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LUMINOUS SUPERSOFT X-RAY SOURCES

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ABSTRACT
Luminous supersoft X-ray sources were discovered with the Einstein observatory and have been established as an important new class of X-ray binaries on the basis of observations with the Roentgen Satellite (ROSAT). They have extremely soft spectra (equivalent blackbody temperatures of ∼15–80 eV) and are highly luminous (bolometric luminosities of 10^{36}–10^{38} erg s^{-1}). Correcting for the heavy extinction of soft X rays by interstellar neutral hydrogen, their numbers in the disks of ordinary spiral galaxies like our own and M31 are estimated to be of the order of 10^3. Their observed characteristics are consistent with those of white dwarfs, which are steadily or cyclically burning hydrogen-rich matter accreted onto the surface at a rate of order 10^{-7} $M_\odot$ year^{-1}. The required high accretion rates can be supplied by mass transfer on a thermal time scale (10^6–10^7 years) from close companion stars that are more massive than the white dwarf accretor, typically 1.3–2.5 $M_\odot$. Steady burning can also occur in a post-nova stage, but for shorter time scales, and it has been observed in a few classical novae and symbiotic novae. A few supersoft sources have been found to be recurrent transients. They are possibly connected with very massive white dwarfs accreting at high rates. Luminous supersoft sources may make a considerable contribution to the Type Ia supernova rate in spiral and irregular galaxies.

1. INTRODUCTION

The luminous supersoft X-ray sources (SSS) were recognized as an important new class of intrinsically bright X-ray sources by Trümper et al (1991) (see also Greiner et al 1991). A careful analysis of the X-ray spectral properties of the first few sources of this type found in the Large Magellanic Cloud (LMC) showed

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that while their X-ray luminosities are of the order of the Eddington limit (about 10^{38} erg s^{-1}), their X-ray spectra are extremely soft, peaking at energies in the range 15–80 eV, on average of order 30–40 eV. This corresponds to a blackbody temperature typically of ∼300,000–500,000 K, some two orders of magnitude lower than for that of the classical X-ray binaries which contain neutron stars or black holes. As these peak energies of around 40 eV are below the lower energy limit of the ROSAT detectors, the extrapolations of the observed tails of the energy distributions towards lower energies are, of course, rather uncertain, especially since at these energies extinction by interstellar neutral hydrogen plays a large role. Nevertheless, taking realistic error margins in these extrapolations into account, the total X-ray luminosities of these LMC sources always come out close to the Eddington limit (Greiner et al 1991, van Teeseling et al 1996a). Therefore, there can be no doubt that they are intrinsically highly luminous. The discovery of a large ionization region with a diameter of several tens of parsecs around the supersoft LMC source CAL 83 (Remillard et al 1995) is a further confirmation of their very high soft X-ray luminosities.

So far, some 35 luminous SSS have been found with ROSAT, 16 in the Andromeda Nebula (M31), 11 in the two Magellanic Clouds, 7 in our own Galaxy and 1 in the Local Group galaxy NGC 55 (see Table 1). In view of the very large interstellar extinction of soft X rays, the sources in the other galaxies can only be observed when they are near the outer edge of the interstellar neutral hydrogen layer, at our side of that galaxy. Taking this into account, the total numbers of sources in M31 and in our Galaxy are estimated to be some two orders of magnitude larger than the observed numbers, and in the LMC some 20 times larger (cf Rappaport et al 1994b). The SSS therefore constitute a major new population of highly luminous X-ray sources in spiral galaxies like our own.

In this article, we review the observed characteristics of these luminous SSS ($L_x = 10^{36}$–10^{38} erg s^{-1}) and the theoretical models that have been put forward for them. [Other types of less luminous supersoft sources have also been discovered with ROSAT in our Galaxy, in our local neighborhood, for example PG 1159 stars, certain CV systems, and some nuclei of planetary nebulae (see Greiner 1996b). These are not the subject of this review. The same holds for active galactic nuclei (AGNs) with supersoft spectra.] The now generally accepted model for the luminous SSS is that, with few exceptions, these sources are accreting white dwarfs (WDs) in binaries, which are burning hydrogen in their envelopes in a steady or intermittend way (van den Heuvel et al 1992). In Section 2, we review how the luminous supersoft sources were first recognized as a separate class of X-ray sources and how the accreting binary WD model with surface nuclear burning has arisen. In Section 3, we review the observations in terms of source samples, both in X rays and at other wavelengths, in external galaxies as well as our own Galaxy. Section 5 is devoted to physical models of accreting WDs with nuclear burning and Section 6 to the evolutionary history of the different types of luminous SSS. We also review in Section 6 the results of population synthesis calculations, and we compare these results with the observations. Finally, in Section 7 we discuss the possible relation between SSS and Type Ia supernovae (SN Ia). Important recent publications on the subject of SSS can be found in the proceedings of a recent workshop on this subject (Greiner 1996a).

2. THE RECOGNITION OF THE LUMINOUS SSS AS A NEW CLASS AND THE WD MODEL WITH SURFACE NUCLEAR BURNING

2.1 *Discovery*

Four of the luminous SSS, CAL 83 and CAL 87 in the LMC and 1E 0035.4-7230 and 1 E0056.8-7154 in the Small Magellanic Cloud (SMC), had already been discovered with the Einstein satellite around 1980 by Long et al (1981) and Seward & Mitchell (1981), respectively. It was recognized that the sources have unusually soft spectra, but since the Einstein satellite had a different energy range and a lower spectral resolution than ROSAT, they were not recognized as a separate class. Since black hole sources often also have quite soft spectra, the first idea was that CAL 83 and CAL 87 are black holes in binary systems (Smale et al 1988, Cowley et al 1990, Cowley 1992, Wang et al 1991, Wang & Wu 1992). What is called soft in connection with the black hole sources is, however, still a fairly hard type of X ray (i.e. with a large flux in the 0.1- to 1-keV range); in addition, black hole sources always have an important hard component (Tanaka & Lewin 1995), which is completely lacking in the SSS. It was only thanks to ROSAT that the SSS could be clearly distinguished from the classical strong point X-ray sources (accreting neutron stars and black holes in binaries) and from the X-ray emission of coronae of nearby solar type stars, on the basis of their observed ROSAT X-ray spectra, as depicted in Figure 1. The classical strong point X-ray sources typically have blackbody temperatures on the order of several times 10^7 K, and therefore their main emission is observed in the hardest ROSAT energy band, with hardly any emission in the softest ROSAT bands. Stellar coronae (solar-type stars) typically have temperatures of about 1–3 $\times$ 10^6 K, which causes them to produce, in addition to a strong signal in the lowest energy bands of ROSAT, a significant signal also in the harder ROSAT band. Figure 1 shows that the SSS can be immediately recognized as a distinct class with extremely soft spectra. The peak of their energy distributions is actually lower than the lower cutoff of the softest ROSAT band.

Table 1 Summary of all known luminous supersoft X-ray sources[a]

Name	Count rate (cts/s)	T (eV)	L_{bol} (erg/s)	Type	Period	Ref.[b]
LMC						
RX J0439.8-6809	1.35	21–27 (wd)	$0.6–1.5 \times 10^{37}$	CV	3.37 h	1–4
RX J0513.9-6951	<0.06–2.0	34–54 (wd)	$1.2–4.8 \times 10^{37}$	CBSS	18.3 h	2, 5–10
RX J0527.8-6954	0.004–0.25	27–68 (wd)	$0.038–3.0 \times 10^{37}$	CBSS?		2, 7, 11–15
RX J0537.6-7034	0.02	18–30 (bb)	$0.6–2 \times 10^{37}$			16–17
CAL 83	0.98	34–54 (wd)	$0.38–4.8 \times 10^{37}$	CBSS	1.04 day	12, 18–19
CAL 87	0.09	68–86 (wd)	$1.2–9.5 \times 10^{37}$	CBSS	10.6 h	18–22
RX J0550.0-7151	<0.02–0.9	25–40 (bb)				2, 7
SMC						
1E0035.4-7230	0.33	34–54 (wd)	$0.38–1.2 \times 10^{37}$	CV	4.1 h	23–25
RX J0048.4-7332	0.19	25–45 (wd)	$0.48–1.2 \times 10^{37}$	Sy-N		22, 26–29
RX J0058.6-7146	<0.001–0.7	15–70 (bb)	2×10^{36}			22
1E0056.8-7154	0.29	27–43 (wd)	$1.5–3.8 \times 10^{37}$	PN		30
Milky Way						
RX J0019.8+2156	2.0	21–27 (wd)	$3–9 \times 10^{36}$	CBSS	15.8 h	43–45
RX J0925.7-4758	1.0	70–100 (wd)	$3–7 \times 10^{35}$	CBSS	3.8 day	40–42
Nova 1983 Mus	0.1	25–35 (bb)	$1–2 \times 10^{38}$	CV-N	85 min	31, 32–36
1E 1339.8+2837	0.01–1.1	20–45 (bb)	$0.12–10 \times 10^{35}$			46–47
AG Dra	1.0	10–15 (bb)	1.4×10^{36}	Sy	554 day	49–50
RR Tel	0.18	14 (wd)	1.3×10^{37}	Sy-N	387 day	29, 48
Nova V1974 Cygni	0.03–76		2×10^{38}	CV-N	1.95 h	38, 39
M31						
a. RX J0037.4+4015	0.3×10^{-3}	43 (bb)				51
b. RX J0038.5+4014	0.8×10^{-3}	45 (bb)				51
c. RX J0038.6+4020	1.7×10^{-3}	43 (bb)				51

d. RX J0039.6+4054	0.4×10^{-3}	45 (bb)				51
e. RX J0040.4+4009	0.8×10^{-3}	42 (bb)				51
f. RX J0040.7+4015	1.3×10^{-3}	42 (bb)				51
g. RX J0041.5+4040	0.3×10^{-3}	40 (bb)				51
h. RX J0041.8+4059	0.5×10^{-3}	43 (bb)				51
i. RX J0042.4+4044	1.7×10^{-3}	43 (bb)				51
j. RX J0043.5+4207	2.2×10^{-3}	45 (bb)				51
k. RX J0044.0+4118	2.5×10^{-3}	42 (bb)				51
RX J0045.4+4154	$<10^{-5}$–0.03	70–90 (wd)				52
l. RX J0045.5+4206	3.1×10^{-3}	20–48 (bb)				53
m. RX J0046.2+4144	2.1×10^{-3}	38 (bb)				51
n. RX J0046.2+4138	1.1×10^{-3}	40 (bb)				51
o. RX J0047.6+4205	1.0×10^{-3}	39 (bb)				51
NGC 55						
RX J0016.0-3914	4.5×10^{-3}					54

