Super Soft X-ray Sources (SSS)

-Energy generation by surface H-burning on a WD
-Source types: Close Binary SS, Symbiotics, CVs
-Statistical considerations/Pop. synthesis results

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Discovered by ROSAT (1990) thanks to its very low low-energy cut-off

Several of the sources had already been discovered by Einstein (~1981) but had been thought to be black holes in the "bright-soft" state: CAL 83 and CAL 87

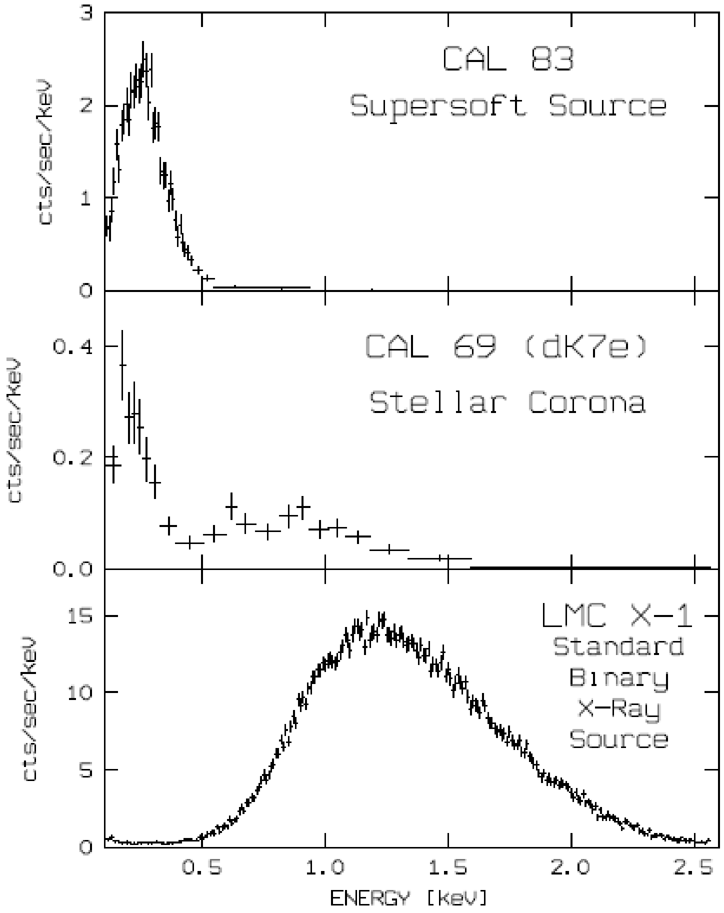


Figure 1 ROSAT PSPC count spectra of three objects in the Large Magellanic Cloud (LMC) field: the SSS CAL 83, the dK7e foreground star CAL 69, and the black hole candidate LMC X-1 (similar to Figure 2 of Trümper et al 1991).

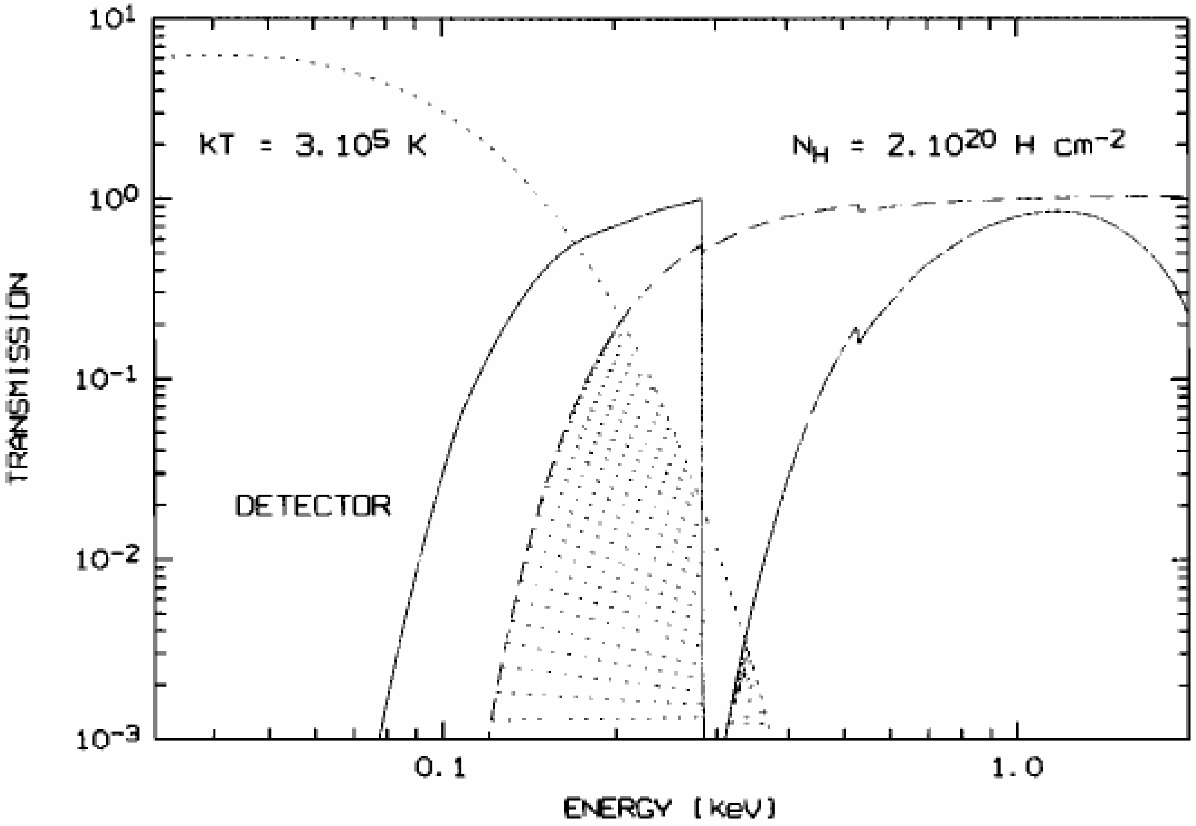


Figure 2 ROSAT PSPC efficiency (*solid curve*), transmission of ISM for hydrogen column of 2.10^{20} H atoms cm^{-2} (*dashed line*), distribution of a 3.10^{5}-K blackbody spectrum (*dotted line*) and folded (observed) distribution (*hatch marks*) (SA Rappaport, private communication).

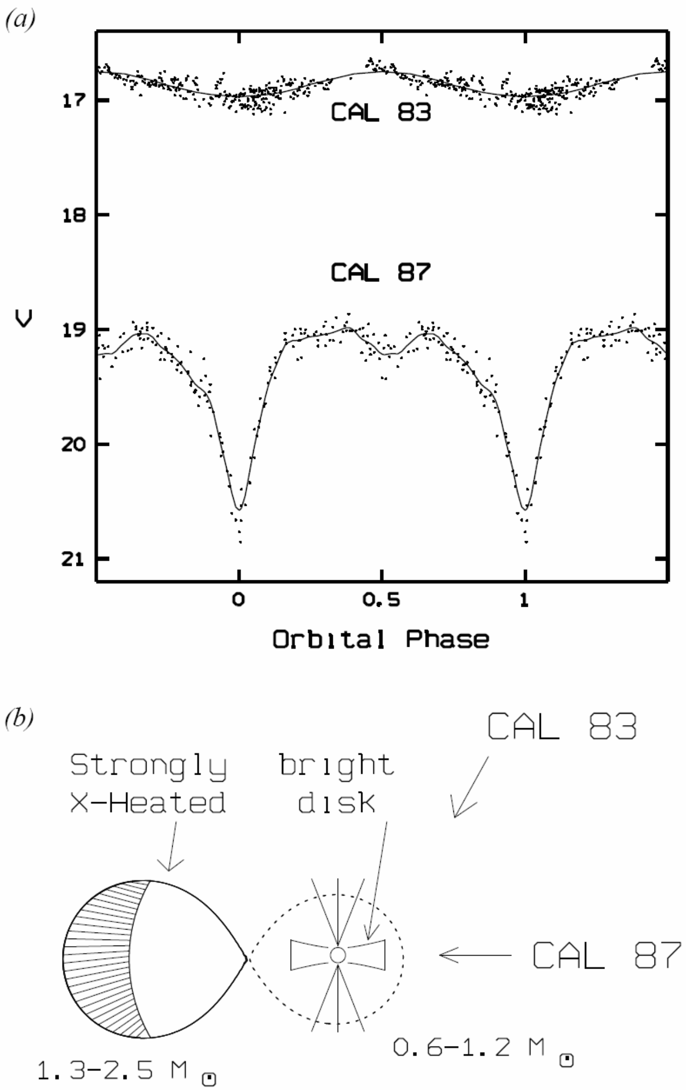
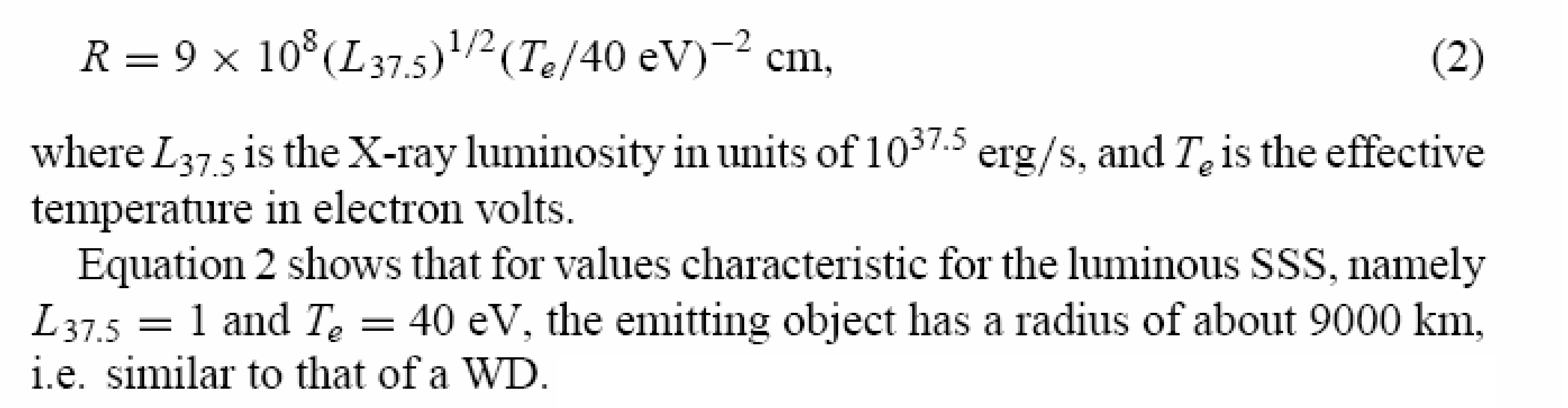


