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Evidence for massive white dwarfs in the M 31 supersoft sources

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Abstract. Simulating *ROSAT PSPC* hardness ratios HR1 and HR2 and count rates for NLTE white dwarf atmosphere spectra one finds that the 15 supersoft sources in the spiral galaxy M 31 contain hot $\approx 3.0 - 4.5 \times 10^5$ K white dwarfs. If they undergo steady nuclear burning and if they are located close to the stability line then they harbor massive white dwarfs $M_{\rm WD} \approx 0.85 - 1.0\ M_\odot$ in agreement with what has been found for the galactic supersoft sources. The recurrent supersoft transient RX J0045.4+4154 affords a very hot $\approx 8.4 \times 10^5$ K white dwarf. If it is on the stability line then it has a white dwarf mass of $\approx 1.26\ M_\odot$. Taking a mass distribution of steadily nuclear burning white dwarfs into account one expects that there exist at least about 650 supersoft sources in M 31. The spectral parameters of the so far most distant ($D \sim 1.3$ Mpc) supersoft source found in the galaxy NGC 55 imply a hot ($\sim 6 \times 10^5$ K) and massive ($M_{\rm WD} \sim 1.1\ M_\odot$) white dwarf. The number of such sources seen in a galaxy at this distance is derived from a luminosity function of supersoft sources.

Key words: galaxies: individual: M 31 – galaxies: individual: NGC 55 – binaries: close – X-rays: stars – stars: evolution – white dwarfs

1. Introduction

Supersoft sources constitute an interesting new class of X-ray binary sources (cf. van den Heuvel et al. 1992). This is due to the fact that their spectra are extremely soft (effective temperatures of a few 10^5 K) and their luminosities are substantial ($10^{36} - 10^{38}$ erg s^{-1}). They thus can not only be studied in the Milky Way and the near-by Magellanic Clouds (LMC and SMC) but also in more distant galaxies (the Andromeda galaxy M 31 and the spiral galaxy NGC 55). For a review see Hasinger (1994) and Kahabka & Trümper (1996) and Kahabka & van den Heuvel (1997), see also Greiner (1996). They are considered to be at least one class of progenitors of type Ia supernovae (cf. Branch et al.1995, Livio 1996).

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2. The sample of supersoft sources in M 31

16 firm candidate supersoft sources have been found in M 31 with *ROSAT PSPC* (Supper et al. 1997, Greiner, Supper & Magnier 1997). The spectral parameters of the M 31 supersoft sources can be further constrained if the *ROSAT PSPC* hardness ratios HR1 and HR2 as given in Greiner, Supper & Magnier (1997) are taken into account. These hardness ratios should be compared with theoretical hardness ratios derived using white dwarf atmosphere spectra.

These hardness ratios have been calculated (cf. Kahabka 1997) for model M4 (NLTE, LMC abundance, log g=9) for the temperature grid available from the model atmosphere spectra (cf. Heise et al. 1994, van Teeseling et al. 1996, Hartmann & Heise 1997) and for Hydrogen column density 0 and in the range 2 to 50 $\times$ 10^{20} cm^{-2} making use of the X-ray spectroscopy package described in Kahabka (1997). In Fig. 1 and Fig. 2 these hardness ratios are presented for these models and in Fig. 3 the *ROSAT PSPC* count rate is given for a steadily nuclear burning source. Greiner, Supper & Magnier (1997) give for the 16 M 31 supersoft sources hardness ratios HR1 and HR2. Selection as a supersoft source was according to the criterion $HR1{+}\sigma_{\rm HR1} \le -0.80$. If one assumes that the hydrogen column extends over the range $8-20\times10^{20}$cm^{-2} one finds making use of the M4 model and combining the HR1, HR2 and the count rate information of the sources given in Table 1 that the effective temperature is constrained to the range $\approx 3.0 - 4.5 \times 10^5$ K. The lower bound of the temperature has been derived from the $N_{\rm H}$-$T_{\rm eff}$ plane of individual sources (cf. the example given for the recurrent transient RX J0045.4+4154 (White et al. 1994) in Fig. 5) by extrapolating the parameter confidence regions below the lower bound of the presently used temperature grid of 4×10^5 K. The range of white dwarf masses derived from this temperature range (assuming the stability line relation given in Fig. 4) is consistent with the properties found for the galactic supersoft sources: Massive ($M_{\rm WD}{\gtrsim}1.0 M_\odot$) white dwarfs are found which undergo steady nuclear burning and which can be found in the Hertzsprung-Russell diagram of hot steady nuclear burning white dwarfs (cf. Iben 1982, Fig. 2 and this Fig. 4) close to the stability line. The stability line is the location where the plateau and the cooling track join for different white dwarf masses (Fig. 4).

