**RX J0045.4+4154: A Recurrent Supersoft X-ray
Transient in M31**

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549523

Accepted for publication in *Ap. J. Letters* 1995, March 20

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ABSTRACT

Using data extracted from the *ROSAT* archive we have discovered a recurrent supersoft X-ray transient RX J0045.4+4154 in M31. The first outburst began on 1992 Feb 2 and continued for at least four days, until the end of the observation sequence. A second outburst that lasted > 6 days was seen to begin on 1993 Jan 7. The X-ray spectrum on both occasions yields a characteristic blackbody temperature of ~ 90 eV. For a range of plausible continuum models, the hydrogen column density is $0.8\text{--}1.5 \times 10^{21} \text{ cm}^{-2}$ and is consistent with the source being located in M31. This implies an unabsorbed 0.1–2.0 keV peak luminosity of $\sim 10^{38} \text{ erg s}^{-1}$. This is the first recurrent X-ray transient to be found in M31, and is particularly notable because it is much softer than the bright X-ray transients seen in our galaxy. The spectrum is characteristic of the supersoft class of X-ray sources, which are thought to be accreting white dwarfs that have a hydrogen burning surface layer. A fit to a white dwarf model atmosphere gives a temperature of 10^6 K, the hottest found so far. This high temperature is consistent with a white dwarf mass of $1.3\text{--}1.4 M_{\odot}$, approaching the Chandrasekhar limit, and burning close to the nuclear stability limit.

Subject headings: novae – X-rays: stars – stars: individual (RX J0045.4+4154)

1. Introduction

ROSAT observations have established a new class of X-ray binary called supersoft sources which have a characteristic blackbody temperature of a few tens of eV, a bolometric luminosity of $\sim 10^{38}$ erg s $^{-1}$, and in some cases transient outbursts (Trümper *et al.* 1991; Greiner, Hasinger and Kahabka 1991; Hasinger 1994). The supersoft sources are in most cases only detected below 0.5 keV, so that within our own galaxy they are mostly hidden by interstellar absorption in the galactic disk. They are, however, readily evident in external galaxies, with ~ 10 found in the Magellanic Clouds and at least 15 seen in M31 (Hasinger 1994; Supper 1994). Supersoft sources have now been discovered in our galaxy (*e.g.* Motch, Hasinger and Pietsch 1994) and in the globular cluster M3 (Hertz, Grindlay and Bailyn 1993). Blackbody fits imply Eddington limited and in some cases super-Eddington bolometric luminosities for a neutron star or white dwarf (Kahabka *et al.* 1994). Several supersoft source show transient outbursts *e.g.* RX J0513.9-6951 (Schaeidt, Hasinger and Trümper 1993), some of which are recurrent (Kahabka 1995) while others appear to be stable on a timescale of years (Hasinger 1994).

Models for the supersoft sources include: the hot inner region of an accretion disk surrounding a white dwarf (Kahabka, Pietsch and Hasinger 1994); super-Eddington accretion onto a neutron star (Kylafis and Xilouris 1993); and nuclear burning of hydrogen on a white dwarf accreting material at a high rate of $\sim 10^{-7} M_{\odot}$ yr $^{-1}$ (van den Heuvel *et al.* 1992; Pacynski and Zytkow 1978). The identification of a supersoft source with the classical nova GQ Mus (Ogelmann *et al.* 1993) and white dwarfs in several other systems (van den Heuvel *et al.* 1992) favours the nuclear burning model. The use of white dwarf model atmospheres instead of simple blackbody fits means that super-Eddington luminosities are not required (Heise, van Teeseling and Kahabka 1995). Instabilities in the nuclear-burning layer can naturally account for the variability (recurrent transient behaviour) seen in some supersoft sources. Optical and IUE observations imply the presense of a bright accretion disk in such systems indicating high mass transfer rates $> 10^{-8} M_{\odot}$ yr $^{-1}$ (Pakull *et al.* 1993).