Figure 3 (*a*) Optical light curves in the Johnson V-band of CAL 83 and CAL 87 plotted on the same scale for comparison. The *solid curves* give the mean light curves. The upper light curve is adapted from Smale et al (1988), the lower light curve from Schmidtke et al (1993). (*b*) Schematic model for 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].

P_{orb} = 1.04 days

P_{orb} = 10.6 hours



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

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.

In order to generate this luminosity by accretion onto a WD, the accretion rate should be ≥ 4.10^{-6} M_{sun} /yr. However, such an accretion rate would cause all soft X-rays to be absorbed!

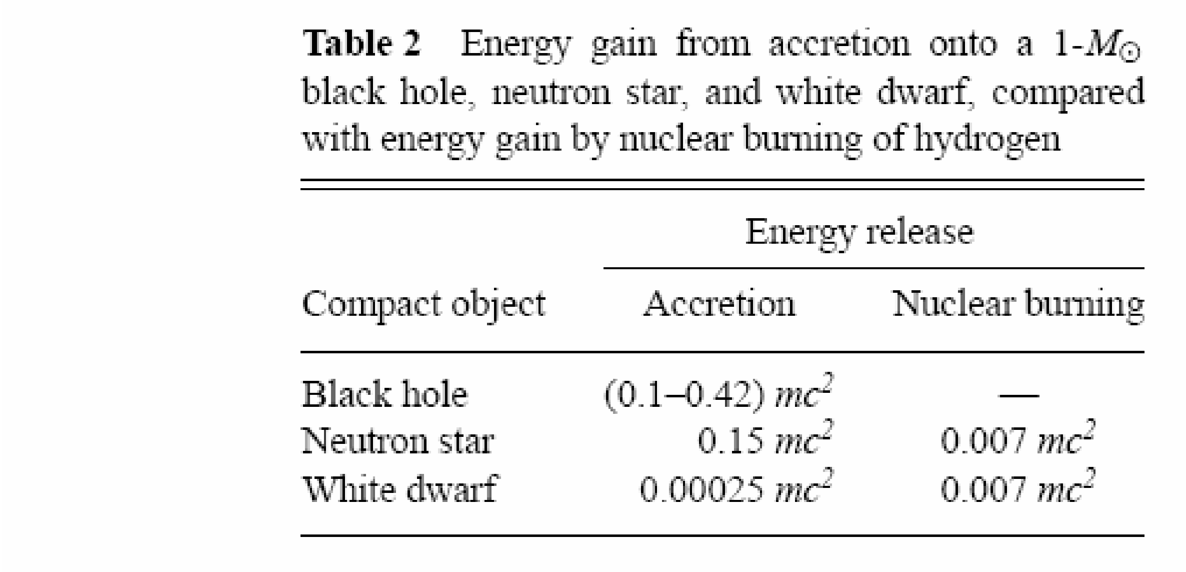


Table 2 Energy gain from accretion onto a 1-$M_\odot$ black hole, neutron star, and white dwarf, compared with energy gain by nuclear burning of hydrogen

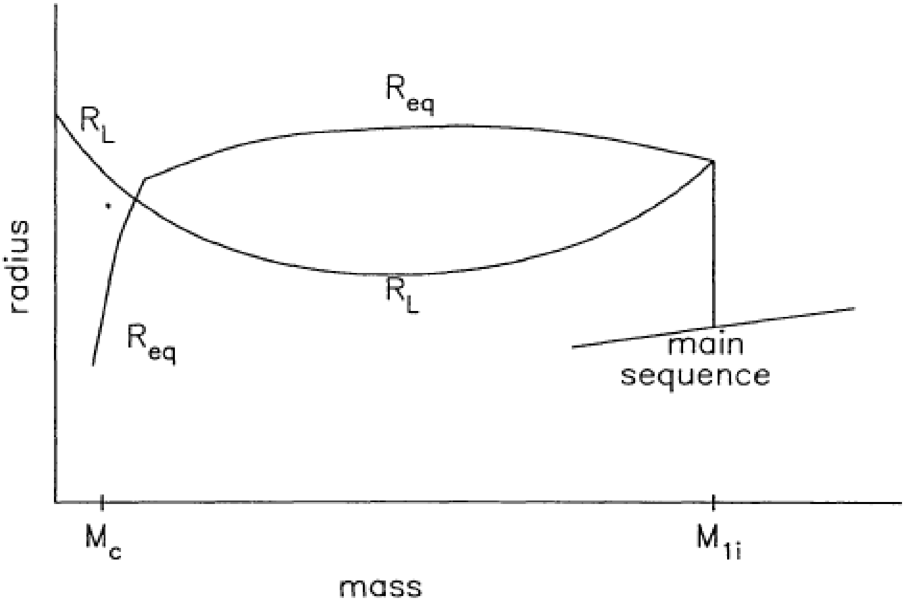
	Energy release	
Compact object	Accretion	Nuclear burning
Black hole	(0.1–0.42) mc^2	—
Neutron star	0.15 mc^2	0.007 mc^2
White dwarf	0.00025 mc^2	0.007 mc^2

Nuclear burning of Hydrogen on the WD surface generates same X-ray luminosity at a 30 times lower accretion rate ~ 10^{-7} M_{sun} /yr: Now the X-rays can come out!

Once the more massive star overflows its Roche lobe and transfers matter to its companion, its Roche-lobe radius *shrinks* while its thermal equilibrium radius stays about the same; if it has a radiative envelope the star temporally shrinks due to the mass loss, but it then expands on a thermal timescale to restore its thermal equilibrium. As a result it continues to transfer matter until it has become the less massive component of the system and further mass transfer causes its Roche lobe to expand. The entire process takes ~ τ(thermal):

$$M_{dot} \sim 0.8M/\tau_{(thermal)} \sim 0.8M^3/(3.10^7) \quad [M_{sun}/yr]$$

$$\longrightarrow \quad \text{for } M \geq 1.5M_{sun}, \quad M_{dot} \geq 10^{-7}\ M_{sun}/yr$$



RXJ 0513-6951 in the LMC

P_{orb} = 18,3 hours

When X-rays are “on”, the optical light is low, when X-rays are “off”, optical light is high: the energy then comes out in the optical, so accretion and burning still continue during X-ray off state!

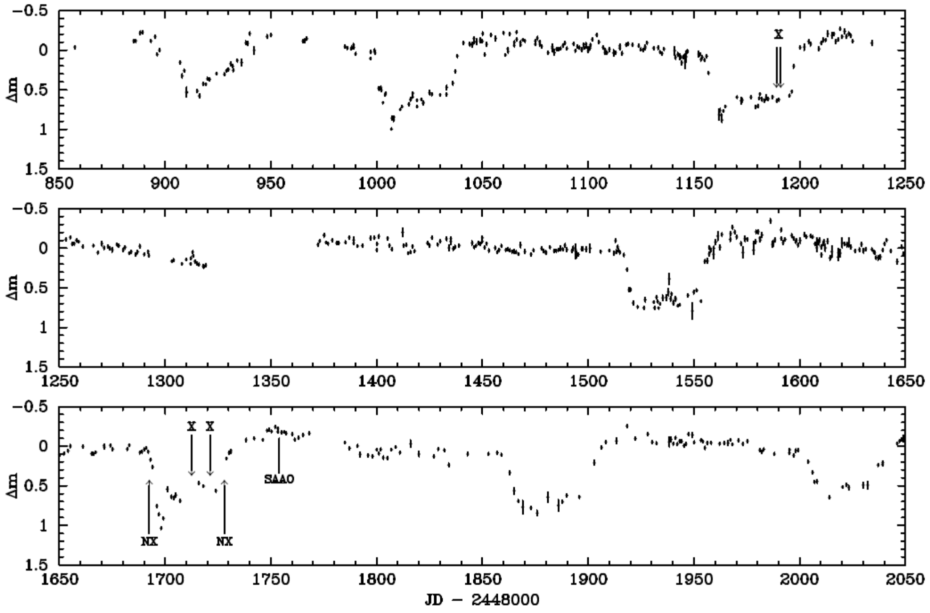


Figure 7 Optical light curve of RX J0513.9-6951 from August 22, 1992, to November 27, 1995, obtained with the MACHO project. Downward and upward *vertical arrows* indicate times at which the system was known to be on (X) or off (NX) in X rays, respectively (from Southwell et al 1996b).

