The Supersoft X-ray Source in the Globular Cluster M3 (NGC 5272)

Tadayasu Dotani and Kazumi Asai
Institute of Space and Astronautical Science
3-1-1 Yoshino-dai, Sagamihara, Kanagawa 229, Japan
and
Jochen Greiner
Astrophysical Institute Potsdam
An der Sternwarte 16, 14482 Potsdam, Germany

Abstract

We studied nature of the transient supersoft X-ray source (SSS) 1E1339.8+2837 in the globular cluster M3 (NGC 5272) using the ASCA data and the archival ROSAT data. We found that 1E1339.8+2837 was observed most of the time as a CV-type X-ray source and had a hard energy spectrum approximated by a bremsstrahlung model of 5 keV. It switched to a high state only during 1991–92 at a luminosity of 10^{35} erg s^{-1}, which is larger than that in the low state by nearly two orders of magnitude. We confirmed the very soft energy spectrum characteristic of the SSS during the high state. Thus, 1E1339.8+2837 is considered to be a white dwarf binary making a transition between the SSS and the CV. We discuss a possible model of 1E1339.8+2837, a dwarf nova including a massive white dwarf.

Key words: Stars: white dwarf — X-rays: binaries — X-rays: sources

1 Introduction

X-ray sources of two distinct luminosity classes are known to exist in the globular clusters (Hertz and Grindlay 1983b). One class includes about a dozen X-ray sources having a high X-ray luminosity ($> 10^{36}$ erg s^{-1}). Most of these sources are type I X-ray bursters, and hence they are believed to be binary systems consisting of a neutron star and a low-mass companion (Lewin, van Paradijs and Taam 1993). X-ray sources of the other class have a low luminosity ($< 10^{35}$ erg s^{-1}) and are sometimes referred to as low-luminosity globular cluster X-ray sources (LLGCXS). LLGCXS were first discovered by the Einstein satellite through the survey observations of globular clusters (Hertz and Grindlay 1983a). The nature of LLGCXS is not clear yet because of the limited observational information. Various possibilities have been suggested including cataclysmic variables (Hertz & Grindlay 1983a), quiescent X-ray transients (Verbunt et al. 1984), RS CVn stars (Bailyn et al. 1990; Belloni et al. 1993), and millisecond radio pulsars (Danner, Kulkarni and Thorsett 1994). Among the ROSAT observations of LLGCXS, the X-ray source in M3 (NGC 5272) was found to have an exceptionally soft energy spectrum (Verbunt et al. 1995). This spectrum could be approximated by a blackbody model with a temperature of ~ 45 eV, a temperature typical for the so-called supersoft X-ray sources (see Greiner 1996 and references therein).

Supersoft X-ray sources (SSSs) are a distinct class of objects characterized by a high luminosity ($10^{36} - 10^{38}$ erg s^{-1}) and an extremely soft energy spectrum (blackbody temperature of 10–50 eV). They might be a heterogeneous class of objects, but most of them are considered to be close binary systems containing a white dwarf. Large mass accretion rate onto the white dwarf ($\sim 10^{-7}$ M$_\odot$ yr^{-1}) leads to stable hydrogen burning in the white dwarf atmosphere thus producing the large X-ray luminosity in the soft X-ray band. M3 is the only globular cluster in which an SSS has been detected so far (Greiner 1996).

The X-ray source in M3 was first discovered with the Einstein satellite, and was designated as 1E1339.8+2837. The Einstein observation yielded an X-ray luminosity of 4×10^{33} erg s^{-1} (Hertz and Grindlay 1983a), typical for LLGCXS, assuming 5 keV exponential spectrum. During the ROSAT all-sky survey, a very soft source (blackbody temperature of $\sim$45 eV) was detected in M3 with a bolometric luminosity of $\sim 1.3 \times 10^{35}$ erg s^{-1} (Verbunt et al. 1995). A ROSAT HRI observation detected a soft and bright source ($kT \sim$ 20 eV and 2×10^{35} erg s^{-1} in 0.1–2.4 keV) at the position consistent to 1E1339.8+2837 in 1992 January, but the source was faded away below the HRI detection limit in 1992 June (Hertz, Grindlay and Bailyn 1993).