Using the *ROSAT* archive we have found a new recurrent transient supersoft source in M31. The discovery was first announced in White *et al.* (1994a). In this *letter* we report the details of the discovery, the overall source properties and how this source fits into the supersoft class.

2. Results

The one degree radius field of view of the *ROSAT* position sensitive proportional counter, PSPC, combined with its large collecting area and low background (Trümper 1983) means that any given observation makes a X-ray survey of the region of sky surrounding the target. Over the 3 yr pointed phase of the mission about 10% of the sky was covered, with varying degrees of sensitivity. Most of these data are now available in the public archive and we have undertaken a

project to catalog the sources in each field (White, Giommi and Angelini 1994b). An optimized sliding-cell detect is being used to generate a list of X-ray sources for each observation. This software was originally developed to catalog sources detected in the *EXOSAT* low energy imaging telescopes (Giommi *et al.* 1991). To identify highly variable objects a Kolmogorov-Smirnov (KS) test was made where the arrival time distribution of the photons for each pixel coordinate is compared with the corresponding distribution for the entire field. The result of the KS test is a χ^2 value (with 2 degrees of freedom) that is used to assign an intensity value to each pixel in an image. In this way pixels where the distribution of photon arrival times is not consistent with that of the entire image will be assigned high intensity values (high χ^2 values). The resulting *time variability image* visualize sources with strong time variability (Giommi, White and Angelini 1994). Test runs were made on a few fields of differing complexity and a time variability image produced in one of these runs revealed a transient X-ray source in an observation of M31 made in January 1992.

The left panel in Figure 1 shows the image from a 45,000s *ROSAT* exposure of the NE region of M31 made in January/February 1992. Many sources are detected, and these are most likely either bright X-ray binaries in M31 or background AGN (Supper 1994). In the time variability image, shown in the right panel of Figure 1, one source clearly stands out. A lightcurve of that source shows an abrupt outburst began on 1992, February 2 (Figure 2). Prior to that time the source was not detected. We examined the *ROSAT* archive for all instances where this source position was observed, and Table 1 gives a list of the *ROSAT* observation request (ROR) number, the offset angle of the source in the detector, the exposure time and whether it was detected. The first outburst lasted at least until the end of that ROR, four days later. The source was not detected during the next *ROSAT* observation of this region in August 1992, nor in observations made in July 1991 (Supper 1994). A second outburst was seen to begin on 1993 Jan 7, and lasted for at least 5.5 days. The last observation in this sequence shows the source to be quite faint, which may indicate the end of the outburst. The first outburst is from a single ROR, but the second spans 12 different pointing positions (Table 1) which makes the analysis more complex. For each pointing position the count rate was corrected for the appropriate telescope off-axis response and local point spread function, PSF. The corrected background subtracted lightcurve of each outburst is shown in Figure 2.

The best position was estimated using eight observations made where the source was within 17 arc minutes of the pointing position. This minimizes uncertainties due to the distortion of the PSF at larger off axis angles. This gives in J2000 equinox $\alpha = 00^h45^m29.0^s$ and $\delta = 41^\circ54'7.6''$. The root-mean-square deviation of the measured positions is 13 arc second, which is consistent with the 90% confidence error radius for *ROSAT* PSPC detections. The source is designated RX J0045.4+4154 (= 1WGA J0045.4+4154; White *et al.* 1994b).

The first outburst was contained in one observation, with the source at the same off-set angle. A spectrum was accumulated for the entire outburst, and a corresponding background spectrum taken from a nearby region. The detector response matrix was corrected for the effects