Red- and Blue-shifted components of emission lines: jets with outflow velocities ≥ 4000 km/s: same order as escape velocity from surface of a WD.
Proof that SSS are WDs!!

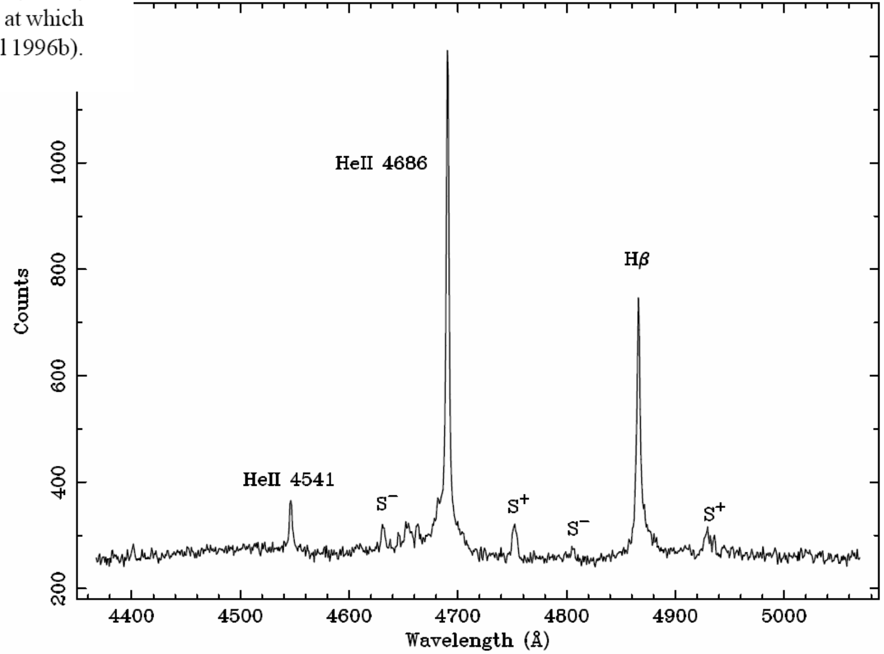
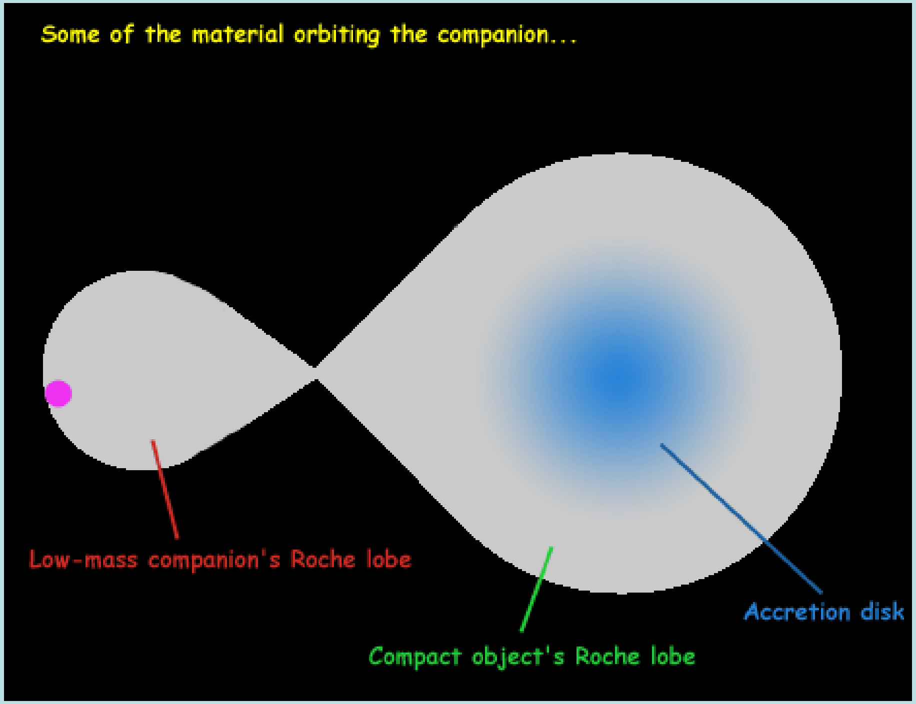


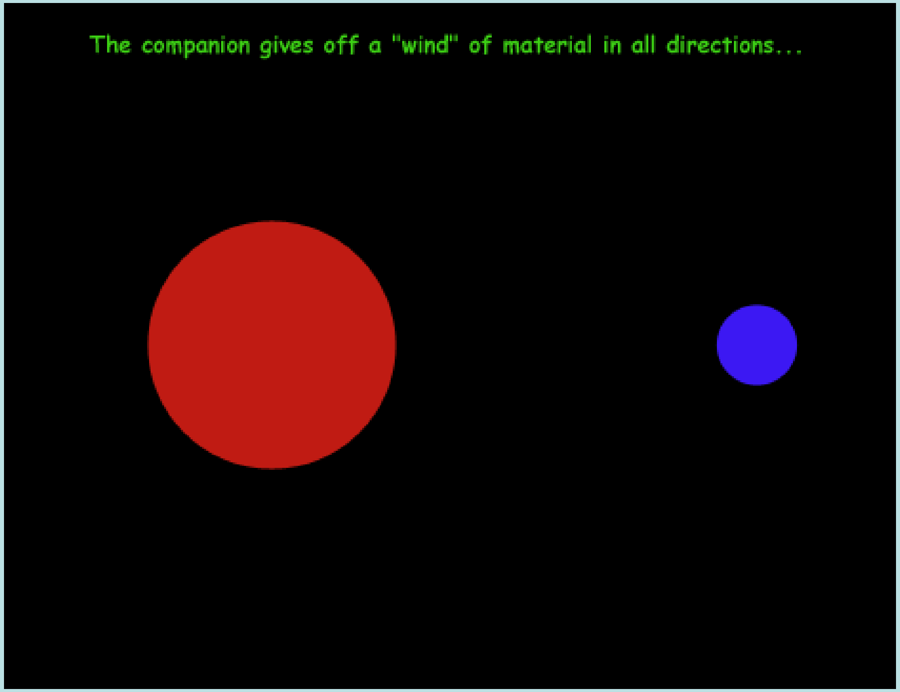
Figure 8 Average blue spectrum of RX J0513.9-6951. The principal He II and H emission features are marked, along with their associated Doppler-shifted components (from Southwell et al 1996b).

Two possible ways for capturing matter from a companion

Roche-lobe overflow:
-Close Binary SS (also called "Algol" SS)
-CV supersofts

Stellar wind accretion
-Symbiotic Super Softs





(All of these systems may show "nova" outbursts after which they may burn residual H lasting ~ 10 to ~200 yrs; such systems are "recurrent" SSS)

The difference between a CV and an "Algol" SS is that in the CV systems, the orbit is so narrow that mass-transfer is driven by Angular momentum loss, possibly supplemented by internal evolution of the donor. In "Algol" SS it is triggered purely by the internal evolution of the donor.

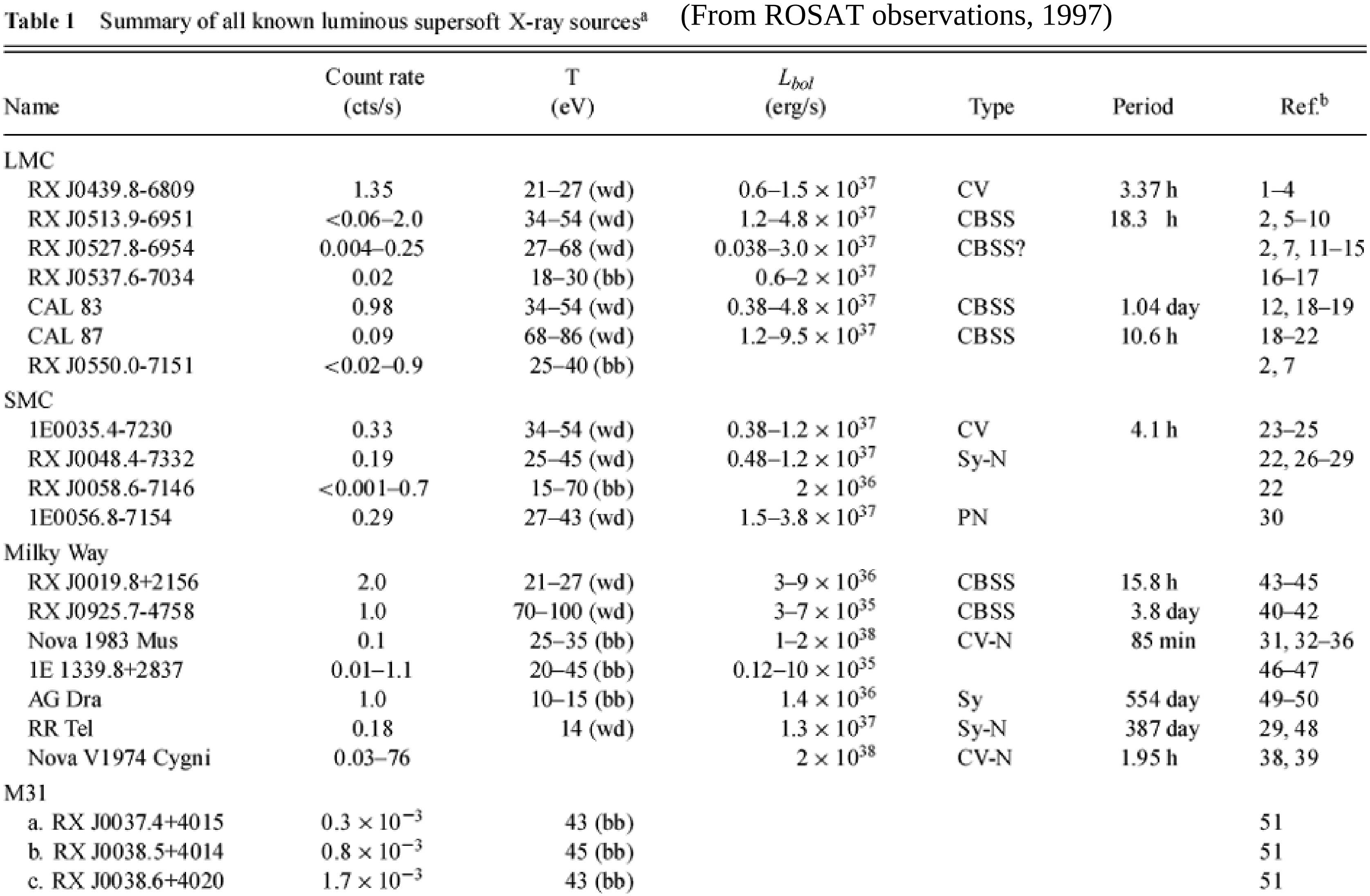


Table 1 Summary of all known luminous supersoft X-ray sources[a] (From ROSAT observations, 1997)