In this paper, we present the results obtained from the analysis of the ASCA observation of 1E1339.8+2837 and the complete ROSAT archival data, and discuss the nature of the source.

2 Observations

We observed 1E1339.8+2837 with ASCA from 1997 January 18, 19:30 through January 19, 8:00 (UT) for a net exposure of 21 ksec. ASCA (Tanaka et al. 1994) carries two kinds of detectors, the solid state imaging spectrometer (SIS; Burke et al. 1994) and the gas imaging spectrometer (GIS; Ohashi et al. 1996; Makishima et al. 1996). SIS has a superior position and energy resolution (2 % at 6 keV), whereas GIS covers a larger field of view ($50'$ in diameter) with higher time resolution. The observation was carried out in 1 CCD faint mode of SIS, which covers $11' \times 11'$ square area, and in standard PH mode of GIS.

ROSAT archival data were also analyzed to investigate the long-term behaviour of 1E1339.8+2837 and to make a detailed comparison with ASCA data. Some results from the ROSAT data in 1990–1992 were already published (Hertz et al. 1993; Verbunt et al. 1995). However, much more data are available with the PSPC in 1993 July and 1994 July, and with the HRI in 1994 July and 1995 July. We therefore reanalyzed the old 1990–1992 data together with the 1993–1995 data to obtain coherent results. Part of the PSPC data in 1994 July were taken with the Boron filter. We did not analyze this part of the data, because the data did not bring further information useful to understand the nature of the source. The journal of the observations is summarized in Table 1 together with other information.

3 Analysis and Results

3.1 ASCA data

We first calculated the total band images separately for SIS and GIS data. An X-ray point source was detected in both images at the position consistent with 1E1339.8+2837. We determined the source position using only the SIS data, because SIS has superior spatial resolution than GIS. We also applied the temperature dependent attitude correction to the data, which greatly reduces the systematic error of the source position (Ueda, private communication; see also Gotthelf 1996). The source position is determined as R.A. = $13^{\rm h}42^{\rm m}09\overset{\rm s}{.}3$, Decl. = $+28^\circ 22' 50''$(J2000) with an error radius of $0.5'$. No other source was detected within $5'$ from the source in the SIS/GIS images.

Next, we calculated the energy spectra separately for SIS and GIS. Source photons are extracted from a circular region ($3'$ radius for SIS and $6'$ radius for GIS) centred on the source, and the background photons from the rest of the chip for SIS and from an annulus region (inner and outer radii of $3'$ and $6'$) for GIS, respectively. Spectra from SIS-0 and SIS-1 are added to improve the statistics, and also for GIS-2 and GIS-3. Because the two spectra are consistent with each other, we performed a combined model fitting to the spectra. The spectra can be approximated either by a power law of a photon index of $\sim$1.7 or a Bremsstrahlung of $\sim$5 keV. The source flux was 1.3×10^{-13} erg s^{-1} cm^{-2} (0.5–10 keV), which translates into a luminosity of 1.6×10^{33} erg s^{-1} for the source distance of 10.1 kpc (Djorgovski and Meylan 1993). The energy spectrum is rather hard, and is very different from that of an SSS. This prompted us to investigate the ROSAT archival data of 1E1339.8+2837.

3.2 ROSAT data

The position of M3 was scanned during the ROSAT all-sky survey on 1990, July 15 for a total of 10 scans (corresponding to an exposure time of 240 sec) and again on 1991, January 15–16 for a total of 12 scans (260 sec exposure time). The latter set of survey data was analyzed by Verbunt et al. (1995). 1E1339.8+2837 was not detected in 1990 July, with a 3σ upper limit of 0.038 cts s^{-1} in the PSPC. However, it was clearly detected in 1991 January at a mean count rate of 1.15$\pm$0.3 cts s^{-1}. We confirmed the source position (R.A. = $13^{\rm h}42^{\rm m}10\overset{\rm s}{.}1$, Decl. = $+28^\circ22'53''$(J2000) with an error radius of $15''$) and the very soft energy spectrum (blackbody temperature of $kT = 36 \pm 20$ eV for the galactic column of $N_{\rm H}^{\rm gal} = 1.1\times10^{20}$ cm^{-2}; Dickey & Lockman 1990) of the source, as found by Verbunt et al. Although we used an absorbed blackbody to fit the energy spectrum for simplicity, the luminosity depends strongly on the assumed reddening, and is also different for a blackbody fit and for a white-dwarf atmosphere, as discussed by Verbunt et al.