[a] Excluding PG 1159-type stars and supersoft AGNs. Given for each source are the name (column 1); the ROSAT PSPC count rate (column 2); the best-fit X-ray temperature (bb = blackbody, wd = white dwarf) (column 3); the bolometric luminosity (column 4); the type of the system (CBSS = close binary supersoft source, PN = planetary nebula, Sy = symbiotic system, N = Nova, CV = cataclysmic variable) (column 5); the binary period (column 6); references (column 7) (from Greiner 1996a,b). Columns 3 and 4 in part from Kahabka & Trümper 1996; P Kahabka, in preparation.

[b] References: (1) Greiner et al (1994); (2) Cowley et al (1996); (3) van Teeseling et al (1996b); (4) Schmidtke & Cowley (1996); (5) Schaeidt et al (1993); (6) Pakull et al (1993); (7) Cowley et al (1993); (8) Crampton et al (1996); (9) Hutchings et al (1995); (10) Schaeidt (1996); (11) Trümper et al (1991); (12) Greiner et al (1991); (13) Orio & Ögelman (1993); (14) Hasinger (1994); (15) Greiner et al (1996b); (16) Orio & Ögelman (1993); (17) Orio et al (1996); (18) Long et al (1981); (19) Smale et al (1988); (20) Pakull et al (1988); (21) Schmidtke et al (1993); (22) Kahabka et al (1994); (23) Wang & Wu (1992); (24) Orio et al (1994); (25) Schmidtke et al (1996); (26) Vogel & Morgan (1994); (27) Morgan (1992); (28) Jordan et al (1996); (29) Mürset et al (1996); (30) Heise et al (1994); (31) Krautter & Williams (1989); (32) Diaz & Steiner (1989); (33) Diaz & Steiner (1994); (34) Diaz et al (1995); (35) Ögelman et al (1993); (36) Shanley et al (1995); (37) Krautter et al (1996); (38) Shore et al (1993); (39) Shore et al (1994); (40) Motch et al (1994); (41) Motch (1996); (42) Ebisawa et al (1996); (43) Beuermann et al (1995); (44) Greiner & Wenzel (1995); (45) Gänsicke et al (1996) (46) Verbunt et al (1993); (47) Hertz et al (1993); (48) Jordan et al (1994); (49) Viotti et al (1996); (50) Greiner et al (1996d); (51) Greiner et al (1996b); (52) White et al (1994); (53) R Supper, in preparation; (54) Singh et al (1995).

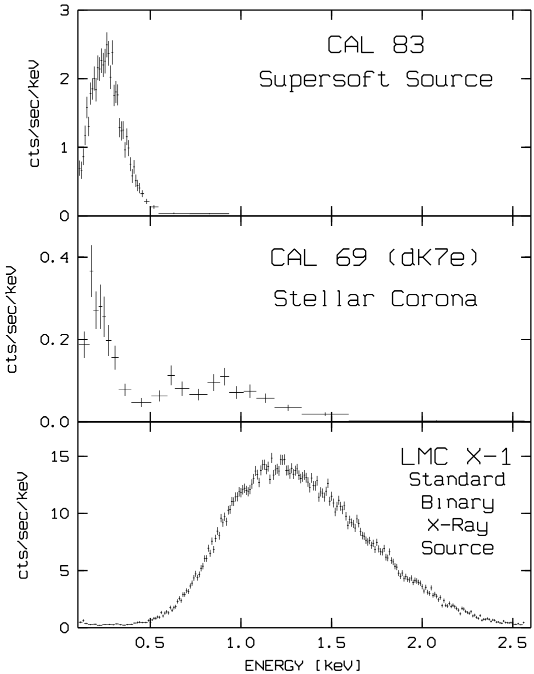

Figure 1 ROSAT PSPC count spectra of three objects in the Large Magellanic Cloud (LMC) field: the SSS CAL 83, the dK7e foreground star CAL 69, and the black hole candidate LMC X-1 (similar to Figure 2 of Trümper et al 1991).

The effects of extinction by interstellar neutral hydrogen on their ROSAT spectra is schematically illustrated in Figure 2. For large column densities, the soft part of the spectrum is completely blocked by the interstellar medium (ISM), and only the "hard" tail of the spectrum is observed. The figure illustrates the expected ROSAT response to a 300,000-K blackbody spectrum, for a hydrogen column density of 2.10^{20} cm^{-2} (SA Rappaport, private communication). As the column density towards a source is not known beforehand, the analysis of the observed ROSAT spectra yields combinations of L_X and T_{eff} (assuming a blackbody) that still depend on the assumed column density.

2.2 *The Binary Nature of CAL 83 and CAL 87*

CAL 83 was optically identified with a star of magnitude V = 16.8 by Smale et al (1988) and CAL 87 with a star of magnitude about V = 20 by Pakull et al (1988). The optical studies of CAL 83 by Smale et al (1988) revealed regular photometric variations with a period of 1.04 days. The light curve

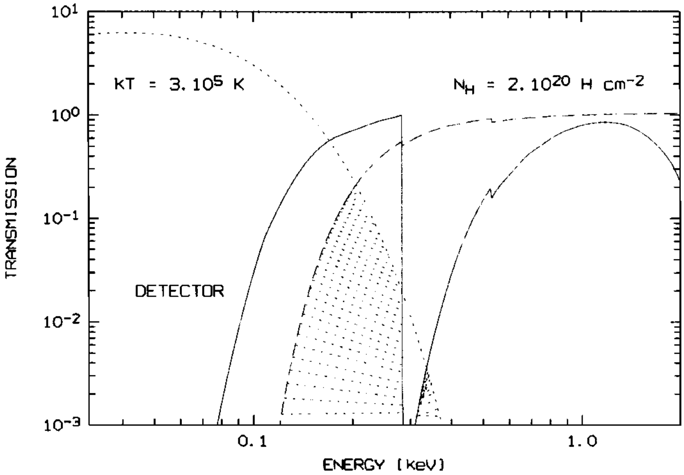

Figure 2 ROSAT PSPC efficiency (*solid curve*), transmission of ISM for hydrogen column of 2.10^{20} H atoms cm^{-2} (*dashed line*), distribution of a 3.10^5-K blackbody spectrum (*dotted line*) and folded (observed) distribution (*hatch marks*) (SA Rappaport, private communication).

is approximately sinusoidal with an amplitude of about 0.1 magnitude (mag). Similarly, CAL 87 was found to show regular photometric variations with a period of 10.6 h (Cowley et al 1990). The light curve resembles that of an eclipsing binary with a deep primary minimum (about 1.3 mag) and a small and variable secondary minimum (cf Schmidtke et al 1993). Figure 3 depicts the average light curves of CAL 83 and CAL 87, together with a proposed schematic explanation of the shapes in terms of a model with an optically bright accretion disk and a companion that is strongly heated on one side (see Figure 3 caption).