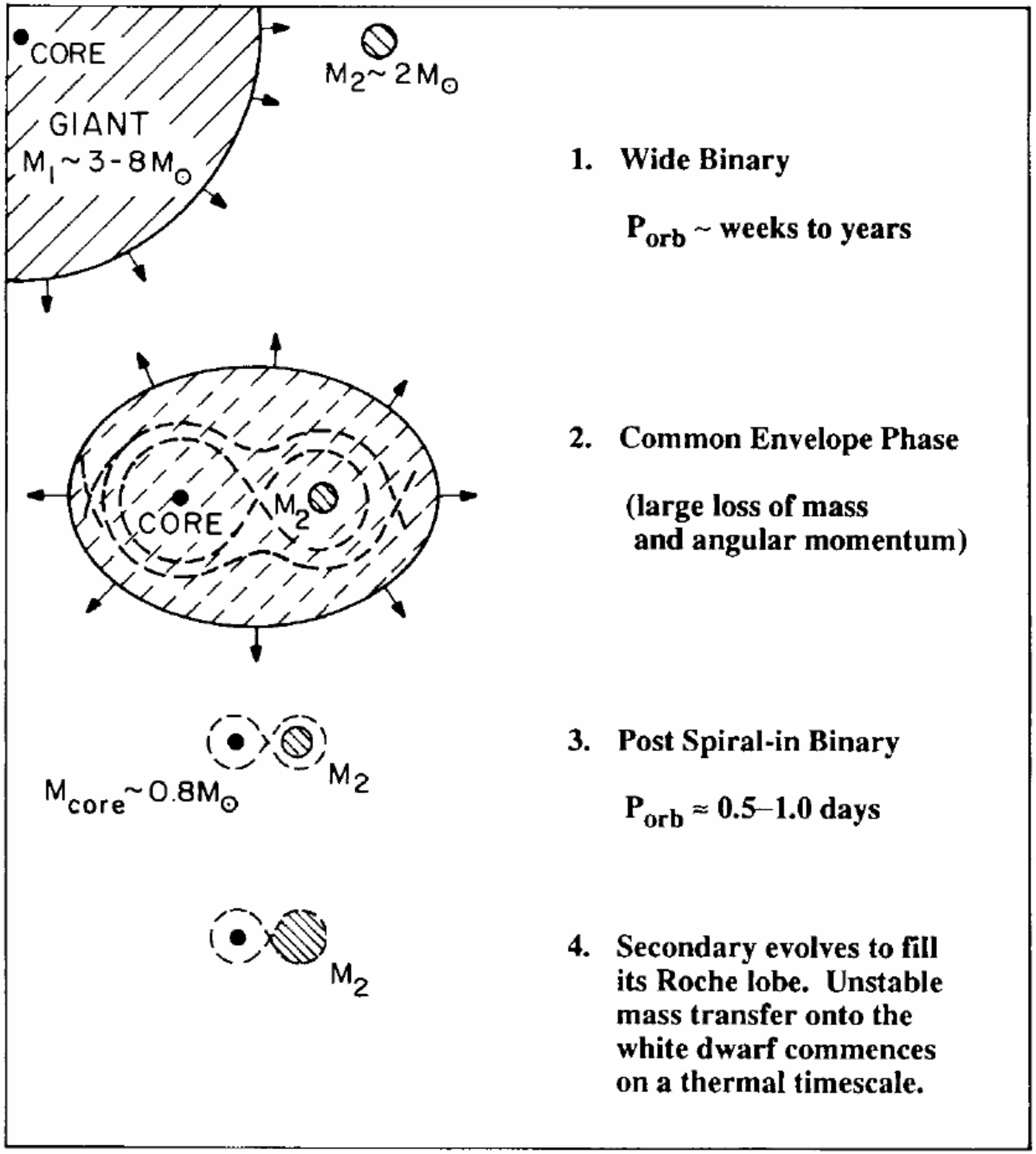
Name	Count rate (cts/s)	T (eV)	L_{bol} (erg/s)	Type	Period	Ref.[b]
LMC						
RX J0439.8-6809	1.35	21–27 (wd)	$0.6–1.5 \times 10^{37}$	CV	3.37 h	1–4
RX J0513.9-6951	<0.06–2.0	34–54 (wd)	$1.2–4.8 \times 10^{37}$	CBSS	18.3 h	2, 5–10
RX J0527.8-6954	0.004–0.25	27–68 (wd)	$0.038–3.0 \times 10^{37}$	CBSS?		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

Plus 13 more (M31 *d* through *o)*

NGC 55

RXJ 0016.0-3914 4.5×10^{-3}

NB: Many of the ROSAT Supersofts in M31 had disappeared by 2005 and Chandra saw OTHER ones.



1. **Wide Binary**

   P_{orb} ~ weeks to years

2. **Common Envelope Phase**

   (large loss of mass and angular momentum)

3. **Post Spiral-in Binary**

   $P_{orb} \approx 0.5–1.0$ days

4. **Secondary evolves to fill its Roche lobe. Unstable mass transfer onto the white dwarf commences on a thermal timescale.**

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

Origin of a CBSS System: by Common-Envelope evolution from a wide Red Giant plus main-sequence star System.

Exactly the same evolutionary scenario as for making CV-binaries.
The only difference is that here M2 is larger: anywhere between ~1.5 and ~5 Msun

Population Synthesis results for producing SSS:

Rappaport, Di Stefano and Smith (1994, Ap.J.426,692) and Di Stefano and Rappaport, 1994 (Ap.J.437,733) : Focussed on CBSS ("Algols")

Yungelson,Livio et al., 1996 (Ap.J. 466,890): Considered the 3 main types of SSS plus a number of additional ones (e.g. He accretors)

Federova, Tutukov and Yungelson (arXiv:astro-ph/0309052v1 2 sept 2003) and Yungelson (arXiv:astro-ph/0409677v1 28 sept 2004) further refined the latter calculations .

Recently Förster, Wolf, Podsialowski and Han (MNRAS 368,1893,2006) obtained results quite similar to those of the latter authors.

Production of “Algol” type SS (=CBSS) systems) 1994

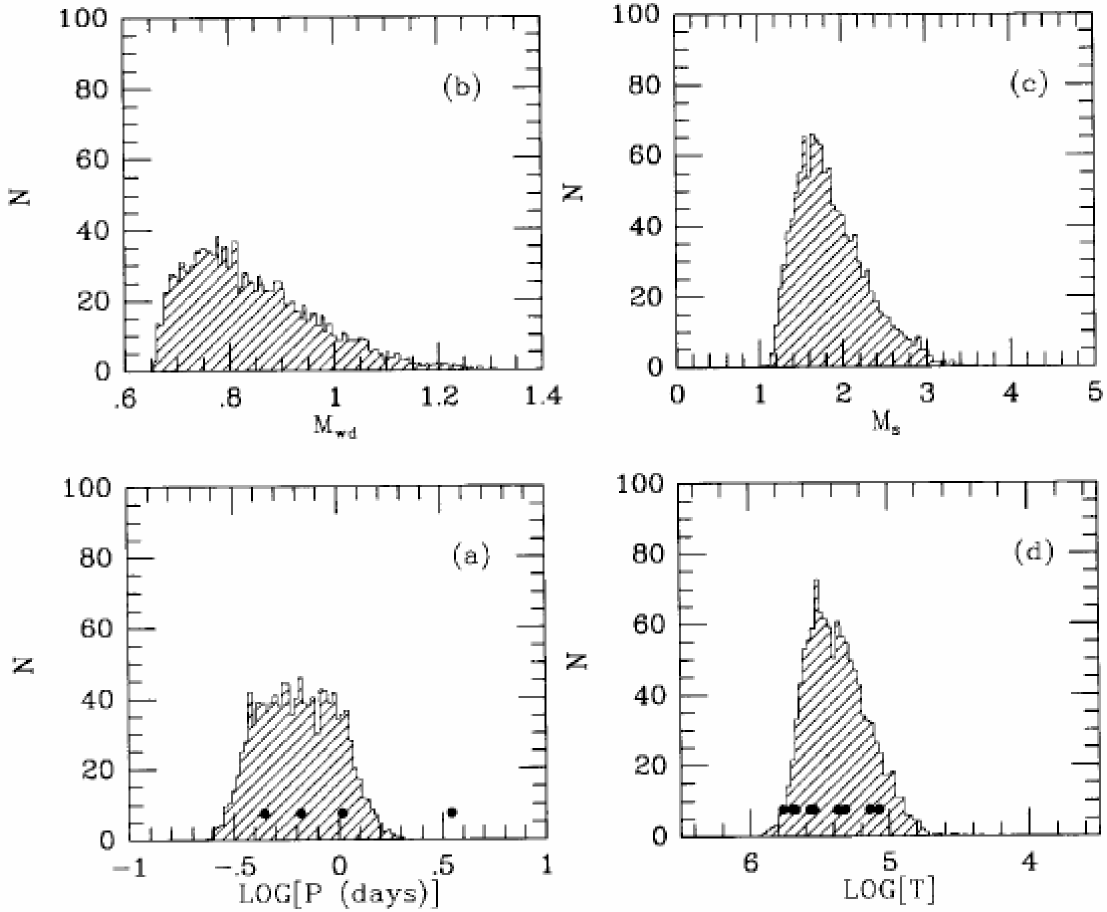


Figure 10 Expected distributions of white dwarf (WD) (M_{WD}) and donor (M_s) mass, orbital period P_{orb}, and effective temperature T_{eff} as derived in the population synthesis study of Rappaport and Di Stefano as compared with observed systems (*black dots*)