of vignetting and the energy dependent point spread function. The spectrum was fit to a variety of simple models. A blackbody model gave a reduced χ^2_ν of 1.01 with a temperature of 0.087 ± 0.007 keV and an equivalent hydrogen absorption of $(1.2 \pm 0.2) \times 10^{21} \text{ cm}^{-2}$. The unabsorbed 0.1–2.0 keV flux is $6 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$, which corresponds to a luminosity at 690 kpc of $3 \times 10^{38} \text{ erg s}^{-1}$. The best fitting model is shown in Figure 3 and the residuals given in the lower panel indicate the fit to be reasonable, although there is a single high channel around 0.8–0.9 keV. A thermal bremsstrahlung model resulted in a χ^2_ν of 1.32 with a temperature of 0.13 ± 0.02 keV and absorption of $(1.7 \pm 0.4) \times 10^{21} \text{ cm}^{-2}$. A Mewe and Kaastra, *meka* model for emission from a solar abundance plasma in thermal equilibrium (Kaastra 1992, Mewe, Gronenschild, and van den Oord 1985) gives a χ^2_ν of 1.01 with a temperature of 0.16 ± 0.02 keV and an absorption of $(0.9 \pm 0.3) \times 10^{21} \text{ H cm}^{-2}$. The emission measure for a source located in M31 is $\sim 5 \times 10^{60} \text{ cm}^{-3}$, which is extremely large.

There is variability through the outburst and spectra were accumulated according to low, medium and high count rate. A blackbody model with absorption was simultaneously fit to all three spectra. The count rates were 0.017 counts s^{-1} , 0.051 counts s^{-1} and 0.073 counts s^{-1} for the low, medium and high intervals, respectively. The absorption parameter was simultaneously fitted to all three spectra, whereas the temperature and normalisation were allowed to vary. The temperature increases with intensity giving 0.061 ± 0.014 , 0.080 ± 0.007 and 0.091 ± 0.008 keV for the low, medium and high intervals, respectively. The corresponding 0.1–2.0 keV flux for each interval was 3.4×10^{-13} , 1.0×10^{-12} and $1.2 \times 10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$. The equivalent hydrogen column density was $1.3 \times 10^{21} \text{ cm}^{-2}$ and the χ^2_ν 0.8.

In the off-state the best upper limit to any detection is during the long 30,000s exposure made in July 1991 (ROR=600066) when the source was close to on-axis (Table 1). This gives a three sigma upper limit of $9.1 \times 10^{-4} \text{ counts s}^{-1}$, a factor of 100 less than the peak outburst count rate. We also examined *Einstein* (HEAO-2) archival data from this region (see Trinchieri and Fabbiano 1991). An IPC observation including the position of RX J0045.4+4154 was made on 1979, January 11-12, but the source was not detected. The upper limit to the count rate was $4 \times 10^{-3} \text{ counts s}^{-1}$. The source position was close to the edge of the field of view in an *Einstein* HRI observations made in 1979 August and 1980 January, but it was again not detected.

3. Discussion

The equivalent hydrogen column density that we measure to RX J0045.4+4154 of $0.8\text{--}1.7 \times 10^{21} \text{ cm}^{-2}$ is comparable to the value expected from the galactic disk, based on HII measurements, of $0.8 \times 10^{21} \text{ cm}^{-2}$ (Stark *et al.* 1992). This is consistent with RX J0045.4+4154 being associated with M31, rather than a foreground object. Bright transient X-ray sources are a feature of our galactic X-ray binary population (see *e.g.* White, Kaluzienski and Swank 1984) and it is not surprising to find a similar event in M31. Variability of the M31 X-ray sources is already well established (Primini, Forman, and Jones 1993; Trinchieri and Fabbiano 1991). A comparison of *EXOSAT* and *Einstein* images of the M31 bulge taken 4 yr apart revealed two bright transient

sources (White and Peacock 1988). RX J0045.4+4154 is the first recurrent X-ray transient system to be seen in M31.