As for their optical spectra, both sources—as well as other LMC sources—show strong emission of He IIλ4686 as well as the Balmer lines of hydrogen, but the CIII/NIII-complex near λ4640 (Figure 4) usually seen in low-mass X-ray binaries is absent in CAL 87 and only weakly present in CAL 83. [The similarity of the optical spectra with those of low-mass X-ray binaries led at first to the suggestion that SSS might be neutron stars (cf Greiner et al 1991, Kylafis & Xilouris 1993).] In CAL 87, the strengths of the emission lines are not strongly dependent on orbital phase (Cowley et al 1990), which indicates that they must arise in a volume that is large in comparison to the eclipsing donor star: They probably arise in a corona around the binary system or in a stellar wind emanating from the disk, the X-ray source, or the heated side of the donor star (van den Heuvel et al 1992). The X rays in CAL 87 do show an eclipse

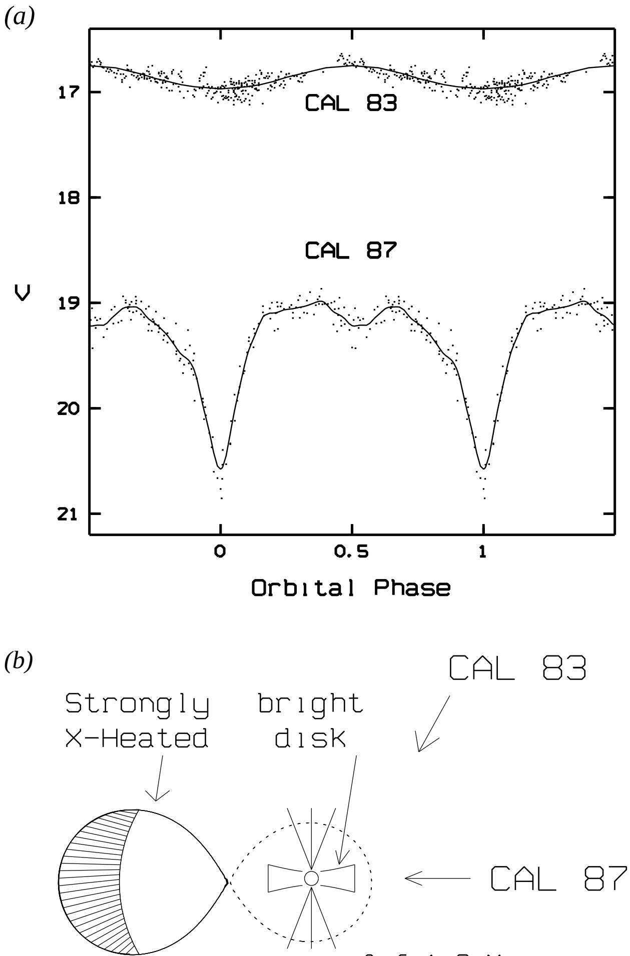

Figure 3 (*a*) Optical light curves in the Johnson V-band of CAL 83 and CAL 87 plotted on the same scale for comparison. The *solid curves* give the mean light curves. The upper light curve is adapted from Smale et al (1988), the lower light curve from Schmidtke et al (1993). (*b*) Schematic model for explaining the optical light curves of CAL 83 and 87: The main light sources in the systems are the very bright accretion disk and the X-ray heated side of the donor star. In CAL 87 the accretion disk is regularly eclipsed; CAL 83 is seen at low inclination, such that only the heating effect is observed [after van den Heuvel et al (1992); for a refined model, see S Schandl et al (1996); see also section on The "Standard" CBSS].

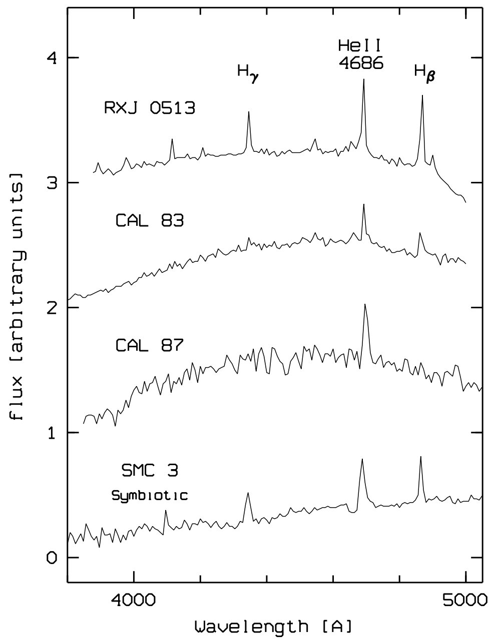

Figure 4 Optical spectra of RX J0513.9-6951 and CAL 83 (from Cowley et al 1993), CAL 87 (from Pakull et al 1988), and SMC 3 (from Morgan 1992).

(Kahabka et al 1994), although not as deep as the optical photometric eclipse. They therefore arise in a smaller volume than the emission lines. Recently, from HST observations, Deutsch et al (1996) discovered that CAL 87 has two very close optical companions (distances 0.88″ and 0.66″) that contribute significant light at the time of minimum light. These are a mid-G type subgiant and a late A main-sequence star. Outside eclipse, they together contribute 20–25% of the light. Therefore, the eclipse of the system is in fact deeper than depicted in Figure 3, and also, the close optical companions, with a combined spectrum of type F, dominate the optical spectrum of the system observed at minimum light, as they provide some 70% of the light at this orbital phase. Hence, unfortunately, this spectrum does not provide accurate information about the intrinsic spectral type (unheated) that one expects to be observed at the dark side of the star.

2.3 *Why Nuclear Burning on the Surface of a WD?*

The luminosity and effective temperature of a star allow one to derive its radius by using Stefan-Boltzman's law:

$$L = 4\pi R^2 \sigma T^4, \quad (1)$$

Table 2 Energy gain from accretion onto a 1-$M_\odot$ black hole, neutron star, and white dwarf, compared with energy gain by nuclear burning of hydrogen

	Energy release	
Compact object	Accretion	Nuclear burning
Black hole	(0.1–0.42) mc^2	—
Neutron star	0.15 mc^2	0.007 mc^2
White dwarf	0.00025 mc^2	0.007 mc^2

which yields

$$R = 9 \times 10^8 (L_{37.5})^{1/2} (T_e/40\ \mathrm{eV})^{-2}\ \mathrm{cm}, \tag{2}$$

where $L_{37.5}$ is the X-ray luminosity in units of $10^{37.5}$ erg/s, and T_e is the effective temperature in electron volts.

Equation 2 shows that for values characteristic for the luminous SSS, namely $L_{37.5} = 1$ and $T_e = 40$ eV, the emitting object has a radius of about 9000 km, i.e. similar to that of a WD. For this reason, Grindlay suggested (JE Grindlay, personal communication) that, in analogy with the accreting neutron stars and black holes in the classical X-ray binaries, the X rays are generated here by accretion of matter onto a WD. In this case, in order to generate $10^{37.5}$ erg/s, as Table 2 shows, a solar mass WD with a radius of 6000 km should accrete some $2.10^{-6}\ M_\odot$ year^{-1}, a huge amount!

A simple calculation shows, however, that with such an accretion rate, the inflowing matter would have an optical thickness large enough to block the soft X rays from coming out.

There is, however, a great difference between the energy generation by accretion onto neutron stars and black holes on the one hand and WDs on the other, as Table 2 shows, namely the following: The energy release by accretion of hydrogen onto neutron stars and black holes per unit mass is some 20 times more than the energy release by nuclear fusion of hydrogen in the same amount of mass. Therefore, in the case of neutron stars and black holes, nuclear fusion makes a negligible contribution to the energy generation. On the other hand, in the case of a WD, the energy release by accretion is some 30 times smaller than the energy release by nuclear fusion in the same amount of matter. van den Heuvel et al (1992) realized that if the accreted matter on the surface of a WD begins to burn steadily, an accretion rate is necessary that is some 30 times lower than the rate required for energy generation purely by accretion. The required rate then is only of order $10^{-7}\ M_\odot$ year^{-1}, and in this case the soft X rays can be shown to be able to escape.

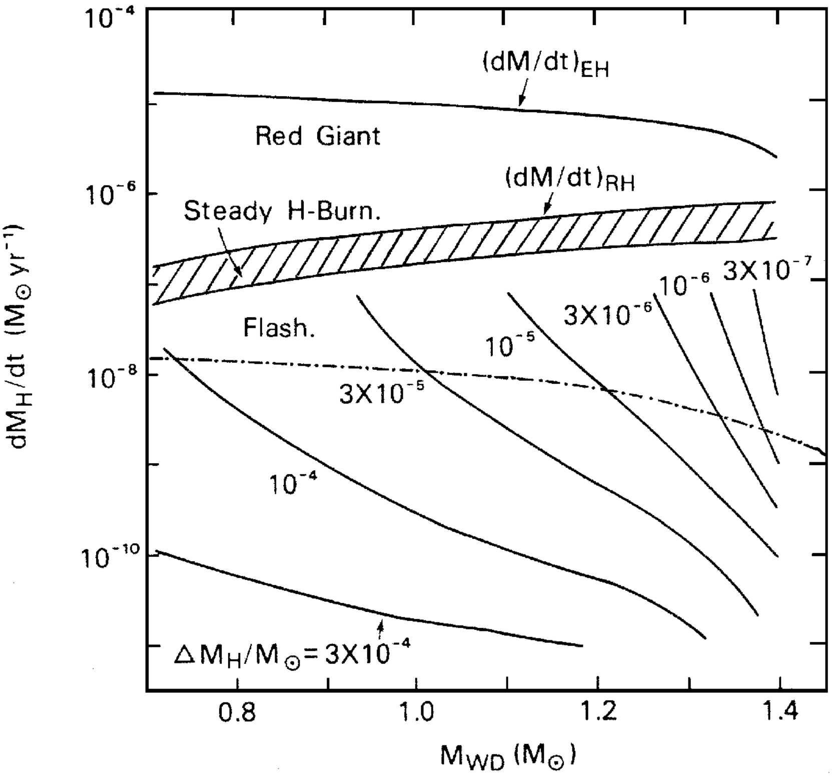

Figure 5 Regimes of steady nuclear burning, weak flashes (cyclic burning), and strong flashes (novae) in the $\dot{M}$–M_{WD} plane (cf Fujimoto 1982a,b, Nomoto 1982, DiStefano & Rappaport 1995). The ΔM_H values indicate envelope masses (for a given accretion rate) at which burning is ignited. Below the *dash-dot line*, flashes produce nova explosions.