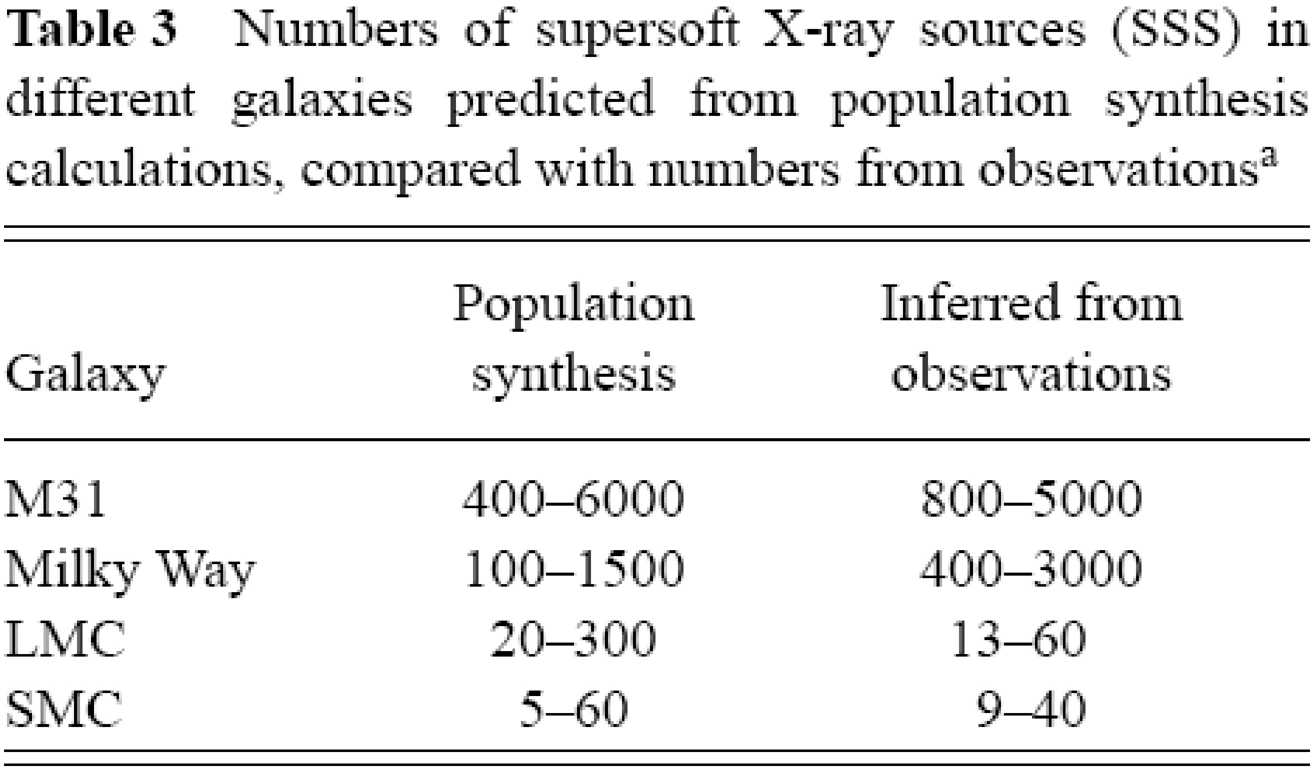


Table 3 Numbers of supersoft X-ray sources (SSS) in different galaxies predicted from population synthesis calculations, compared with numbers from observations[a]

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

Algol-type SS systems
After Rappaport et al (1994) and Di Stefano and Rappaport (1994)

WDs grow also by the weak-flash–burning at accretion rates > 10^{-8} Msun /yr

At still lower accretion rates, when Nova explosions occur, still part of the accreted H may be retained and steadily burned after the explosion (Schwartzman, Kovetz and Prialnik 1994). Therefore, also in Novae (from CVs, Algols and Symbiotics) the WD may grow in mass.

Yungelson et al. (Ap.J.466,890,1996) included also these possibilities in their Population-synthesis calculations for SSS

Diagram from Yungelson 2004

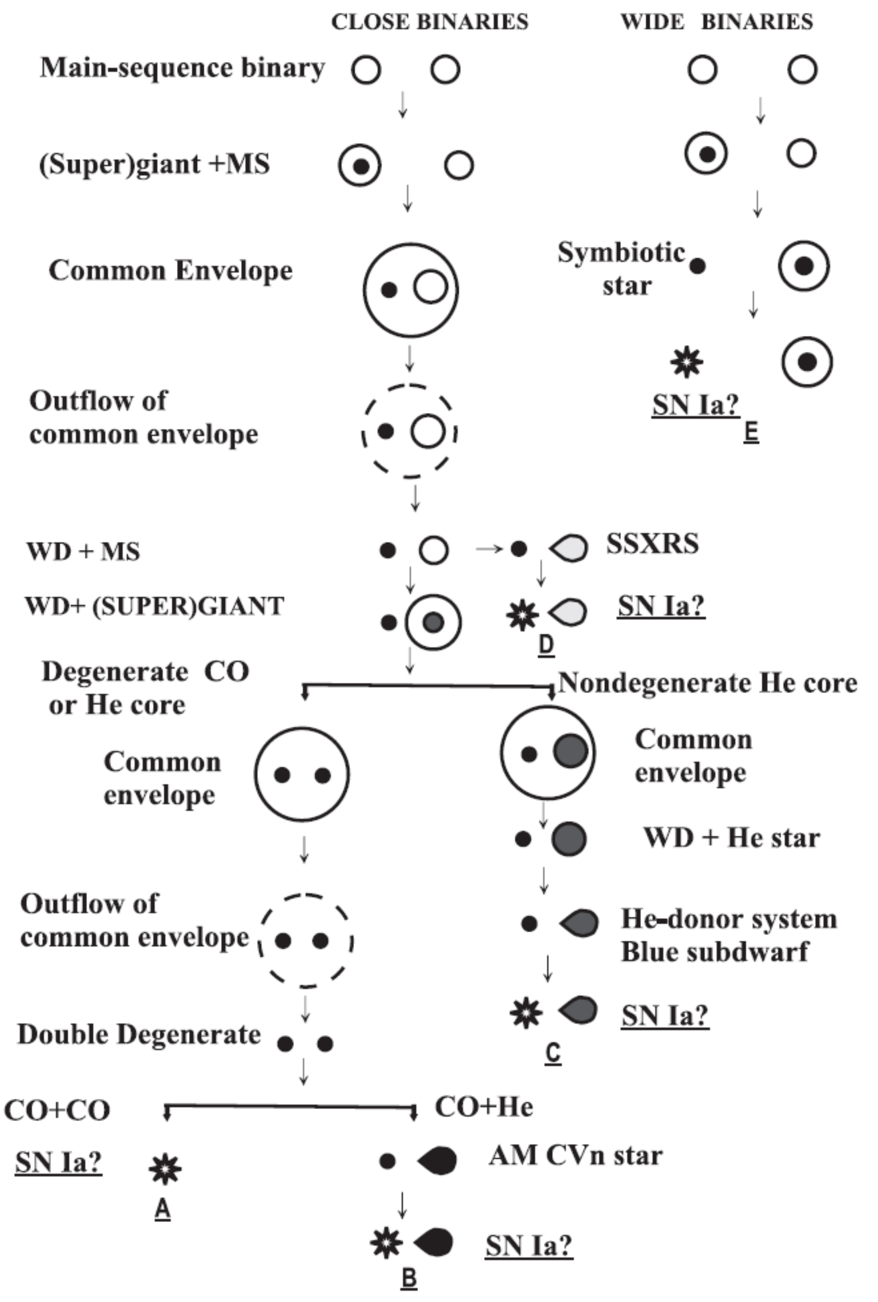


Figure 1: Evolutionary scenarios for possible progenitors of SN Ia.