The RX J0045.4+4154 blackbody temperature of ~ 90 eV and bolometric luminosity of $\sim 10^{38}$ erg s $^{-1}$ are unusual compared to the X-ray transients typically seen in our galaxy. These have characteristic temperatures that are much higher ranging from 1 keV in the ultra-soft black hole transients, to 5–10 keV in low mass X-ray binaries with neutron stars, to flat power-law spectra for the X-ray pulsars in high mass X-ray binaries (White *et al.* 1984). The low temperature of RX J0045.4+4154 would have made it difficult to detect with traditional X-ray all-sky monitors, which typically cut-off at 1–2 keV (see *e.g.* Friedhorsky and Holt 1987). The location of RX J0045.4+4154 in M31 is one degree away from the center. If a similar source had appeared in our galaxy away from the galactic center, then even at a distance of 7 kpc it would be extremely bright, with *e.g.* in the *ROSAT* all-sky survey a count rate between 80 and 1000 counts s $^{-1}$, for a hydrogen column density ranging from 5×10^{20} to 5×10^{21} cm $^{-2}$.

RX J0045.4+4154 is most probably a member of the supersoft class of X-ray source. The 90 eV temperature is extreme for this population, where 10–50 eV is typical and most are not detected above 500 eV (Hasinger 1994). But exceptions are CAL87 in the LMC (Kahabka, Pietsch and Hasinger 1994) and RX J0925.7-475 in our galaxy (Motch *et al.* 1994). The bolometric luminosity of RX J0045.4+4154 derived from the blackbody model is super-Eddington for an accreting white dwarf or neutron star, similar to CAL87 (Kahabka *et al.* 1994). The transient nature of RX J0045.4+4154 is reminiscent of RX J0527.8-6954, a transient supersoft source in the LMC (Schaeidt *et al.* 1993).

The *ROSAT* PSPC supersoft spectra have been characterized by Heise, van Teeseling and Kahabka (1995) as a step-function consisting of a constant flux (in erg cm $^{-2}$ s $^{-1}$) up to an edge E_{edge} , plus interstellar absorption. This is based on model atmospheres in the soft X-ray range which can be characterized by a slowly varying flux up to an absorption edge and a negligible flux beyond this. Moreover, supersoft source spectra are not consistent with purely scattering dominated atmospheres (Heise *et al.* 1994). Most of the supersoft sources in the Magellanic Clouds are consistent with an edge of the order of 0.4 keV and therefore most likely represent spectra which exhibit a continuum up to the CV edge at 0.39 keV. CAL87, however, requires a step function fit at $E_{\text{edge}} = 0.71$ keV, consistent with the OVII edge at 0.74 keV. A step function fit to RX J0045.4+4154 gives a narrow range of parameters: an absorption edge at $0.84^{+0.03}_{-0.03}$ KeV with an absorption column of $6.7^{+0.9}_{-1.2} \times 10^{20}$ cm $^{-2}$. In the soft X-ray range RX J0045.4+4154 is slightly harder than CAL87, but exhibits a lower interstellar absorption. It is compatible with an ionization edge of OVIII at 0.87 keV.

We have fit to the RX J0045.4+4154 spectra models for optically thick emission of a plasma in radiative equilibrium confined by a constant gravitational field (Heise, van Teeseling and Kahabka 1995). A grid of model LTE atmospheres at cosmic abundances (Heise 1995) in steps of 10,000 K were constructed for $\log(g) = 8 - 10$ (g in cm s $^{-2}$) in steps of 0.25 ranging from 2×10^5 to

the Eddington limit indicated in Figure 4. The high densities in these atmospheres guarantee the validity of LTE and are appropriate close to the nuclear burning stability limit for white dwarfs. These are representative of steady nuclear burning on accreting white dwarfs. The results verify the general impression obtained from fits with a characteristic step function. Models with $\log(g) < 8.75$ do not fit the data, because static LTE-atmospheres could not be made hot enough to show the OVIII ionization edge before blowing apart. To obtain an OVIII ionization edge at 0.87 keV requires a minimum gravity of $\log(g) = 8.75$, for which the resulting luminosity in the fits is of order $1 \times 10^{38} \text{ erg s}^{-1}$ and the source radius is $4 \times 10^8 \text{ cm}$ at an assumed distance of 670 kpc. The radius, independently found from the normalization to the fit, is consistent with the gravity used for a high mass white dwarf. We note, however, that at lower gravity ($\log g \sim 7$) and with temperatures close to the Eddington limit non-LTE conditions are appropriate. Such models, when eventually available, might produce the OVIII ionization edge at lower gravity and somewhat lower temperatures.