The condition for various types of nuclear burning on the surface of a WD had already been studied about a decade earlier by various authors, e.g. Paczyński & Zytkow (1978), Prialnik et al (1978), Sion et al (1979), Sienkiewicz (1980), Nomoto (1982), Fujimoto (1982a,b), Iben (1982), and more recently by Prialnik & Kovetz (1995). These authors found that there are, broadly speaking, three possible regimes of nuclear burning in the surface layers of a WD, which depend on the accretion rate and the WD mass as follows (Figure 5) (after Nomoto 1982; SA Rappaport, private communication).

1. In a narrow range of accretion rates, roughly 1–4 $\times$ 10^{-7} $M_{\odot}$/year for a solar mass WD, the accreted hydrogen burns steadily, without much radius

expansion of the WD (Nomoto et al 1979). This is the hatch-marked region in Figure 5.

2. For accretion rates below the range for steady burning, the accreted matter burns in flashes, which for decreasing accretion rates have longer intervals between them and become more and more violent. In typical novae (cataclysmic variables, CVs), the accretion rates in general range between 10^{-9} and 10^{-8} solar masses per year (see, for example, Livio 1994).

3. For very high accretion rates, above the range for steady burning without radius expansion, the radius expands to red giant dimensions, and the matter keeps burning steadily in a thin shell around the WD. This is, in fact, the standard model for a red giant of mass lower than about 8 solar masses (cf Kippenhahn & Weigert 1994).

Recent more-refined calculations have shown (Hachisu et al 1996) that in the regime of very high accretion rates, instead of forming a red giant envelope, the burning of the accreted matter may cause the formation of a very strong stellar wind, opaque to soft X rays, which flows out at high speeds from the WD (velocity typically on the order of the escape velocity from the WD surface, i.e. about 5000 km/s). In any case, for accretion rates above the hatch-marked region in Figure 5, one does not expect the X rays to escape. We return to this in more detail in Sections 3.4 (Symbiotic Systems; Long-Term Variations) and 5.

From the above, it should be clear that in binaries with donor stars that are able to provide accretion rates in the region hatch-marked in Figure 5, a WD will become a steady, very luminous supersoft X-ray source. We now consider which companions will be able to provide just this required rate.

2.4 *Which Companions Are Able to Provide the Right Accretion Rate for Producing a Luminous SSS?*

NEAR MAIN-SEQUENCE COMPANIONS MORE MASSIVE THAN THE WHITE DWARFS The simplest type of binary configuration in which accretion rates as high as 1–4 $\times\ 10^{-7}\ M_{\odot}$/year can be achieved is that in which the companion has a mass larger than that of the WD and has a radiative envelope. A possible companion is a star with a mass larger than about 1.3 $M_{\odot}$, which is still fairly close to the main sequence, i.e. a slightly evolved star of spectral type earlier than about F5. In such a system, once the companion overflows its Roche lobe (Roche lobe overflow, RLOF), mass transfer will take place on a thermal time scale of the donor star. This is due to the fact that mass transfer from the more massive to the less massive component of a binary causes the orbit to shrink, whereas the thermal equilibrium radius of a star that has an evolved (i.e. He-rich) core does not decrease when mass is taken away from its envelope. As a result, the mass transfer and associated shrinking of the orbit will cause the donor to become thermally unstable: It will start transferring mass on its thermal timescale until it has become the less massive of the two, and the orbit can expand when further mass transfer occurs (cf Paczyński 1971, van den Heuvel 1994). The thermal timescale of a star in or close to the main sequence is roughly given by

$$t_{th} = 3 \times 10^7 \Big/ \left(\frac{M}{M_\odot}\right)^{-2} \text{years.} \tag{3}$$

As $\dot{M} \simeq M/t_{th}$, the result is roughly

$$\dot{M}_{th} \simeq 3 \times 10^7 \left(\frac{M}{M_\odot}\right)^{3} M_\odot/\text{year.} \tag{4}$$

Thus for stars with $M \gtrsim 1.3\ M_\odot$, one has $\dot{M} \gtrsim 10^{-7}\ M_\odot/\text{year}$.

Typically, near–main-sequence companions in the mass range 1.3–2.5 $M_\odot$ can thus provide $\dot{M}$ in the range 1–4 $\times$ 10^{-7} $M_\odot$/year (van den Heuvel et al 1992). It is striking that this is indeed the estimated mass range of the companions of CAL 83 and CAL 87, as derived from their orbital periods and absolute luminosities. At present, five of the luminous SSS have been identified with binaries with periods in the range 10 h to a few days, which fits this model (see Table 1). We call these systems close binary supersoft sources (CBSS).

SYMBIOTIC SYSTEMS Symbiotic systems are wide binaries consisting of a red giant star and a WD (cf Kenyon 1986, Friedjung 1988, Mikolajewska & Kenyon 1992, Viotti et al 1996). This is the second obvious class of binary systems in which high mass-transfer rates towards WDs can be achieved such that nuclear burning in the surface layers can be ignited. Sion & Starrfield (1994) were the first to realize this (see also Iben & Tutukov 1994, Yungelson et al 1996b).

Among the symbiotics, one expects two different types of companions that provide different modes of mass transfer, as follows:

1. An approximately one–solar-mass red giant, less massive than the WD, which is overflowing its Roche lobe in a binary with an orbital period longer than about 125 days. Here, mass transfer will be driven by the nuclear evolution of the red giant, which has a degenerate He core. The expected accretion rate in this case (Verbunt 1989, Verbunt & van den Heuvel 1995) is roughly given by

$$\dot{M} \approx (P_o/12.5d)10^{-8}\ M_\odot/\text{year}, \tag{5}$$

where P_o is the orbital period at the onset of mass transfer. So, for orbital periods longer than about 125 days, $\dot{M}$ will be sufficiently large to ensure that steady nuclear burning on the WD can take place. Also, the companion will transfer its envelope on a time scale on the order of a few million years.

2. Wide symbiotic systems in which the red giant is on the asymptotic giant branch (AGB) and is not filling its Roche lobe, but has a very strong stellar wind. The mass-loss rates in AGB winds are on the order of 10^{-5} $M_{\odot}$/year, and the wind velocities are low, about 30 km/s or less. This can yield an accretion rate on the order of 10^{-7} $M_{\odot}$/year on a WD companion, which is sufficient to power a SSS. In this case, the SSS phase probably lasts at most only a few hundred thousand years.

Both types of symbiotic systems have been found among the SSS (see Table 1 and Section 3.4).

3. THE OBSERVED SAMPLE

3.1 *The ROSAT All Sky Survey*

Hasinger (1994) presented the first complete list of SSS candidates, selected out of the 50,000 sources of the ROSAT All Sky Survey (RASS), later refined by Kahbaka & Trümper (1996). Some of the sources in this list were not luminous SSS, i.e. they are AGNs or PG 1159 stars. These were later rejected. The latest "clean" version of the catalogue of SSS with $L_X > 10^{36}$ ergs/s has been presented by Greiner (1996b). These are the 35 sources listed in Table 1. Of these, 7 are in the LMC, 4 in the SMC, 15 steady plus 1 transient (White et al 1994) in M31 (Greiner et al 1996d), 1 in the nearby spiral galaxy NGC 55, and 7 in our own galaxy. Figure 6 shows the positional distribution of the 16 sources in M31, after Greiner et al (1996d). Motch et al (1994) concluded that the finding of only two galactic SSS with binary periods similar to CAL 87 and CAL 83 is consistent with a distribution that is more concentrated towards the plane of the Milky Way than the distribution of the low-mass X-ray binaries.

One observes from Table 1 that apart from the five systems with detected orbital periods close to one day (like CAL 83 and CAL 87) and the symbiotic systems, there is a third class of objects, a subgroup of the CVs with very short orbital periods: Some novae appear as luminous SSS for a limited period, up to ten years, after the nova outburst. A search for soft X rays from a sample of recent novae showed this phenomenon to be quite rare: 2 of a sample of 26 recently exploded novae show it (Ögelman & Orio 1995). The first system of this type detected is GQ Mus (Nova Muscae 1983), which was discovered by Ögelman et al (1987, 1993) to be a luminous SSS; since its discovery it has "turned off." The second galactic example is Nova Cyg 1992 (V1974 Cyg). The systems RX J0439.8-6809 and 1E 0035.4-7230 in the LMC and SMC,