Table 1. *ROSAT PSPC* count rates, hardness ratios HR1, from NLTE white dwarf atmosphere model M4 derived absorbing hydrogen columns (10^{21} cm^{-2}), effective temperatures $T_{\rm eff}$ (10^5 K) and white dwarf masses $M_{\rm WD}$ ($M_{\odot}$) for the 16 supersoft sources in M 31 (sample of Greiner, Supper & Magnier 1997).

Source name	rate (10^{-3} s^{-1})	HR1	HR2	$N_{\rm H}$ (10^{21} cm^{-1})	$T_{\rm eff}$ (10^5 K)	$M_{\rm WD}$ ($M_{\odot}$)
RX J0037.4+4015	0.31±0.31	-0.93±0.31	0.02±0.71	≤1.6	≤4.0	≤0.95
RX J0038.5+4014	0.80±0.28	-0.92±0.08	-0.49±0.53	0.8-1.6	3.0-4.3	0.86-0.98
RX J0038.6+4020	1.73±0.29	-0.93±0.06	0.32±0.66	0.8-1.2	3.2-4.4	0.87-0.99
RX J0039.6+4054	0.44±0.44	-0.92±0.02	-0.04±0.71	≤1.6	≤ 4.2	≤0.97
RX J0040.4+4009	0.85±0.32	-0.94±0.06	-0.90±0.10	0.8-1.6	3.2-4.2	0.87-0.97
RX J0040.7+4015	1.26±0.32	-0.94±0.06	-0.31±0.64	0.8-1.5	3.2-4.4	0.87-0.99
RX J0041.5+4040	0.32±0.18	-0.95±0.05	-0.62±0.44	0.8-1.6	3.6-3.9	0.91-0.95
RX J0041.8+4059	0.49±0.24	-0.93±0.07	-0.63±0.43	0.8-1.8	3.4-4.1	0.89-0.96
RX J0042.4+4044	1.69±0.32	-0.93±0.07	-0.07±0.70	0.8-1.4	3.2-4.4	0.87-0.99
RX J0043.5+4207	2.15±0.55	-0.92±0.08	-0.27±0.66	0.8-1.4	3.2-4.5	0.87-1.00
RX J0044.0+4118	2.46±0.42	-0.94±0.06	0.11±0.81	0.8-1.3	3.7-4.5	0.93-1.00
RX J0045.4+4154	29.6±1.0	+0.78±0.03	-0.59±0.03	4.0-4.2	8.4-8.5	1.26-1.27
RX J0045.5+4206	3.14±0.34	-0.89±0.07	-0.29±0.65	1.0-1.3	4.1-4.6	0.96-1.01
RX J0046.2+4144	2.15±0.39	-0.93±0.07	0.62±0.40	0.8-1.2	3.1-4.4	0.87-0.99
RX J0046.2+4138	1.12±0.40	-0.91±0.09	-0.27±0.65	0.8-1.7	3.4-4.4	0.89-0.99
RX J0047.6+4205	1.05±0.36	-0.92±0.07	0.06±0.70	≤1.6	≤4.0	≤0.95