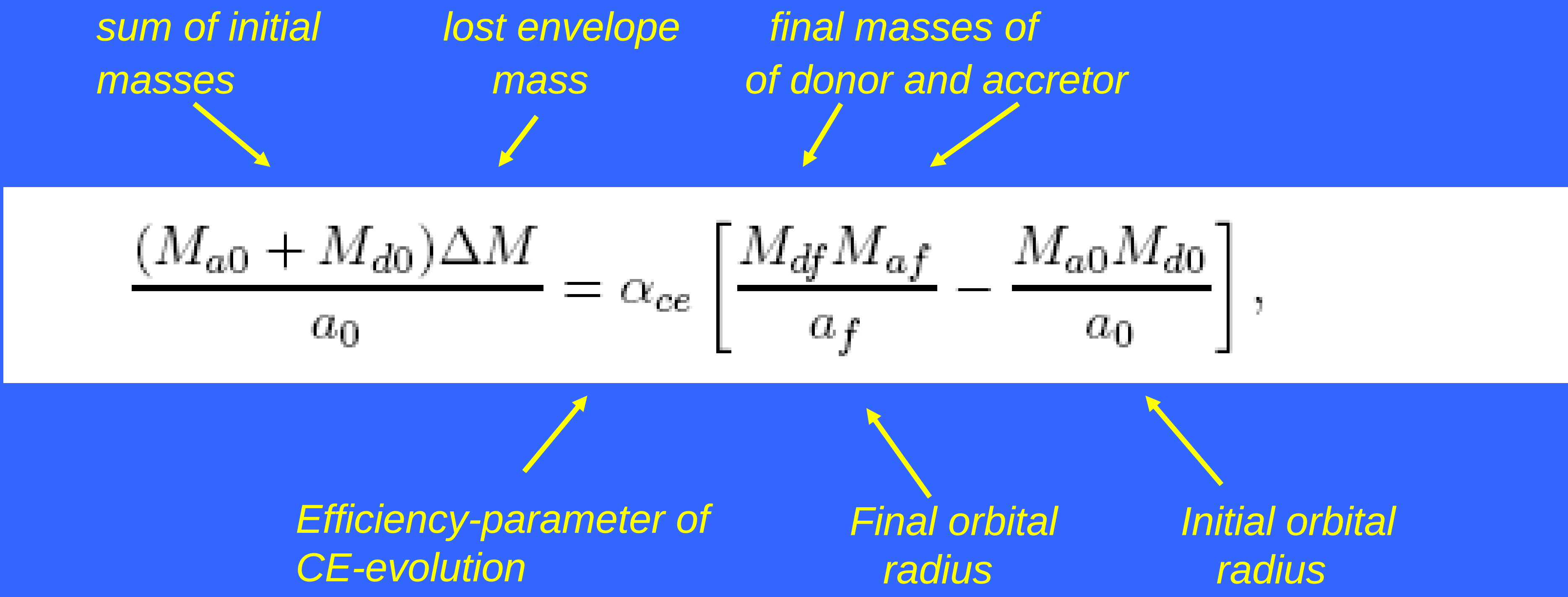
Symb.SS

"Algol" and CV SS

He SS

Double Degen.

Tutukov-Yungelson formalism for Common-Envelope Evolution



sum of initial masses

lost envelope mass

final masses of of donor and accretor

$$\frac{(M_{a0}+M_{d0})\Delta M}{a_0} = \alpha_{ce}\left[\frac{M_{df}M_{af}}{a_f} - \frac{M_{a0}M_{d0}}{a_0}\right],$$

Efficiency-parameter of CE-evolution

Final orbital radius

Initial orbital radius

In general: initial and final mass of te donor(= inspiralling star) is the same;
Initial accretor mass = mass of the giant;
Final accretor mass = mass of degenerate core of the giant.

Yungelson et al. 1996 Ap.J.

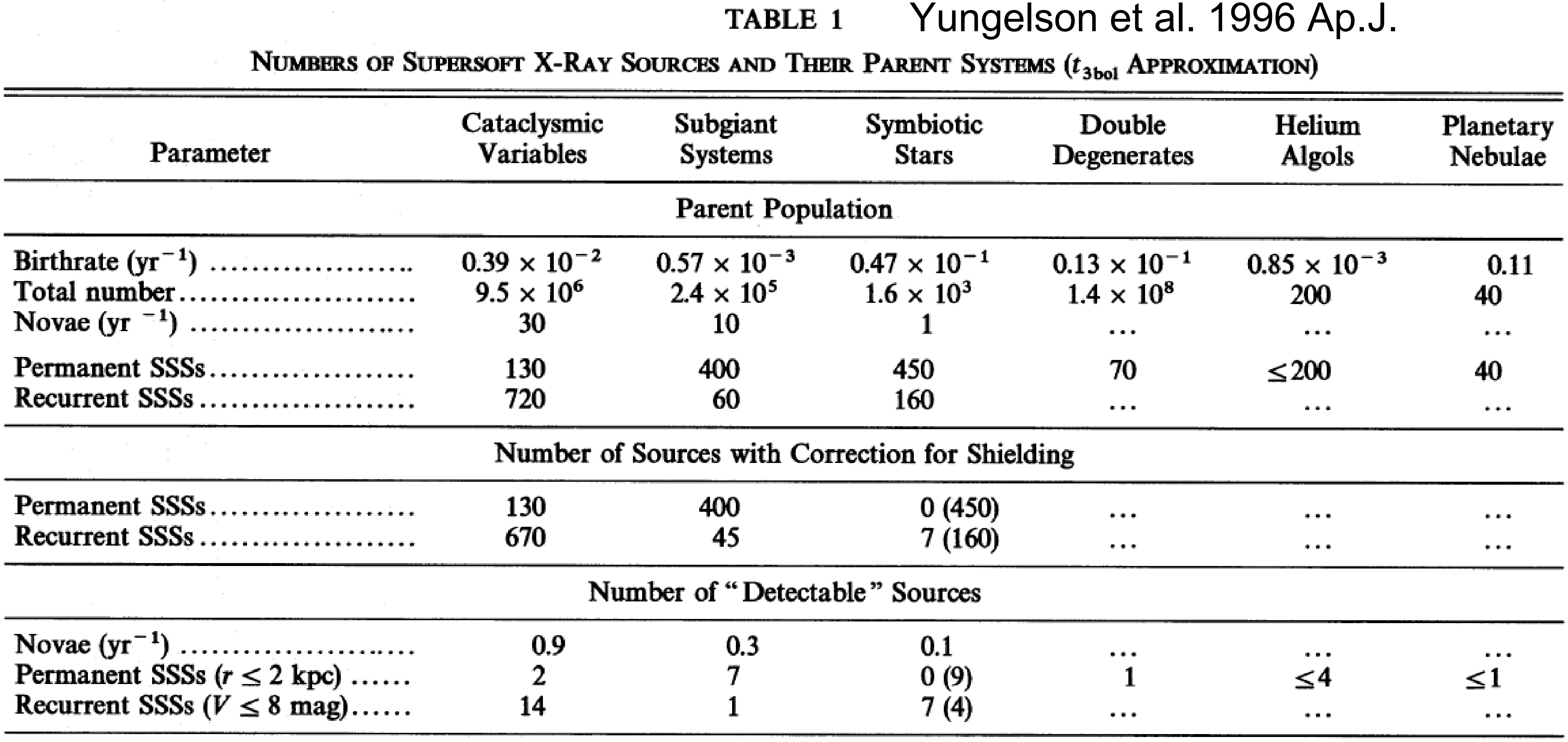


TABLE 1

NUMBERS OF SUPERSOFT X-RAY SOURCES AND THEIR PARENT SYSTEMS ($t_{3\mathrm{bol}}$ APPROXIMATION)

Parameter	Cataclysmic Variables	Subgiant Systems	Symbiotic Stars	Double Degenerates	Helium Algols	Planetary Nebulae
Parent Population						
Birthrate (yr^{-1})	0.39×10^{-2}	0.57×10^{-3}	0.47×10^{-1}	0.13×10^{-1}	0.85×10^{-3}	0.11
Total number	9.5×10^{6}	2.4×10^{5}	1.6×10^{3}	1.4×10^{8}	200	40
Novae (yr^{-1})	30	10	1	...	...	...
Permanent SSSs	130	400	450	70	≤ 200	40
Recurrent SSSs	720	60	160	...	...	...
Number of Sources with Correction for Shielding						
Permanent SSSs	130	400	0 (450)	...	...	...
Recurrent SSSs	670	45	7 (160)	...	...	...
Number of "Detectable" Sources						
Novae (yr^{-1})	0.9	0.3	0.1	...	...	...
Permanent SSSs ($r \leq 2$ kpc)	2	7	0 (9)	1	≤ 4	≤ 1
Recurrent SSSs ($V \leq 8$ mag)	14	1	7 (4)	...	...	...

"Corrected for shielding" means: circumstellar matter thin enough for SuperSoft X-rays to come out. "Detectable" means: corrected for Interstellar Absorption.

Difference in input physics between DiStefano &Rapp., and Yungelson et al.: (i) steady burning "belt" in Mdot-Mwd diagram adopted by D&R is about factor 2 lower than in Y.et al.; (ii) Binary fraction D&R is lower, (iii) q-distribution is different, etc. Correcting for all this, Y. et al. find approximately the same Nrs. of CBSS as found by Di Stefano and Rappaport.