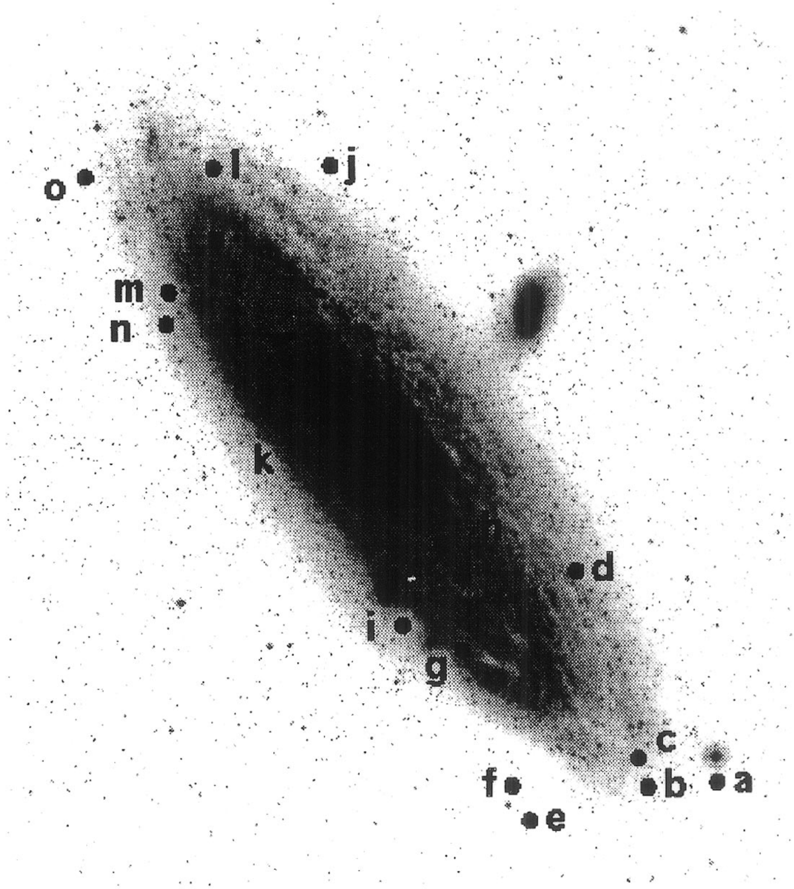

Figure 6 The location of the 16 SSS in M31 plotted over an optical image of this galaxy. Letters (*a* to *o*) denote M31 X-ray sources from Table 1. The source RX J0045.4+4154 (White et al 1994) is shown as a square (from Greiner et al 1996d).

respectively, may well be of the same type. Their orbital periods are in the range of those of CVs. The only difference with the two galactic SSS novae is that the latter two have orbital periods below the period gap of CVs, whereas the Magellanic Cloud systems both have periods above this gap. It is as yet not clear whether this difference is of any physical significance (P Kahabka & E Ergma, in preparation). The reason that nova systems may in some cases for some time appear as luminous SSS is that not all the accreted matter is ejected during the outburst. The possible reasons for this are discussed by MacDonald (1996).

3.2 *Classification*

A first classification scheme of SSS has been introduced by DiStefano & Nelson (1996): CVs, CBSSs, wide binary SSS (WBSSs), and symbiotics. Another, more refined scheme has been proposed by Kahabka (1996b). In this review, for simplicity, we use the scheme of DiStefano & Nelson (1996).

3.3 *Luminosities and Temperatures of SSS Derived Using WD Atmosphere Models*

In the foregoing sections, for the sake of argument the sources were assumed to have a blackbody spectrum. For hot WDs, this is a poor approximation, as was shown by Heise et al (1994) (see also van Teeseling et al 1996a). The flux distributions of local thermodynamic equilibrium (LTE) WD atmosphere models, calculated by the above authors (as a function of log T_e and log g), show absorption edges due to various heavier elements (from carbon onward). These edges have recently been observed with the Japanese X-ray observatory ASCA in RX J0925.7-4758 and CAL 87 (Ebisawa et al 1996; K Ebisawa, K Mukai, F Nagase, et al, in preparation).

Extrapolating from the flux observed in the softest ROSAT band, which is in the tail of the flux distribution of the WD, one obtains with LTE WD atmosphere models a considerably lower bolometric luminosity than if one uses the blackbody approximation. The resulting bolometric X-ray luminosities are not larger than the Eddington limit, and they fit well to the models for stable nuclear burning on the WD surface (van Teeseling et al 1996a).

3.4 *Optical Characteristics and Variability of Sources*

For a review of the optical observations of LMC sources, see Cowley et al (1996). For a discussion of the ultraviolet (UV) spectra of RX J0019.8+2156, CAL 83 and RX J0513.9-6951 we refer to Gänsicke et al (1996) and for a discussion of the UV spectrum of CAL 87 to Hutchings et al (1995). Optical identifications with blue emission line objects have been achieved for most SSS in the Magellanic Clouds and for nearly all galactic sources. We now briefly describe the results of these optical studies. We restrict ourselves to the Close Binary SSS (CBSS) and the Symbiotic systems.

THE "STANDARD" CBSS *CAL 83 and 87* The optical light curves and spectra of these sources were already briefly discussed in Section 2.2, where it was shown that the light variations of these binaries can be understood in terms of a model in which the two dominant light sources in the systems are a very bright accretion disk and the X-ray heated side of the donor star (see Figure 3; cf van den Heuvel et al 1992). This model appears to be the "standard" model for understanding the optical light curves of the five presently known CBSS discussed in this section. In CAL 87, our line of sight practically coincides with the orbital plane such that regular deep eclipses of the bright disk occur. The secondary minimum occurs when the disk eclipses a part of the strongly heated side of the donor star.

The CAL 83 system is seen at much lower inclination, such that no eclipses of the disk occur. The sinusoidal optical modulation is simply due to the one-sided heating of the donor star.

Although this model qualitatively explains the observed light curve of CAL 87, quantitatively it needs refinement in order to explain (*a*) the width and asymmetry of the primary eclipse and (*b*) the depth of the secondary eclipse. Refined models were therefore constructed by Schandl et al (1996) and Naber (1996). Schandl et al (1996) showed that in order to explain the asymmetry and width of the primary eclipse, the disk must have a rim of considerable height, highest on the trailing side (the place where the accretion stream impacts on the disk). Both Schandl et al (1996) and Naber (1996) showed that in order to explain the depth of the secondary eclipse, there must be a disk corona or wind from the disk of considerable optical depth, which blocks a sizeable part of the light from the heated side of the donor. The variability of the depth of the secondary eclipse can then be explained by variations in the density in the corona or wind.

The variable source RX J0513.9-6951 This LMC source was discovered by Schaeidt et al (1993); it closely resembles CAL 83 in its X-ray, UV, and optical luminosities and spectra (Pakull et al 1993). However, while CAL 83 is a practically permanent X-ray source (only in April 1996 was it briefly absent; cf Kahabka 1996c, Kahabka et al 1996), RX J0513.9-6951 shows long "off" states, lasting up to many months, with irregularly spaced "on" intervals in between (see Figure 7).

Radial velocity measuremants by Crampton et al (1996) and photometry on 6 nights by Motch & Pakull (1996) suggested a period close to 0.76 days, confirmed by MACHO-photometry over more than 400 nights by Southwell et al (1996a), which yields $P = 0.^{d}76278$. The blue light curve derived from the latter observations is nearly sinusoidal with an amplitude of only 0.0213 mag. The same interpretation as the light curve of CAL 83 is consistent with a one-sided heated donor star seen at very low orbital inclination.

The spectrum of this source, depicted in Figure 8, is most remarkable in that the bright emission lines ($He\ II\lambda4686$ and H_β) show blue- and red-shifted

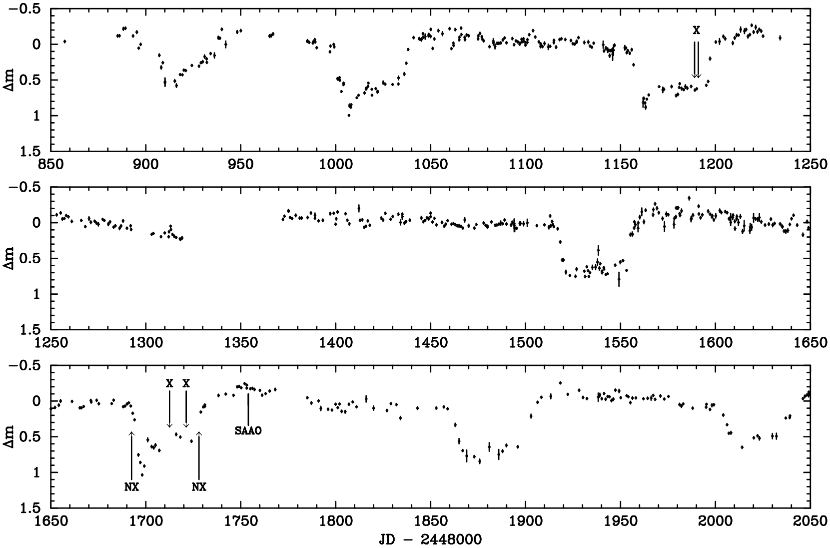

Figure 7 Optical light curve of RX J0513.9-6951 from August 22, 1992, to November 27, 1995, obtained with the MACHO project. Downward and upward *vertical arrows* indicate times at which the system was known to be on (X) or off (NX) in X rays, respectively (from Southwell et al 1996b).

satellites, corresponding to Doppler velocities of 3800 km/s (Pakull et al 1993, Cowley et al 1996). As in SS 433, this strongly suggests a bipolar outflow pattern, with velocities somewhat larger than this value (we see only the projection on the line of sight). In such outflows, the outflow velocities are expected to be of the same order as the escape velocity from the stellar surface (Casinelli 1979, Castor et al 1975). As the observed velocities are of the order of the escape velocity from the surface of the WD, this provides strong evidence that the central object here is indeed a WD, as realized by Southwell et al (1996b). In view of the low inclination of the system, we are looking almost perpendicular to the orbital plane and the accretion disk. The observations are therefore consistent with the jets oriented perpendicularly to the disk, as in the usual configuration of jets from accretion disks (e.g. see Shu et al 1988, Appl & Camenzind 1992, Ostriker & Shu 1995).