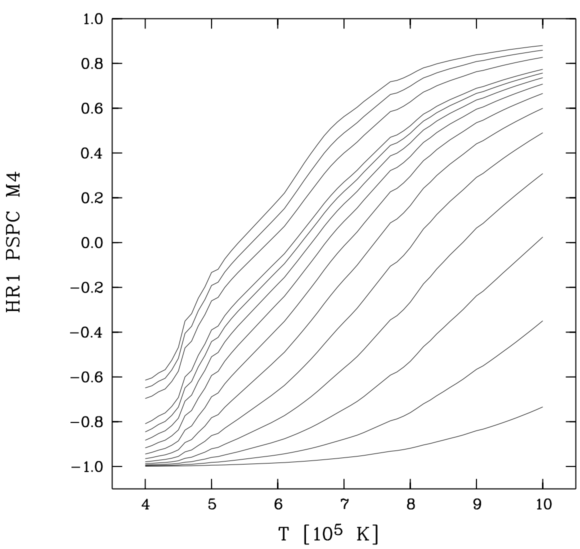

Fig. 1. Hardness ratio HR1 for *ROSAT PSPC* and model M4 (NLTE, log g=9, LMC opacitiy). Isolines are given for H-columns of $0, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 30, 40, 50 \times 10^{20}$ cm^{-2} (from bottom to top).

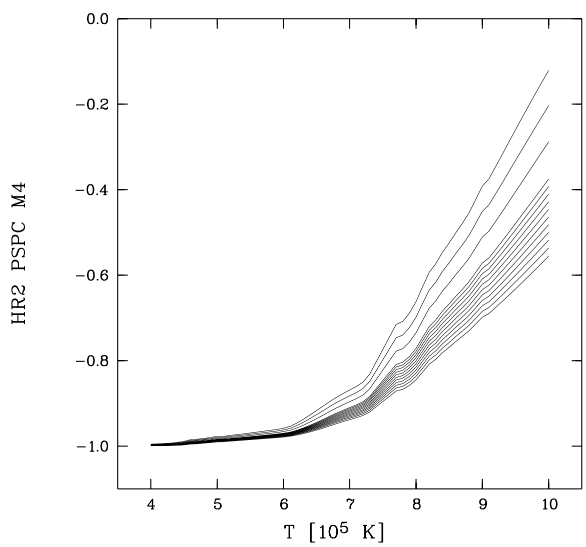

Fig. 2. Hardness ratio HR2 for *ROSAT PSPC* and model M4 (NLTE, log g=9, LMC opacitiy). Isolines are given for H-columns of $0, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 30, 40, 50 \times 10^{20}$ cm^{-2} (from bottom to top).

The question arises where are the less hot (and most probably less massive) steady nuclear burning white dwarfs? They have according to Fig. 1 a hardness ratio HR1 very close to HR1=-1 and more importantly they are faint. They cannot be easily detected in a galaxy like M 31. The important conclusion which can be drawn from this is that there are ~15 massive ($M_{\rm WD} \sim 0.85 - 1.0\ M_{\odot}$) white dwarfs in M 31 undergoing steady nuclear burning. Widening the upper $N_{\rm H}$ bound to 3×10^{21} cm^{-2} would not affect this mass constraint at all. Another point to mention is that the supersoft transient source RX J0045.4+4154 must indeed be connected with a very massive white dwarf. For HR2=-0.6 one finds with Fig. 2 a temperature $T \approx 8.4 \times 10^5$ K assuming $N_{\rm H} \approx 4. \times 10^{21}$ (cf. Fig. 5 for the $N_{\rm H}$-$T_{\rm eff}$ parameter plane).

This temperature is similarly high as for CAL 87 (Parmar et al 1997) or RX J0925.7-4758 (Ebisawa et al. 1996). It corresponds assuming that the source is on the stability line to a white dwarf mass $M_{\rm WD} \sim 1.26\ M_{\odot}$. Taking this important mass constraint into account and assuming that about 4.6% of the supersoft sources have white dwarf masses $\gtrsim 0.86 - 1.0\ M_{\odot}$, which