There were total of 6 pointed observations, 4 with the HRI and 2 with the PSPC, of M3 perfromed by ROSAT. Among these, two sets of HRI data in 1992 were analyzed by Hertz et al. (1993). We investigated all these datasets using the full information over the total energy band. We confirmed the results obtained by Hertz et al. for the 1992 observations, i.e. positive detection at a count rate of 0.144 cts s^{-1} in January and an upper limit of 0.004 cts s^{-1} in June. A clear point source was found at the position consistent to 1E1339.8+2837 in the rest of observations, except for the one in 1994 July (HRI data). We determined the source positions for the data with positive detection of the source. The source positions, which are listed in Table 1, are all consistent with each other. Especially, the HRI position determined from the 1992 January data is within only $3''$ of the position derived with the HRI data in 1995 July and within $6''$ of the position from the all-sky survey data. The astrometric analysis done by Hertz et al. (1993) using several background objects is also consistent to these positions. This positional coincidence supports the interpretation that all the EINSTEIN, ROSAT and ASCA observations detected the same source, 1E1339.8+2837. We discuss the source identification in §4.

Careful inspection of the ROSAT PSPC data revealed the presence of a faint source about $1'$ east of 1E1339.8+2837. The source is present in both 1993 July and 1994 July data with similar intensity. Thus it may be a persistent source. The source flux is about an oder of magnitude smaller than 1E1339.8+2837. Analysis of the ROSAT data is not affected by the presence of this faint source, because it is well separated in the image.

On the other hand, the ASCA data might be contaminated by this source, but the effect should be negligible because the flux of the contaminating source is also expected to be an order of magnitude smaller than 1E1339.8+2837 in the ASCA band.

We determined the energy spectra of 1E1339.8+2837 with the PSPC data in 1993 July and 1994 July. The two PSPC spectra are very similar to each other except for a factor of 2 larger flux in 1993 as compared to 1994. The spectra are hard and are very different from those of SSS. The spectra can be approximated by a power law of a photon index of $\sim$2. Because the spectral parameters obtained from ROSAT and ASCA data are very similar to each other, we tried a combined fitting. In the fitting, separate model normalizations are used for each energy spectrum, but the other parameters (temperature, photon index, and absorption column) are tied to each other. The results are shown in Fig. 1. We found that a power law of a photon index 1.7 ± 0.2 with $N_{\rm H} = (2.2 \pm 0.8) \times 10^{20}$ cm^{-2} or a Bremsstrahlung of $kT = 5^{+3}_{-2}$ keV with $N_{\rm H} = (1.4 \pm 0.4) \times 10^{20}$ cm^{-2} can satisfactory fit the combined energy spectrum. The spectral shape seems to have not changed very much between 1993 and 1997 with only a slight decrease in normalization.

3.3 Long-term variations

To investigate the long-term behavior of 1E1339.8+2837, we calculate the source luminosities using all the available sets of ROSAT and ASCA data. Because the source seems to have shown a large change in the spectral shape, and the energy ranges covered by ROSAT and ASCA are different, we calculate a bolometric luminosity using appropriate model functions. When we combine the ASCA data with those of ROSAT, we notice that the luminosity change of 1E1339.8+2837 is coupled with the spectral change. The source seems to have been bright in 1991–1992 (hereafter a high state), whereas it was dimmer by nearly two orders of magnitude since 1993 (hereafter a low state). According to the PSPC data, the energy spectrum was hard in the low state (e.g. 1993 July and 1994 July), but was very soft during the high state (e.g. 1991 January). This correspondence also holds for the ASCA data. Thus, it may be justified to assume the same correspondence also for the ROSAT HRI data. Based on these results, we use an energy spectrum of a

Bremsstrahlung of $kT = 5$ keV ($N_{\rm H} = 1.4 \times 10^{20}$ cm^{-2}) for the low hard state, and a blackbody model with a temperature of 36 eV ($N_{\rm H} = 1.1 \times 10^{20}$ cm^{-2}) for the high soft state to calculate the X-ray luminosities. HRI count rate and the upper limits are also converted to luminosities under these same assumptions. The results are listed in Table 1 and plotted in Figure 2.