The galactic CBSS sources RX J0019.8+2156 and RX J0925.7-4758 The first-mentioned source, RX J0019.8+2156, was the first luminous SSS found in our Galaxy (Reinsch et al 1993). It has a relatively bright optical counterpart of 12.5 mag. This star was studied photometrically and spectroscopically by Beuermann et al (1995), who derived a photometric and spectroscopic period

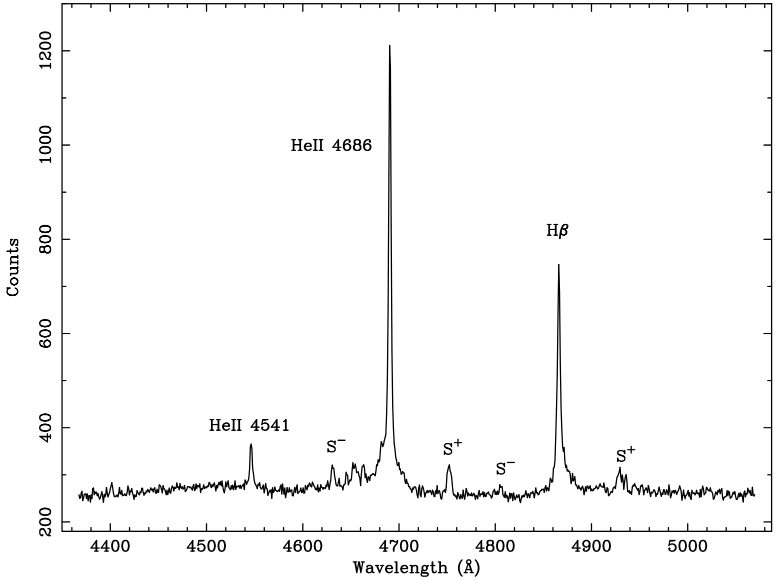

Figure 8 Average blue spectrum of RX J0513.9-6951. The principal He II and H emission features are marked, along with their associated Doppler-shifted components (from Southwell et al 1996b).

of about 0.66 days. Greiner & Wenzel (1995), from observations taken in the interval 1955–1993, found a period of 0.6604565($\pm$ 15) days, while Will & Barwig (1996) derived for the interval September 1992 to October 1995 a period of 0.6604721 ($\pm$ 72) days. The light curve derived by Will & Barwig (1996) resembles that of CAL 87 in that it has a fairly deep primary minimum (about 0.3 mag) as well as a secondary minimum. The smaller depth of the primary minimum than in CAL 87 suggests that the orbit is seen at lower inclination than in this source.

The second important galactic SSS is RX J0925.7-4758, discovered by Motch et al (1994). It was identified by them with a highly reddened star of V $=$ 17 mag [E(B-V) $=$ 2.1 mag]. It shows the usual emission spectrum of SSS, including CIII/NIIIλ4640–60. V-band photometry suggests an orbital period of $3.^{d}79 \pm 0.^{d}24$, in agreement with a spectroscopic period of $3.^{d}78$ (cf Motch et al 1994, Motch 1996).

SYMBIOTIC SYSTEMS Two of the three symbiotic SSS (Table 1) are symbiotic novae: RR Tel and SMC 3 ($=$ RX J0048.4-7332) (cf Mürset et al 1996). These systems show nova-like optical outbursts. In 1944, RR Tel brightened by $\sim$7 mag to reach $M_V = -5$ mag, returning to its original state in subsequent years.

The cool component of RR Tel is a low-mass red giant that normally shows Mira-type light variations (Mayall 1949). SMC 3 has been in outburst since 1981 (Morgan 1992). The ROSAT PSPC count rate of this source is higher than that of RR Tel, even though its distance is 20 times larger (Kahabka et al 1994). Its minimum effective temperature (260,000 K) is about 2 times that of RR Tel, and its X-ray luminosity (12000 $L_\odot$) some 4 times larger than that of RR Tel. For details, see Mürset et al (1996). The orbital periods of symbiotic novae are on the order of a year, e.g. in RR Tel: 387 days. Therefore, it is likely that in some phase of the Mira pulsations, the cool component may overflow its Roche lobe, giving rise to the outburst. Alternatively, it has been suggested that the outburst is generated by a hydrogen flash in matter that was accreted by the WD from the wind of the giant during the quiet phase between outbursts. In view of the relatively short orbital periods for symbiotic stars, the RLOF explanation seems the more likely one to us.

The third symbiotic SSS, AG Dra, is not known to be a symbiotic nova. Like all symbiotics, it shows brightness increases by several magnitudes ("outbursts") at irregularly spaced times (cf Viotti et al 1996). During its most recent outburst (1994/1995), its soft X-ray flux greatly decreased and returned to its original value in the decline of the burst (Greiner et al 1996a). Greiner et al (1996a) suggest that this anticorrelation of optical and X-ray brightness is due to a temporary expansion of the photosphere of the burning compact star, owing to a temporarily increased state of mass transfer.

LONG-TERM VARIATIONS Apart from the symbiotic systems, several of the sources show interesting long-term variations. We briefly describe here some well-studied cases.

RX J0513.9-6951 ("Schaeidt's Source") As mentioned above, RX J0513.9-6951 shows bipolar outflows with $V = 3800$ km/s and exhibits long X-ray off phases. Thanks to its location in a MACHO field (Alcock et al 1996), Southwell et al (1996a,b) could derive a very accurate long-term optical light curve, which is shown in Figure 7. During the flat optical maxima, the X-ray source is off, while during the optical minima (depth in B about 1 mag) the X-ray source is on (see also Reinsch et al 1996). This behavior strongly suggests that the optically bright phases are phases of enhanced mass transfer, such that the photosphere of the burning compact star has expanded by a factor of two or more, causing the effective temperature to drop and the soft X-ray flux to be converted into an enhanced optical (and UV) flux. [This explanation is similar to Greiner et al's (1996a) explanation for the anticorrelation between X-ray and optical brightness in AG Dra.]

This indicates that the mass-transfer rate $\dot{M}$ in this system is usually higher than the maximum $\dot{M}$ for a steady burning without radius expansion, which is indicated in Figure 5.

This is confirmed by the outflows from the system in the form of jets: As mentioned in Section 2.3, one expects from the work of Hachisu et al (1996) that if $\dot{M}$ is above the upper boundary for a steady burning SSS in Figure 5, a strong stellar wind develops. In the presence of a disk, such a wind will be focused to form bipolar jets perpendicular to the disk, as discussed above.

Recurrent shell flashes The relatively bright ($V \sim 12$ mag) optical counterpart of RX J0019.8+2156, studied on photographic plates taken over the past 100 years, appears to exhibit abrupt rises in optical magnitude by ~0.5 mag, followed by a decay to its initial magnitude in ~20–30 years (Greiner & Wenzel 1995).

Meyer & Meyer-Hofmeister (1996) discuss several possible explanations. They favor an explanation in terms of a WD accreting at a moderate rate ($\sim 10^{-7}$ $M_{\odot}$year^{-1}) undergoing hydrogen shell flashes (cf Kahabka 1995, 1996b). Such behavior in terms of recurrent shell flashes was predicted, for example, by Iben (1982) and Fujimoto (1982a,b) for accretion rates somewhat below the lower boundary for stable nuclear burning in Figure 5. The recurrence time depends, among other factors, on the WD mass and the accretion rate. A semianalytical model for such flashes was worked out by Kahabka (1995, 1996b). In this model the WD envelope mass can be related to the recurrence time scale of the source: Given the X-ray on time and recurrence time, the envelope mass ΔM can be calculated, which, in turn (with Figure 5), yields the allowed range of WD masses. Applying this, one finds that the 40-year recurrence time scale implies a WD mass of ~1.0–1.1$M_{\odot}$.

RX J0527.8-6954 This LMC source has an X-ray spectrum very similar to that of CAL 83 (Trümper et al 1991). Since its discovery with ROSAT in 1990, the X-ray brightness has steadily declined by more than a factor of 20 in 1800 days (Greiner et al 1996b,c). These authors suggest cooling of a massive WD following a H-shell flash on its surface as a likely explanation for the decline. The WD may remain in the stable burning range, but a decrease of a factor of 2 in its bolometric luminosity will then move its T_{eff} so far down that in the ROSAT channels its flux drops by a factor of 20. Assuming a time of 5 years for returning to minimum, and a recurrence time of ~10 years, one derives with the above-mentioned semiempirical model of Kababka (1995) a WD mass $M_{Wd} \approx 1.2$–$1.35\ M_{\odot}$ and $\dot{M}_a \approx 2$–$7 \times 10^{-7}\ M_{\odot}$ year^{-1}. The high WD mass is also compatible with the relatively high value of $T_{eff} \approx 5$–$6 \times 10^5\ K$ of the source (Greiner et al 1996b,c).

4. IONIZATION NEBULAE

The SSS are expected to ionize the surrounding interstellar medium out to distances of several parsecs due to the large ionizing flux (a few times 10^{37} erg s^{-1})

and the long on times (a few times 10^6 year). Therefore a search for nebulae of this type (H II regions) surrounding all known SSS has been initiated (Rappaport et al 1994a, Remillard et al 1995). Surprisingly, only for one source, i.e. CAL 83, has a large ionization nebula been detected. This has been explained by the high density of the surrounding local interstellar medium. The time variable, i.e. recurrent or cyclic illumination (excitation) of the interstellar medium, may make such nebulae less luminous (cf E Chiang & SA Rappaport, in preparation), but it is more likely that the absence of detectable ionization nebulae around other sources is due to a much lower local interstellar density for the other SSS (cf Remillard et al 1995).