Figure 4 shows the T- $\log(g)$ plane with a contour marked 0045.4+4154 where all models are expected that show OVIII as the dominant absorption edge, and in which other strong edges (CV, CVI, NVI, NVII) are ionized away. The top line is the Eddington limit (static atmosphere stability limit). Below (and almost parallel) is the line which represents the nuclear burning stability limit from the H-R diagram of Iben (1982). All stable models for on-state emission must fall between these two lines. Tracks for white dwarfs of different mass are given. Figure 4 illustrates that the white dwarf in RX J0045.4+4154 is amongst the hottest systems and could fall on either side of the nuclear stability line. If close to the stability line, the temperature and luminosity indicates a mass between 1.3 and 1.4 $M_{\odot}$. It corresponds to an extreme model in the high-T top-left hand area in the HR-diagram (*cf* Figure 2 in Iben 1982). The on-off cycle time calculated by Iben (1982) for a 1.4 $M_{\odot}$ white dwarf accreting at a rate of $10^{-7} M_{\odot} \text{ yr}^{-1}$ is approximately consistent with the observed 340 d between outbursts, although the implied on-state time at this accretion rate ($\Delta t_{\text{on}} \sim 30 \text{ d}$) may be too large if the 2nd outburst ended after 14 days (Figure 2). The high observed temperature suggests that RX J0045.4+4154 is an extreme supersoft system, where the white dwarf is close to its Chandrasekhar limit.

This work has made use of archival data extracted from the High Energy Astrophysics Science Archive Research Center, HEASARC operated by the NASA Goddard Space Flight Center. We thank Peter Kahabka for useful discussions, and Walter Lewin and David Helfand for advice and encouragement.

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Table 1. *ROSAT* PSPC Observations used that include RX J0045.4+4154

ROR	Exposure	Offset	Det
s		°	
600065	28323	0.425	N
600066	30812	0.032	N
600067	27970	0.489	N
600121	45038	0.253	Y
600309	2576	0.459	N
600310	2721	0.351	N
600311	1352	0.282	N
600312	2415	0.260	N
600313	2672	0.303	Y
600314	2702	0.378	Y
600315	3033	0.488	Y
600329	1762	0.392	N
600330	2564	0.258	Y
600331	2875	0.144	N
600332	2954	0.091	Y
600333	3042	0.178	Y
600334	2888	0.294	N
600335	2363	0.425	Y
600349	2822	0.386	N
600350	2683	0.257	N
600351	2836	0.133	N
600352	2632	0.080	Y
600353	3007	0.174	Y
600354	2372	0.291	N
600355	1914	0.423	N
600369	2520	0.454	Y
600370	2866	0.349	N
600371	2082	0.270	N
600373	3136	0.292	Y
600374	2692	0.373	N
600375	3196	0.483	Y

ROSAT PSPC M31POS1 1992 Jan 5 Exposure: 45038 s

HEASARC/ESIS
Time Variability Image

Fig. 1.— The image on the left is the M31 field containing RX J0045.4+4154. On the right is the time variability image. The single bright spot indicates that this source is highly variable.

Fig. 2.— The upper and lower panels show the lightcurves of the two outbursts from RX J0045.4+4154. The accumulation time is 1482 s.

Fig. 3.— The upper panel shows the *ROSAT* PSPC spectrum of RX J0045.4+4154 along with the best fitting blackbody model. The lower panel shows the residuals from the model.

Fig. 4.— The temperature- $\log(g)$ plane for the model atmosphere fits to the overall spectrum from RX J0045.4+4154. The models are bounded by the Eddington limit (top curve). The range of models with fits within the $1\text{-}\sigma$ χ^2 -levels are indicated in the area marked 0045.4+4154. The thick line represents the expected relation for steady nuclear burning in accreting white dwarfs (c.f. Iben, 1982). Tracks for nuclear burning white dwarfs of different mass are indicated.