Looking at the long-term light curve, we realize that 1E1339.8+2837 was observed in the high soft state only twice, i.e. in January 1991 and January 1992. The maximum duration of this state is shorter than 2 years as given by the first all-sky survey upper limit and the HRI observation in June 1992. The count rate of the January 1992 observation is 0.126 cts s^{-1} in the HRI. For such a soft spectrum (as argued by Hertz et al. 1993) the conversion factor between HRI and PSPC count rates is 1:7.8 (Greiner et al. 1996). Thus, the intensities of the two high state measurements coincide to within 10 %, implying little variability during this interval. It is worth noting that the transition between the high and the low state is rather rapid. The transition may be as short as half a year, which is shorter than the duration of the high state.

Given the hard X-ray spectrum during the low state we have also investigated the question of whether or not this hard X-ray component could have existed also during the high soft state. During the all-sky survey we do not find any hint for the presence of a hard component. A fit with a sum of a blackbody and a thermal bremsstrahlung component with the temperature of the bremsstrahlung component fixed ($kT_{\rm thbr} = 5$ keV) results in no flux in the bremsstrahlung component (normalization amplitude practically zero). An estimate on the expected source counts of the hard component (assuming the presence of this hard component) confirms this fit result. With an exposure time of 260 sec during the all-sky survey and a low state count rate of 0.02 cts s^{-1} in the PSPC (as during the July 1993 observation which is the maximum low state count rate) one would expect 5 hard photons, not enough to be detectable among the soft photons and the background during the all-sky survey. Thus, the hard component could exist also during the high soft state.

4 Discussion

We detected correlated changes in luminosity and spectral shape from 1E1339.8+2837 using the ASCA data and the ROSAT archival data. The source has a low luminosity ($\sim 10^{33}$ ergs s^{-1}) and a hard spectrum ($kT \sim 5$ keV with a Bremsstrahlung) in the low state. This is in clear contrast to the high state in 1991–1992, during which the source was bright ($L_X \sim 10^{35}$ ergs s^{-1}) and had a very soft energy spectrum ($kT \sim 36$ eV with a blackbody), characteristic to the SSS.

Although the field of the globular cluster is crowded and source confusion could be a potential problem, we found that all the ROSAT and ASCA data are consistent with observations of a single source, 1E1339.8+2837. Three observational results support this conclusion. First, the source positions determined by the two sets of ROSAT HRI data, one in the high state and the other in the low state, coincide with each other within a difference of only 3 arcsec, well within the errors of the individual position determinations. Because the location of 1E1339.8+2837 in the globular cluster is close to the edge of the cluster core, where the source confusion is less severe, it is unlikely that the two HRI observations were looking at different X-ray sources. Second, the spectral shapes are consistent between ASCA and ROSAT observations. ROSAT PSPC and ASCA data show that the spectral shape is basically the same for both observations. Although the accuracy of the position determination is worse for ASCA and ROSAT PSPC, the energy spectra are also consistent to the count rate of the ROSAT HRI data. Third, the energy spectra during the low state are surprisingly constant except for a factor of 2 change in normalization. Thus, all these results support the conclusion that we observed the same source, i.e. 1E1339.8+2837, both in the high and low states. We also note that 1E1339.8+2837 is considered to be actually located within M3, because the chance probability of finding an X-ray source at a flux level of 1.5×10^{-13} erg cm^{-2} s^{-1} (2×10^{33} erg s^{-1} at 10.1 kpc) within the core radius of M3 (25 $''$; Webbink 1985) is only 10^{-4} from the $\log N - \log S$ relation (Ueda 1997).

Although the nature of 1E1339.8+2837 is not clear yet, the compact source in 1E1339.8+2837, if present, must explain the characteristics of both the high and low states of the source.