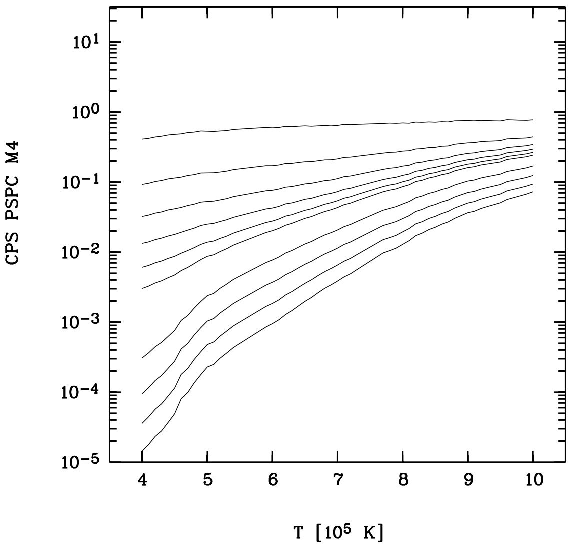

Fig. 3. Count rates [1/s] for *ROSAT PSPC* and model M4 (lower panel) for a distance of 700 kpc (M 31). Isolines are given for H-columns of $0, 2, 4, 6, 8, 10, 20, 30, 40, 50 \times 10^{20}$ cm^{-2} (from top to bottom).

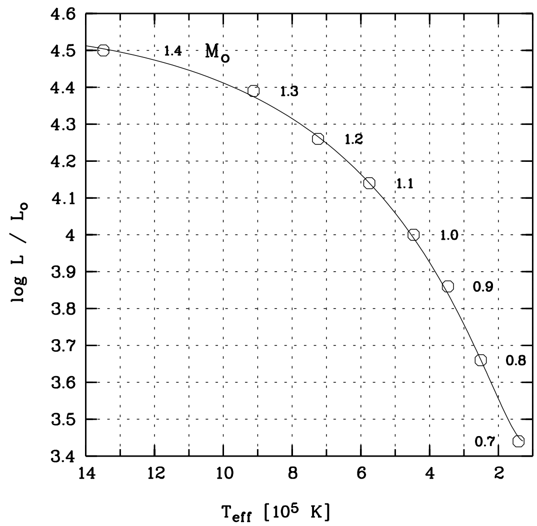

Fig. 4. Stability line of steady nuclear burning in the Hertzsprung-Russell diagram ($T_{\rm eff}$ - L plane) of supersoft sources as deduced from Iben (1982), Fig. 2. Circles mark values for white dwarf masses in the range $0.7 - 1.4\ M_\odot$.

follows from the population synthesis calculations of Yungelson et al. (1996), one expects that there are at least about 650 supersoft sources in M 31. This number increases accordingly if one widens the hardness ratio criterion as then about 30 candidates are found (Hasinger 1994). Due to selection effects (obscuration due to absorption in M 31) not all massive supersoft sources are expected to be seen. Thus the number of 650 supersoft sources is a lower limit on the total number. From the number / count rate diagram shown in Fig. 6, upper panel, investigation of the isoline $N_{\rm H}$ = 8.10^{20} cm^{-2} shows that a detection limit of 0.3×10^{-3} counts/sec corresponds to a white dwarf mass of $\sim 0.85\ M_\odot$. This means only supersoft sources with masses in excess of $\sim 0.86\ M_\odot$ are expected to be seen which is consistent with the lower mass bound of $\sim 0.85 M_\odot$ derived from the spectral properties of the sources. Also it can be seen from this figure that sources seen with an absorption in excess of $N_{\rm H}$ = 20 $\times$ 10^{20} will fall below the detection limit in agreement with the range of $N_{\rm H}$ values derived for the individual sources in Table 1. This result is consistent with the distribution of white dwarf masses derived by Di Stefano (1996) for the M 31 supersoft sources. The fact that only one supersoft source is found for the mass range $\approx 1.2 - 1.3\ M_\odot$ can be explained due to the selection criteria applied by Greiner, Supper & Magnier. From Fig. 1 one finds that a much wider range in HR1, HR1 $\leq$ +0.8, has to be considered to cover the complete sample with temperatures $\approx$3-13 $\times 10^5$K, equivalent to masses $\approx 0.85\ M_\odot \leq M_{WD} \leq 1.4\ M_\odot$. A fraction of these candidates may be contained in the sample of 30 sources mentioned in Hasinger (1994).