5. PHYSICAL PROCESSES

5.1 *Types of Nuclear Burning as a Function of $\dot{M}$ and M_{WD}*

As mentioned in Section 2.3, steady burning of hydrogen (by the CNO cycle) without radius expansion occurs only for a limited range of accretion rates close to 10^{-7} $M_\odot$ year^{-1}, which depends on the WD mass, as depicted in Figure 5. The precise way in which the burning takes place depends, in addition, on the thermal history of the WD (cf Iben 1982, Fujimoto 1982a,b, MacDonald 1983, Prialnik & Kovetz 1995). For simplicity we do not consider this extra complication here.

The dependence of the type of burning on $\dot{M}$ and M_{WD} was calculated by the above-mentioned authors and by Iben et al (1992), Kato & Hachisu (1994), and Sion & Starrfield (1994).

For accretion rates below the lower bound of $\dot{M}$ for steady burning, the accreted matter will burn in flashes. The strength of the flashes depends on the degree of the degeneracy of the matter in the burning shell, which in turn depends on the accretion rate: The lower the accretion rate, the higher the degree of degeneracy of the matter at the moment of ignition, and the stronger the flash. The flashes reach the strengths of nova explosions for $\dot{M} \lesssim 10^{-8}$ $M_\odot$ year^{-1} at low WD masses to $\lesssim 10^{-9}$ $M_\odot$ year^{-1} for high WD masses, as depicted in Figure 5 (cf Starrfield et al 1974, 1985, Prialnik et al 1978, Prialnik 1986, José et al 1993). In this figure, the *dashed lines* are isolines of the critical envelope mass ΔM at which burning is ignited, and a flash occurs.

5.2 *Inferred WD Masses*

Mass determinations on the basis of radial velocity variations of the spectral lines (mostly emission lines are observed) are not expected to be reliable, as one does not know where in the systems these lines are formed.

To determine masses, one can use the core-mass luminosity relation for cold WDs accreting hydrogen (cf Iben & Tutukov 1996):

$$L/L_\odot \approx 4.6 \times 10^4 \, (M_{core}/M_\odot - 0.26). \qquad (6)$$

Alternatively (as mentioned in Long-Term Variations above), for sources with recurrent X-ray flashes, one can derive limits on M_{WD} from the recurrence time of flashes. As mentioned, all these sources appear to harbor quite massive WDs, $M_{WD} \gtrsim 1.1\ M_{\odot}$. The same holds for the recurrent source in M31 (White et al 1994, Kahabka 1995, Kahabka 1996b). For the steady sources, the T_{eff} and L combination yield a value for the radius and for the mass (cf van Teeseling et al 1996a). For CAL 87, one finds that $M_{WD} > 1.2\ M_{\odot}$. These high-mass values do not necessarily imply that one is dealing with O-Ne-Mg WDs: The WDs may well have started out as CO dwarfs of moderate mass, which accreted a He layer of considerable mass due to steady burning. Whether or not this He layer will explode and lead to a double detonation SN Ia is not yet clear (cf Nomoto & Yamaoka 1992, Kato 1996). We return to this problem in Section 7. The reason the WD masses of the SSS in the LMC and M31 tend to be high has been explained by Rappaport et al (1994b): This is due to a selection effect, as the SSS with higher-mass WDs tend to be hotter and more luminous than those with low-mass WDs and therefore are more easily detected (see also DiStefano 1996).

6. EVOLUTION AND POPULATION SYNTHESIS

6.1 *Origin of the CBSS*

The origin of the standard CBSS with orbital periods on the order of one day and donor masses in the range 1.3–2.5 $M_{\odot}$ is very similar to that of CVs, to which they are closely related. Both types of systems are close binaries consisting of a WD and a star of relatively low mass ($\leq 2.5\ M_{\odot}$). The only difference between them is that in the CVs the donor star is less massive than the WD, whereas in the CBSS the donor is more massive than the WD.

The formation history of both types of systems is therefore expected to be basically the same: They formed through common envelope (CE) evolution out of initially very wide binary systems that consisted of a red giant with a degenerate CO (or O-Ne-Mg) core, together with an unevolved main-sequence star of lower mass ($\leq 2.5\ M_{\odot}$), as depicted in the top frame of Figure 9.

When the envelope of the red giant (which at this stage was on the AGB) overflowed its Roche lobe, it engulfed the lower-mass companion. A system resulted that consisted of the latter star and the core of the giant, orbiting each other inside this CE. The large frictional drag on the orbital motion made the companion and the core rapidly spiral inwards, while the frictional heat production caused the envelope to be expelled in the process (cf Meyer & Meyer-Hofmeister 1979, Taam et al 1978, Taam 1996). The time scale of the expulsion is on the order of 10^3 years (Taam 1996). This resulted in the presently observed very close systems.

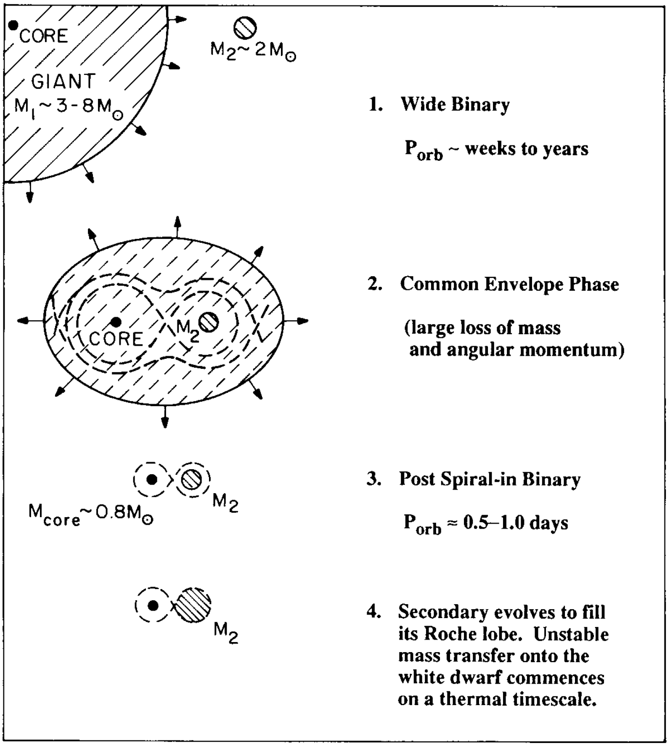

Figure 9 Evolutionary scenario for the formation of a close binary supersoft X-ray source (cf text; from Rappaport & DiStefano 1996).

At a much later stage, when the companion evolves away from the main sequence and overflows its Roche lobe, the system will become a CBSS or a CV. In particular, CVs will be produced if the companion is of low mass ($\leq M_\odot$) and the orbital period after "spiral-in" is sufficiently short ($\leq$12 h) that it decays within a Hubble time, owing to the emission of gravitational waves or to angular momentum losses by magnetic breaking (cf Verbunt 1989, Verbunt & van den Heuvel 1995). The mass-transfer rates driven by these processes are typically 10^{-10}–10^{-9} $M_\odot$ year^{-1}, as is indeed observed in CVs.

6.2 *The Origin of Symbiotic Systems*

Here the initial system was so wide that the two stars evolved in large part independently of each other. The more massive star evolved into a red giant and finally ejected its envelope without much interaction with the at that time still unevolved partner. This resulted in a wide system consisting of a WD and a main-sequence star, resembling the systems of Sirius AB and Procyon AB. At a much later stage, the companion evolved into a red giant and the system became a symbiotic star. For details we refer the reader to Yungelson et al (1995).

6.3 *Results of Population Synthesis Studies*

Pioneering numerical population synthesis calculations for the formation of the CBSS were carried out by Rappaport et al (1994b, hereafter RDS). A review and critical discussion is given by DiStefano & Nelson (1996). For a review of population synthesis techniques with binary evolution, see De Kool (1996).

In population synthesis calculations, one starts out with a population of unevolved binary systems, composed such that it mimics the real population of unevolved binaries in the Galaxy. For composing this input population, one uses the best available observational data (on masses, mass ratios, orbital periods) of unevolved binaries. In addition, one needs a stellar evolution code that is able to incorporate all possible types of evolution of binaries, including CE evolution.

By constructing a population of a large number of binaries (typically 10^7) and evolving them, and assuming a steady state of star formation in the Galaxy (calibrated with the presently observed rate), one typically obtains a realistic population that contains all types of products of binary evolution, including the CBSS- and CV-type systems. The calculations yield the expected distributions of orbital periods, donor masses, WD masses, etc. Figure 10 shows an example of these predicted distributions obtained by RDS (1994). These authors obtained a steady-state population of CBSS in the Galaxy on the order of 10^3. Depending on the adopted input distribution of orbital parameters—some of which are not well known—and input parameters in the evolutionary code, these predicted numbers can still range from 100–1500 in the Galaxy, as shown in Table 3, where the predicted numbers for M31, LMC, and SMC also are shown. These estimates agree with the early analytic estimates ($\sim$360) of van den Heuvel et al (1992). The galactic population inferred from the observations, after taking into account the effects of strong interstellar extinction, is between 400 and 3000 (Rappaport & DiStefano 1994b), roughly consistent with the theoretical predictions.