The characteristics of 1E1339.8+2837 in the low state, i.e. a luminosity of a few times 10^{33} ergs/sec and the hard spectrum, are in good agreement with those of the class of LLGCXS. Although the nature of LLGCXS is not known, its hard energy spectrum may contradict a black hole or a neutron star binary in quiescence (McClintock, Horne and Remillard 1995; Asai et al. 1998). On the other hand, the hard spectrum is rather similar to cataclysmic variables (CVs), i.e. binary systems containing a mass-accreting white dwarf. In fact, a connection between LLGCXS and CV is indicated by recent observations (Ferraro et al. 1997; Hakala et al. 1997), although the CVs in globular clusters may have different properties than those in the galactic disc (Verbunt et al. 1997). On the other hand, 1E1339.8+2837 during the high state is considered to be an SSS. Although the luminosity (a few times 10^{35} erg s^{-1}) is relatively low for an SSS, the luminous supersoft emission is just the key characteristics of the SSS (see Greiner 1996 and references therein). Because both the low and the high state characteristics of 1E1339.8+2837 are similar to those of white dwarf binaries, we consider that 1E1339.8+2837 is most probably a binary system containing a white dwarf.

Long-term variations in the light curve has been observed from a number of SSS (Schaeidt, Hasinger, Trümper 1993, Kahabka 1995, Greiner & Wenzel 1995). Several different mechanisms may be working for the long-term variations. For instance, RX J0513.9−6951 shows correlated variations in the X-ray and optical bands; the optically bright and X-ray dim state is irregularly interrupted by ∼4 week duration optically low states which are accompanied by luminous supersoft X-ray emission (Schaeidt, Hasinger, Trümper 1993). Expansion and contraction of the white dwarf atmosphere is considered to be responsible for this variability, when the mass accreting rate is slightly higher than the burning rate. Similar variability was observed from other sources including CAL 83 (Kahabka, Haberl, Parmar 1996) and V751 Cyg (Greiner et al. 1999), though the interpretation in these sources may be different. However, this type of variation may not fit the behaviour of 1E1339.8+2837, because the thin thermal emission observed in the low state seems to be incompatible with the optically thick atmosphere always present in these white dwarfs. Another example of time variability may be seen when the mass accretion rate is slightly lower than that required for stable hydrogen burning. In this case, hydrogen burning becomes intermittent. Supersoft emission is radiated during the hydrogen burning, whereas gravitational potential energy may power the optically thin emission when hydrogen burning stops. RX J0019.8+2156 is an example which possibly shows this type of variability (Greiner & Wenzel 1995; Meyer & Meyer-Hofmeister 1996), based on the optical light curve. The behavior of 1E1339.8+2837 also seems to be explained by this mechanism.

The mass accretion rate on to 1E1339.8+2837 in the low state is estimated under the assumption that the X-ray luminosity is powered by the gravitational potential energy of the accreting matter and the white dwarf is non-rotating. The estimation gives:

$$\dot{M}_{\rm quiescence} = 3.5 \times 10^{-10} \left(\frac{M_{WD}}{M_\odot}\right)^{-1} \left(\frac{R_{WD}}{10^3 \text{ km}}\right) \text{ M}_\odot/\text{year}. \qquad (1)$$

This mass accretion rate is in fact much smaller than that required for the stable hydrogen burning in the white dwarf atmosphere, $(1-4) \times 10^{-7}$ $\text{M}_\odot$ yr^{-1}, and is typical for CVs with a low-mass main-sequence secondary below the period gap (Kolb 1993). For a wide range of mass accretion rates (including $\sim 10^{-10}$ $\text{M}_\odot$ yr^{-1}) it is known that the accretion disk is thermally and tidally unstable. The instabilities lead to nova outbursts (for a review, see Ozaki 1996). Therefore, 1E1339.8+2837 may be considered to be a dwarf nova. We speculate that the large mass accretion rate during the outburst may ignite the hydrogen burning of the matter accumulated in the white dwarf envelope. In this sense, 1E1339.8+2837 may be rather close to novae because of the ignition of hydrogen, although the mass accretion rate falls in the range of dwarf novae.

