variability observed from Galactic sources. Our observations so far have included mainly the bulge of M 31, where low-mass X-ray binaries (LMXBs) are most prevalent. Such systems commonly show dips, bursts, and quasi-periodic variability rather than coherent pulsations. We expect to detect more X-ray pulsars during planned *XMM* observations of M 31 in fields along the disk of M 31, where population I stars and high-mass X-ray binaries (HMXBs) dominate. We must note also that the sensitivity to variability depends strongly on the brightness of the source, and hence our data are not very sensitive to the variability of the many faint sources.

We have also looked for non-periodic variations on all accessible timescales for the same set of objects. No X-ray burst has been detected, however our sensitivity to bursts is restricted to a relatively small luminosity interval by the low count rate of most sources and by the Eddington limit.

4. Conclusions

In this paper we present results obtained from *XMM-Newton* PV observations of M 31. Two observations separated by half of a year were carried out in June and December of 2000. This paper is the second paper in the series describing results of these observations.

Significant variability of individual sources was detected both between the two *XMM* observations and in comparison with earlier results of other missions. At least $\sim 15\%$ of the sources appear to be variable, and we consider this value to be a conservative lower limit.

A new bright transient source was detected during the observation of June 25 but faded before the December observation. Probably it is an LMXB transient source, similar to a handful of such sources observed in our Galaxy, most of which are supposed to harbour black holes.

Another transient source, first detected by *Chandra* (G2000), was bright during both *XMM-Newton* observations. The flux of the source did not change significantly in observations separated by six months, which is not typical for Galactic X-ray transients but is reminiscent of the behavior of the black hole candidate GRS 1716-249 during its 1993–1994 outbursts (Sunyaev et al. 1994; Revnivtsev et al. 1998).

X-ray pulsations with period of ~ 865.5 s and quasi-sinusoidal pulse profile were detected from one of the supersoft sources in our field. It was bright during the June observation, but had faded such that it became undetectable in December. The period of the detected pulsations is the shortest among known SSSs. A likely source of the pulsations is a magnetized rapidly spinning white dwarf; however, the luminosity of the source is much higher than for typical CV systems. The detected X-ray flux may be generated by steady nuclear burning in a post-nova stage of a classical or symbiotic nova.

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