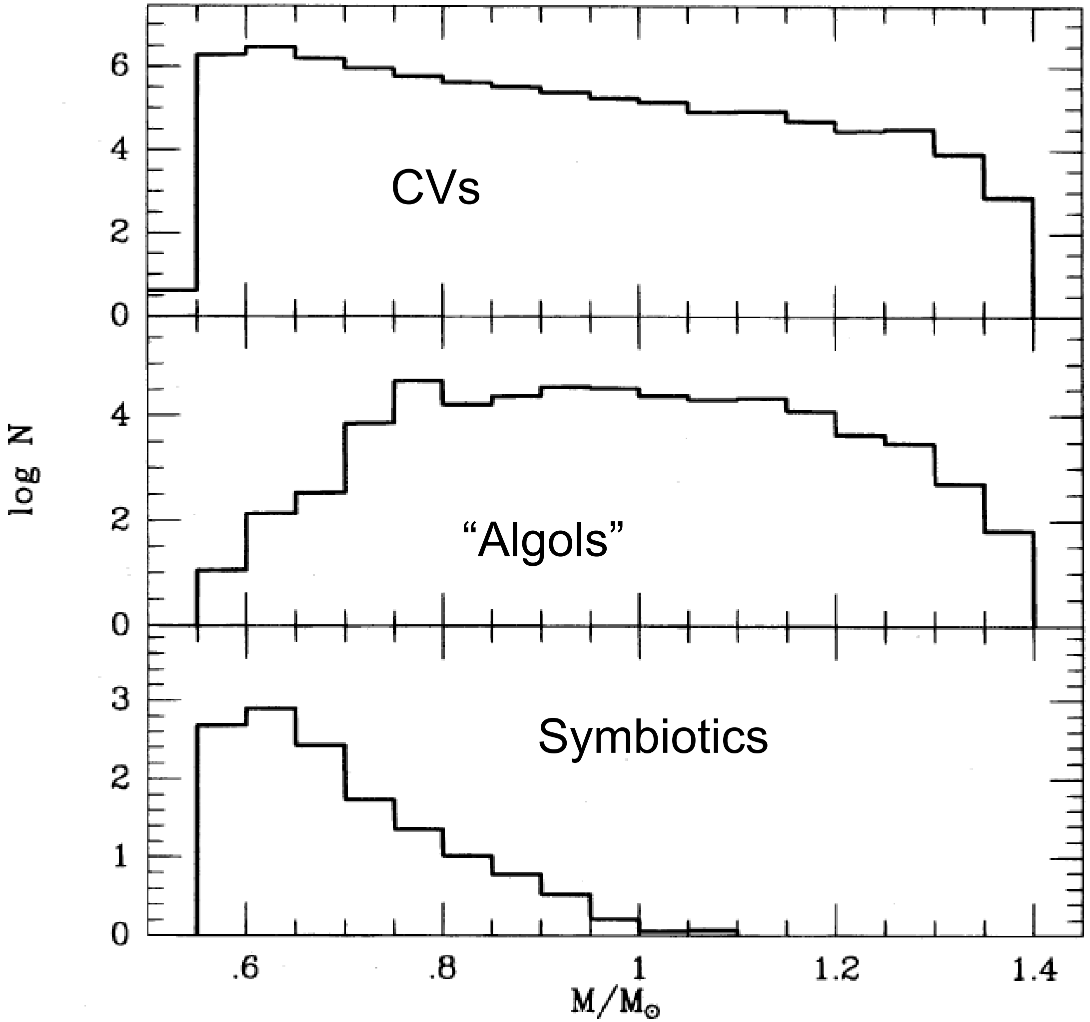


FIG. 4.—Distribution of WDs over mass in cataclysmic variables (*top panel*), systems with subgiant donors (*middle panel*), and in symbiotic binaries (*bottom panel*).

From Yungelson et al. 1996

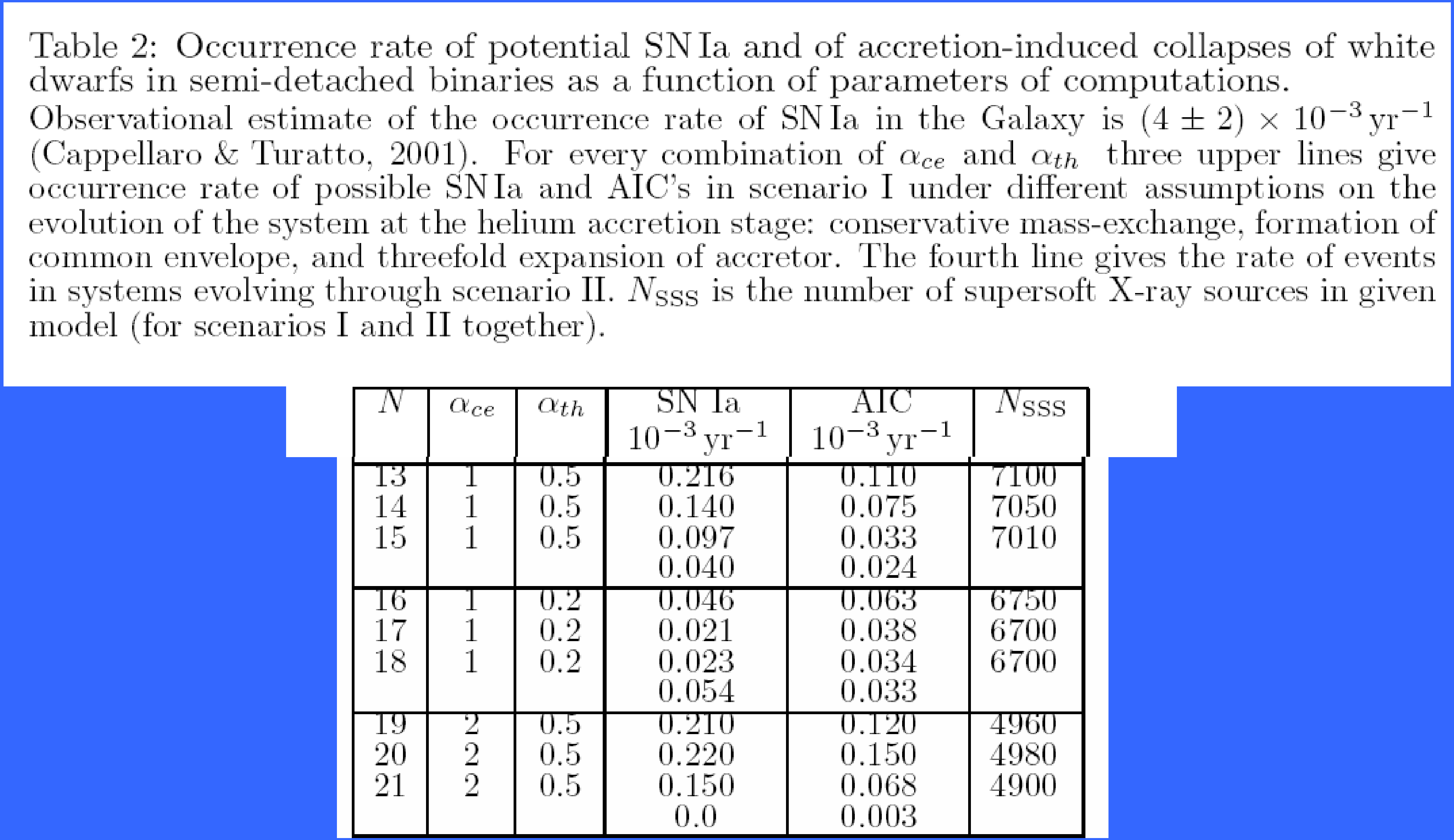
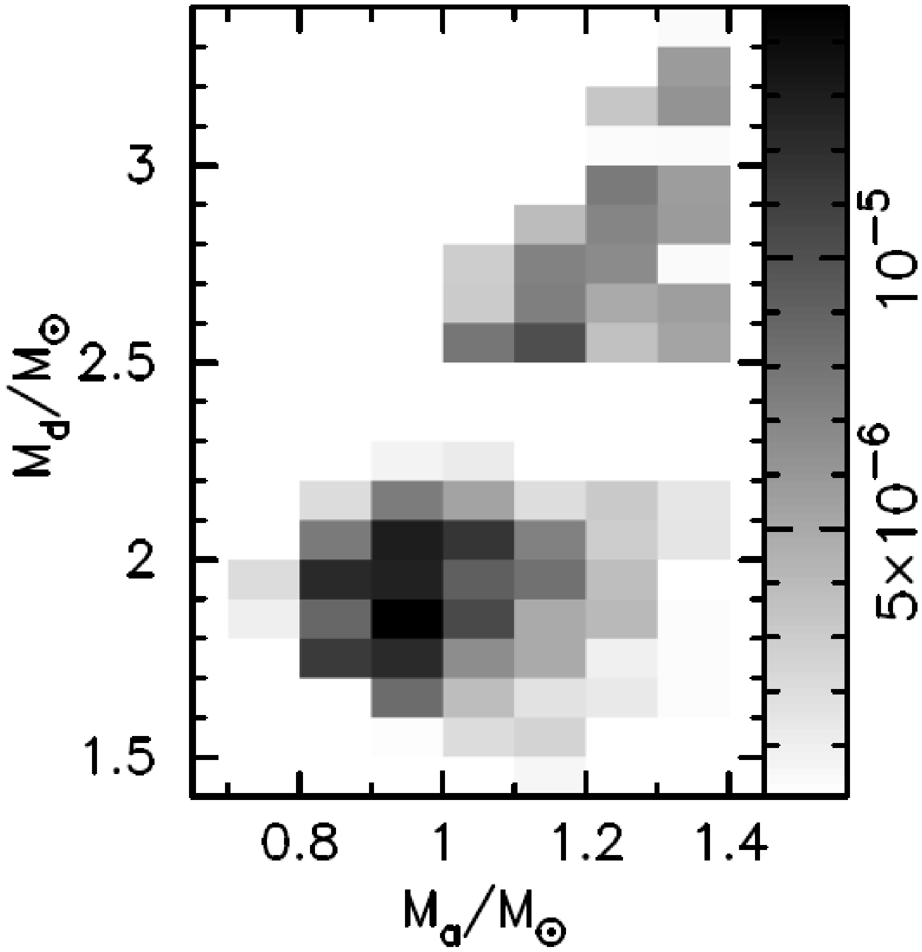


Table 2: Occurrence rate of potential SN Ia and of accretion-induced collapses of white dwarfs in semi-detached binaries as a function of parameters of computations. Observational estimate of the occurrence rate of SN Ia in the Galaxy is $(4 \pm 2) \times 10^{-3}\,\mathrm{yr}^{-1}$ (Cappellaro & Turatto, 2001). For every combination of α_{ce} and α_{th} three upper lines give occurrence rate of possible SN Ia and AIC's in scenario I under different assumptions on the evolution of the system at the helium accretion stage: conservative mass-exchange, formation of common envelope, and threefold expansion of accretor. The fourth line gives the rate of events in systems evolving through scenario II. N_{SSS} is the number of supersoft X-ray sources in given model (for scenarios I and II together).