We found from the ROSAT observations that the duration of the high state of 1E1339.8+2837 is only 1–2 yrs. The time scale of the luminosity change of the hydrogen burning white dwarf is closely related to its mass (Sienkiewicz 1980; Kahabka 1995; Hoshi 1998). To explain the short time scale of the high state, the white dwarf needs to be very massive, close to the Chandrasekhar limit. The relatively high temperature ($\sim$46 eV) obtained from the model fitting of the white-dwarf spectra in high state (Verbunt et al. 1995; see also their figure 5) also favors a massive white dwarf. Such a heavy white dwarf requires a matter of the order of 10^{-6} $\text{M}_\odot$ in the envelope to ignite the hydrogen to switch into the high state. Thus, a few thousand years may be needed to accumulate enough matter to ignite the hydrogen if our interpretation of the low state emission and the accretion rate derived thereof is correct. The matter accumulated in the atmosphere is considered to produce a mean X-ray luminosity of $\sim 10^{38}$ erg s^{-1} during the hydrogen burning. Because the observed luminosity in the high state is only a few times 10^{35} erg s^{-1}, although this value strongly depends on the assumption of the model spectrum, we may have missed the main part of the high state due to the sparse observations, and only observed the cooling track. If the X-ray luminosity indeed went up to $\sim 10^{38}$ erg s^{-1} during the flare, 1E1339.8+2837 would satisfy all the criteria of an SSS.

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Table 1: Summary of the Observations of 1E1339.8+2837

Date (yy/mm)	Exposure (sec)	Detector	Count rate (cnts/sec)	Luminosity[1)] (10^{33} ergs/s)	Source position (R.A., Dec.)	Error (arcsec)	State
1977/9		HEAO A1		< 210[2)]			
1981/1/17		Einstein IPC		6.8	$(13^h 42^m 09^s.7,\ +28^\circ 22' 46'')$[3)]	30	low/hard
1990/7/15	240	ROSAT PSPC	<0.038	< 12.3[2)]	—		low/hard
1991/1/15–16[4)]	260	ROSAT PSPC	1.15 ± 0.3	190	$(13^h 42^m 10^s.8,\ +28^\circ 22' 53'')$	15	high/soft
1992/1/10[5)]	1881	ROSAT HRI	0.126 ± 0.008	160	$(13^h 42^m 09^s.8,\ +28^\circ 22' 48'')$	10	high/soft
1992/6/24[5)]	1462	ROSAT HRI	<0.004	< 4.1[2)]	—		low/hard
1993/7/6-22	13083	ROSAT PSPC	0.014 ± 0.001	4.4	$(13^h 42^m 09^s.7,\ +28^\circ 22' 51'')$	25	low/hard
1994/7/2–4	14599	ROSAT PSPC	0.008 ± 0.001	2.5	$(13^h 42^m 09^s.6,\ +28^\circ 22' 52'')$	25	low/hard
1994/7/3	17280	ROSAT PSPC/B	0.004 ± 0.0005	—	$(13^h 42^m 09^s.6,\ +28^\circ 22' 53'')$	25	low/hard
1994/7/15	2190	ROSAT HRI	< 0.003	< 3.0[2)]	—		low/hard
1995/7/14	4755	ROSAT HRI	0.006 ± 0.001	6.0	$(13^h 42^m 09^s.8,\ +28^\circ 22' 49'')$	10	low/hard
1997/1/18-19	21205	ASCA SIS	0.0028	2.0	$(13^h 42^m 09^s.3,\ +28^\circ 22' 50'')$	30	low/hard

[1)] Bolometric luminosities (upper limits) are calculated assuming a Bremsstrahlung of 5 keV ($N_H = 1.4 \times 10^{20}$ cm^{-2}) for low/hard state and a blackbody of 36 eV ($N_H = 1.1 \times 10^{20}$ cm^{-2}) for high/soft state, respectively. Source distance is assumed to be 10.1 kpc.

[2)] Low/hard state spectrum is assumed.

[3)] Hertz and Grindlay (1983a).

[4)] The data were also analyzed by Verbunt et al. (1995).

[5)] The data were also analyzed by Hertz et al. (1993).

Figure 1 Observed energy spectra (crosses) and the best fit model function (histograms) of 1E1339.8+2837 in the low state. Bare crosses and crosses with circle are the ROSAT PSPC data in 1993 July and 1994 July, respectively. Crosses with filled square and those with open square are the ASCA SIS and GIS data, respectively. Histograms are the best-fit model function, thermal Bremsstrahlung, obtained from the combined fitting to the ASCA and the ROSAT data. Note that a power law can also fit the data similarly well as a thermal Bremsstrahlung (see text).

Figure 2 Long-term variations of the bolometric X-ray luminosity of 1E1339.8+2837. See table 1 for the description of the data. Large increase of X-ray luminosity, nearly by two orders of magnitude, is seen in 1991–92.