A completely independent population synthesis calculation by Yungelson et al (1996b), using a different code, and including CV-type and symbiotic SSS, yields the numbers given in the lower part of Table 3. Yungelson et al (1996a,b) argue that symbiotics will be extremely hard to observe because their soft X rays will practically always be completely absorbed ("shielded") by the winds of their red giant companions. Within the limits for the uncertainties of the input distributions and evolutionary parameters (such as the efficiency

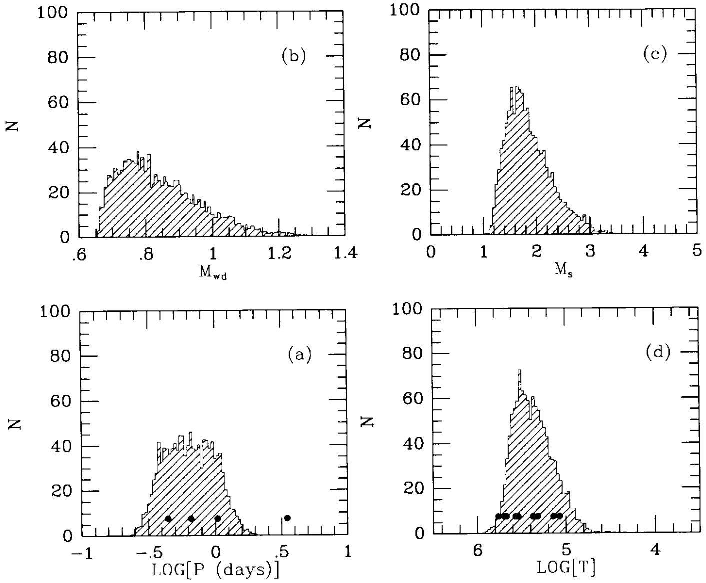

Figure 10 Expected distributions of white dwarf (WD) (M_{WD}) and donor (M_s) mass, orbital period P_{orb}, and effective temperature T_{eff} as derived in the population synthesis study of Rappaport & DiStefano (1996), together with observed quantities (*black dots*).

parameter α of CE evolution), the numbers of CBSS calculated by the above two groups are in agreement with each other, as well as with the latest results of DiStefano & Nelson (1996), in which mass and angular momentum losses from the systems were taken into account. The latter yields a galactic number of CBSS between 1000 and 4000.

7. SN IA PROGENITORS

Supernovae of Type Ia (SN Ia) are most likely to be associated with the thermonuclear explosions of mass-accreting CO WDs, a now widely accepted proposition (Arnett 1969; for reviews see Branch et al 1995, Livio 1994, 1996). The source of accretion can be stellar wind from the donor, RLOF, or the result of the coalescence of two WDs. The exploding WD is usually assumed to be near the Chandrasekhar limit ($\sim$1.4 $M_\odot$), but also the possibility of explosions at sub-Chandrasekhar mass has recently been put forward: Off-center detonations of He on CO WDs in the mass range 0.6–0.9 $M_\odot$, after accreting 0.15–0.20 $M_\odot$ of He (produced by H-shell burning) can trigger explosions that in many respects are similar to SN Ia (Livne 1990, Limongi & Tornambé 1991,

Table 3 Numbers of supersoft X-ray sources (SSS) in different galaxies predicted from population synthesis calculations, compared with numbers from observations[a]

Galaxy	Population synthesis	Inferred from observations	
M31	400–6000	800–5000	
Milky Way	100–1500	400–3000	
LMC	20–300	13–60	
SMC	5–60	9–40	
Type	**Cataclysmic variables**	**Subgiant systems**	**Symbiotic systems**
Permanent SSS	130	400	450
Recurrent SSS	350	70	45

[a]Upper part: numbers of SSS predicted from population synthesis by Rappaport et al (1994b) and inferred from observations by DiStefano & Rappaport (1994); lower part: numbers of SSS for the Milky Way calculated by Yungelson et al (1996b). LMC, Large Magellanic Clouds; SMC, Small Magellanic Clouds.

Woosley & Weaver 1994). This is the so-called double detonation model (see also Ruiz-Lapuente et al 1995, Canal et al 1996).

The most attractive candidate for near-Chandrasekhar mass SN Ia is the merger of a close pair of CO WDs due to orbital decay by losses of gravitational radiation (cf Webbink 1984, Iben & Tutukov 1984), which works in any type of galaxy, i.e. also in elliptical galaxies, which only contain very old stars. Unfortunately, so far no such close massive binary WDs have been found observationally. Alternative candidates put forward are symbiotic stars (Munari & Renzini 1992). These do occur in old stellar systems. Yungelson et al (1995) showed that the WDs in these systems accrete too little mass to allow them to reach the Chandrasekhar limit. They showed, however, that if sub-Chandrasekhar double detonation models (see above) indeed produce SN Ia, then symbiotics might produce at most one third of the SN Ia. With the discovery of the SSS, a new class of potential SN Ia progenitors has been found, as was suggested by RDS and subsequently by many other authors (see Branch et al 1995, Livio 1996, Kato 1996, DiStefano 1996). Here the CBSS are the most interesting subclass, since in the CVs, the accreted mass is violently ejected in nova explosions (cf Livio 1994), and symbiotics yield a too-low rate (see above).

In practically all cases, the CBSS will accrete sufficient mass to at least lead to a sub-Chandrasekhar mass double detonation. With the number of $\sim$1–4 $\times$ 10^3

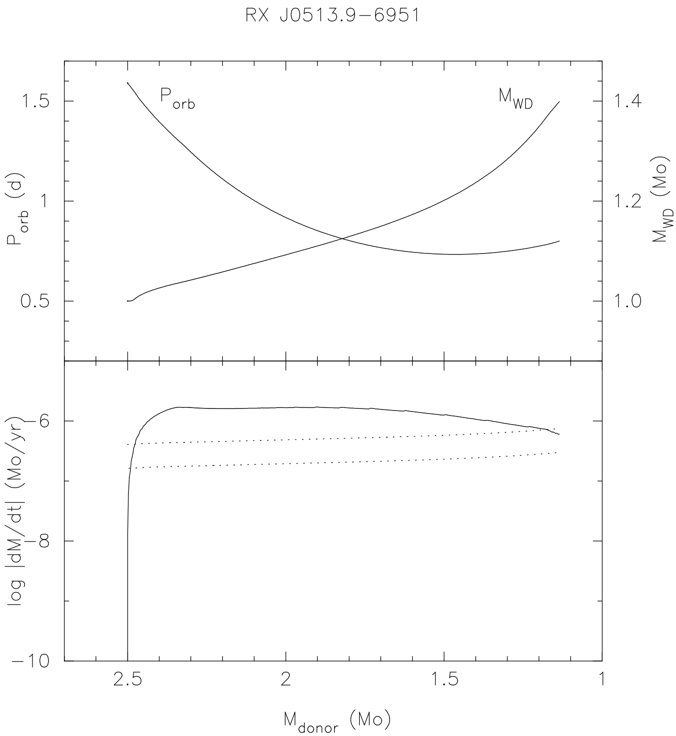

Figure 11 Evolution of orbital period, white dwarf (WD) mass, and $\dot{M}$ of a CBSS with an initial donor mass of 2.5 $M_\odot$ and an initial WD mass of 1 $M_\odot$, in which the mass-transfer rate is mostly $\sim 10^{-6}$ $M_\odot$year^{-1} (from X Li, in preparation). *Dashed lines*: boundaries of the stable burning region without radius expansion.

CBSS in the Galaxy (DiStefano & Nelson 1996), which roughly increase in mass by $\sim$0.2 $M_\odot$ in $\sim 10^6$ years ($\dot{M} \sim 2.10^{-7}$ $M_\odot$ year^{-1}), this may lead to a double detonation rate of order 1–2 $\times$ 10^{-3} year^{-1}, i.e. almost as high as SN Ia rate in spiral galaxies like our own (3×10^{-3} year^{-1}, cf Branch et al 1995). It should be pointed out here that since the donor stars in CBSS have masses $>$1.2 $M_\odot$, they live no longer than $\sim 5 \times 10^9$ years. Therefore CBSS are not good SN Ia progenitor candidates in elliptical galaxies. On the other hand, in spiral and irregular galaxies, they might make a considerable contribution to the SN Ia rate. If SN Ia require growth of the WD to the Chandrasekhar mass, the event rate produced by CBSS will be lower but perhaps not by a large factor. This is because recent full evolutionary calculations (X Li, in preparation) of systems with donors in the mass range 1.5–3.0 $M_\odot$ showed that He detonation may be prevented in many cases, since $\dot{M}$ is sufficiently high for the He to burn only in weak flashes (cf Kato 1996). Mass and angular momentum losses by wind were included in the calculations for evolutionary stages where $\dot{M}$ is too large for stable burning SSS. Figure 11 shows, as an example, the evolution of a CBSS with an initial donor mass of 2.5 $M_\odot$ and an initial WD mass of 1 $M_\odot$, in which the mass-transfer rate is mostly $\sim 10^{-6}$ $M_\odot$ year^{-1}. It is clear that the SN Ia problem has not yet been solved, but, as Branch et al (1995) concluded, in view of their calculated numbers and birth rates, merging double degenerates and close binary SSS are now probably the two most promising progenitor candidates for SN Ia.

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CONTENTS