3. The supersoft source in NGC 55

The catalog of Singh et al. (1995) of a sample of extremely soft sources contains one source (RX J0016.0-3914) in the direction towards the galaxy NGC 55. Schlegel et al. (1997) confirm this source to be supersoft (equivalent blackbody temperature of $\sim$25 eV), most likely associated with the galaxy and of transient nature. They derive a blackbody luminosity of $\sim 9 \times 10^{37}$ erg s^{-1} for a Hydrogen column of $\sim 6 \times 10^{20}$ cm^{-2} and for an assumed distance of 1.3 Mpc (Pritchet et al. 1987). It thus constitutes the most distant supersoft source detected so far. The extreme low galactic column density (of $\sim 1.5 \times 10^{20}$ cm^{-2}) towards this galaxy and the low total column density associated with the source (of $\sim 6 \times 10^{20}$ cm^{-2}) may make the detection of such a distant source rather unique. It has been found that the blackbody description is not the correct description. LTE or NLTE spectral models have to be fitted to the spectra. It follows from Fig. 1 that a hardness ratio of HR1=-0.8 (and using the $N_{\rm H}$ value found from the blackbody fit) gives an effective NLTE temperature of $\sim$6 $\times$ 10^5 K. This temperature is consistent with the temperatures found for the 15 supersoft sources in M 31. It implies a massive $M_{\rm WD} \sim 1.1\ M_\odot$ white dwarf. Taking the white dwarf mass distribution of Yungelson et al. (1996) into account then 1.0% of the white dwarfs are expected to have masses in excess of 1.1 $M_\odot$.

It is challenging to search in galaxies more distant than M 31 ($D \lesssim$3 Mpc) for supersoft sources. The Sculptor group galaxy NGC 55 is the best example that one will most probably be successful. The supersoft source found there is extremely bright (count rate of $\sim 1.10^{-2}$ sec^{-1}) for a source at such a distance. This is due to the low Hydrogen column and the hot (and massive) white dwarf involved. Assuming a detection limit of $\sim 5.10^{-4}$ sec^{-1} (10 counts in 20 ksec) such a source might be

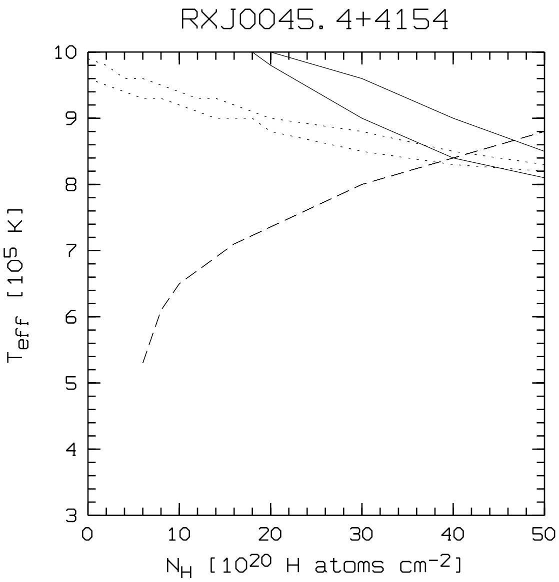

Fig. 5. Effective temperature T_{eff} – absorbing column density N_H plane for the recurrent supersoft source RX J0045.4+4154 (White et al. 1994). Solid band gives the HR1 constraint, dotted band the HR2 constraint and dashed band the count rate constraint.

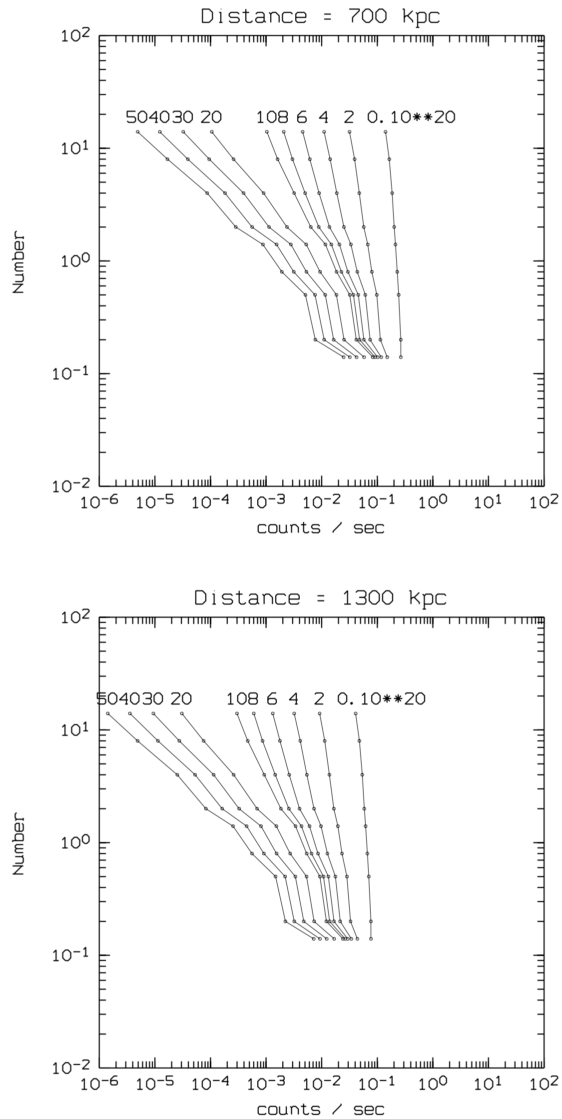

Fig. 6. Number/count rate diagram of supersoft sources for a galaxy of the size of the Milky Way and for a distance of 700 kpc (M 31), upper panel, and 1.3 Mpc (NGC 55), lower panel. Note that a galaxy like M 31 has a mass twice as large as the Milky Way and NGC 55 0.1× as large. These numbers follow from the population synthesis calculations of Yungelson et al. (1996) for the Milky Way galaxy. Labels mark Hydrogen column densities (10^{20} cm^{-2}). Dots mark white dwarf masses (counted from bottom to top) 1.34,1.29,1.25,1.20,1.15,1.10,1.05,1.00,0.95 $M_\odot$.

detected up to distances of $\sim$ 10 Mpc, a huge distance. The most promising region in the sky, i.e. of low ($N_{\rm H} \sim 10^{19}$ H-atomes cm^{-2}) galactic foreground column, is the so-called Lockman hole. Distant supersoft sources might be detected in this area of the sky.

In order to predict the number of supersoft sources seen in more distant galaxies like NGC 55 the expected count rates for supersoft sources with masses in the range 0.7 – 1.4 $M_\odot$ in the *ROSAT* band have been calculated. The number of systems for a given white dwarf mass follows from the population synthesis calculation of Yungelson et al. (1996). Using this information a number/count rate distribution has been calculated which is shown in Fig. 6, lower panel (for a distance of 1.3 Mpc). This diagram is bounded to white dwarf masses in excess of 0.95 $M_\odot$ due to the lower bound of the temperature grid of 4 × 10^5 K. It follows from this figure that about 1 massive ($M_{\rm WD} \sim 1.1\ M_\odot$) white dwarf is expected to be seen at a count rate of $\sim 10^{-2}$ cm^{-2} and for a H-column of $\sim 1.5 \times 10^{20}$ cm^{-2} if the mass of NGC 55 is 10% of the mass of the Milky Way in agreement with the fact that one such system has been discovered.

4. Conclusions

Using the HR1 information deduced for the 15 supersoft sources in M 31 one finds hot ($T_{\rm eff} \approx 3 - 4.5 \times 10^5$ K) white dwarfs. If they undergo steady nuclear burning and if they are close to the stability line then these systems harbor massive ($M_{\rm WD} \sim 0.86-1.0\ M_\odot$) white dwarfs. Taking a white dwarf mass function into account ∼4.6% of such massive systems are expected to exist and there may be at least about 650 supersoft sources in M 31. The recurrent supersoft M 31 transient affords a very hot ($T_{\rm eff} \approx 8.4 \times 10^5$ K) and massive ($M_{\rm WD} \sim 1.26\ M_\odot$) white dwarf. The so far most distant ($D \sim 1.3$ Mpc) supersoft source found in the Sculptor group galaxy NGC 55 implies a hot ($T \sim 6.10^5$ K) and massive ($M_{\rm WD} \sim 1.1\ M_\odot$) white dwarf. A number/count rate distribution for supersoft sources is calculated which can be used to estimate the number of supersoft sources seen for a given Hydrogen absorbing column and distance, for galaxies of the same mass as the Milky Way.

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