N	α_{ce}	α_{th}	SN Ia $10^{-3}\,\mathrm{yr}^{-1}$	AIC $10^{-3}\,\mathrm{yr}^{-1}$	N_{SSS}
13	1	0.5	0.216	0.110	7100
14	1	0.5	0.140	0.075	7050
15	1	0.5	0.097	0.033	7010
			0.040	0.024	
16	1	0.2	0.046	0.063	6750
17	1	0.2	0.021	0.038	6700
18	1	0.2	0.023	0.034	6700
			0.054	0.033	
19	2	0.5	0.210	0.120	4960
20	2	0.5	0.220	0.150	4980
21	2	0.5	0.150	0.068	4900
			0.0	0.003	

(After Fedorova, Tutukov and Yungelson, 2004, Soviet Astron. Lett.).

Here Mdot,donor is assumed to be α_{th} times Mdot,th, and α_{ce} is the efficiency parameter of Common Envelope evolution



Main seq. donors

Subgiant donors

Figure 3: The rate of accumulation of $M_{\rm Ch}$ in the SD-scenario (in $\rm yr^{-1}$), depending on the masses of WD-accretors and MS- or SG-donors at the beginning of accretion stage. *Yungelson 2004/ Fedorovo,Tutukov and Yungelson 2004*

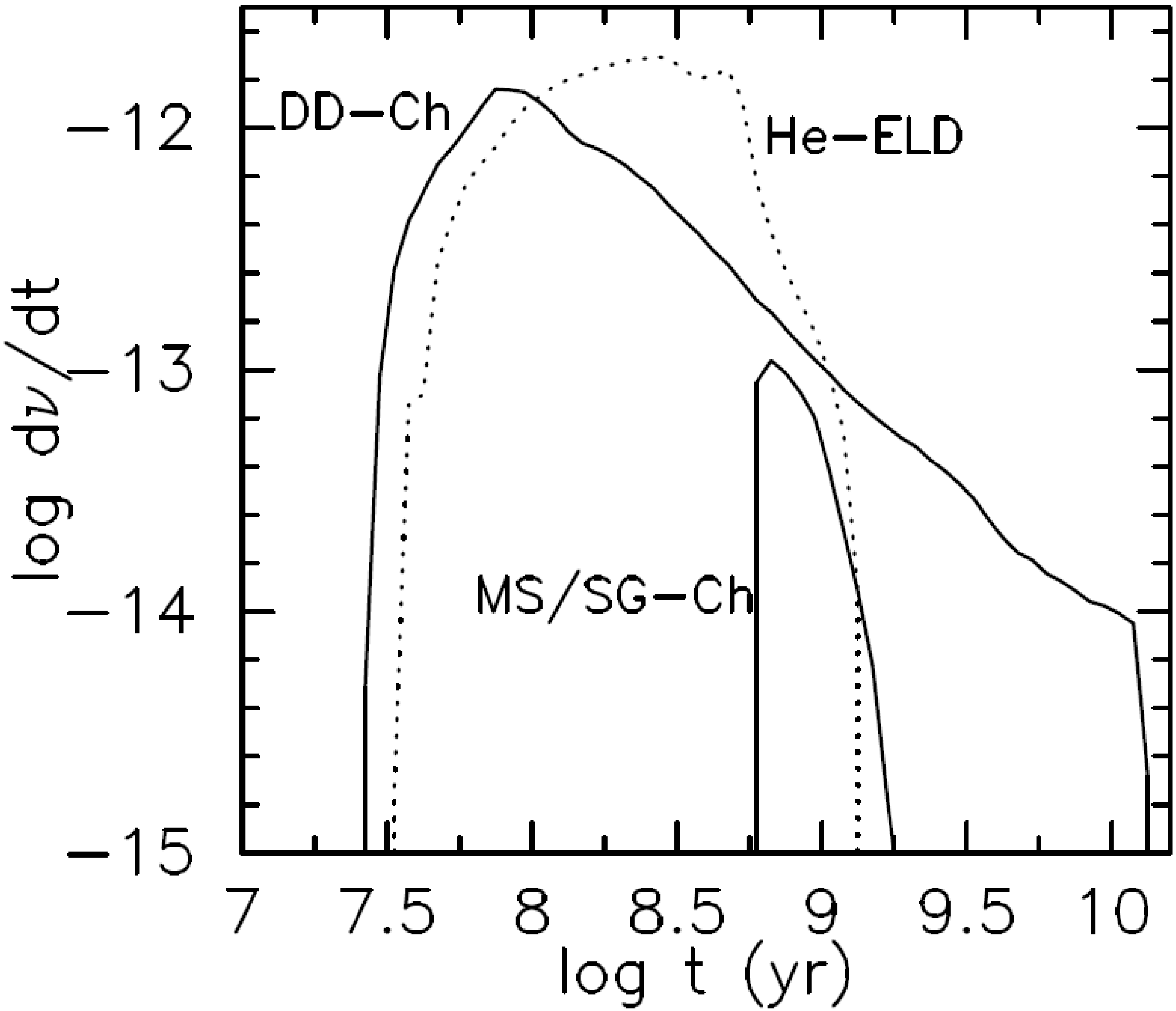


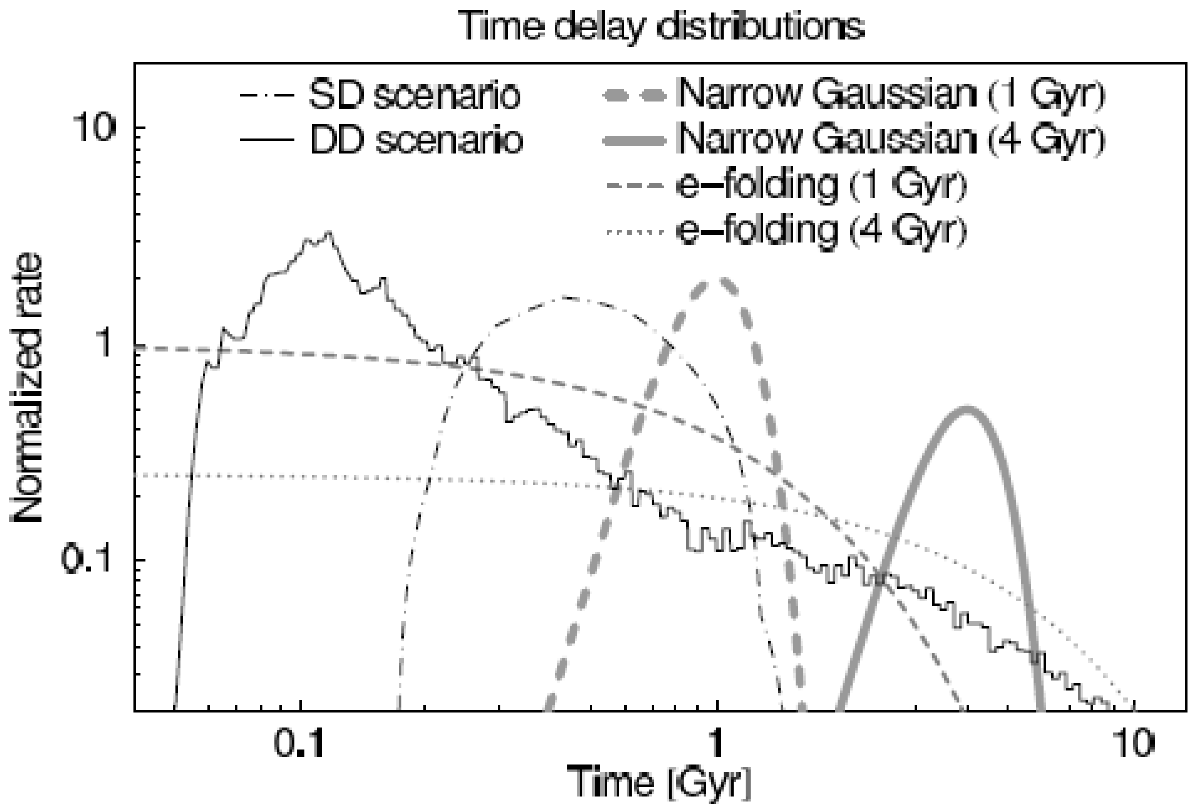
Figure 2: Rates of potential SN Ia-scale events after a 1-yr long star formation burst that produces $1\,M_\odot$ of close binary stars. *Yungelson 2004*

Han and Podsiadlowski (2004) and Förster, Wolf, Podsiadlowski and Han (2006) used the following prescriptions to deal with mass transfer rates > and < the critical ones for steady burning:

- For the > case they assumed Hachisu,Kato,Nomoto&Umeda 1999 (HKNU99) prescription that the excess transferred matter to be blown away in the form of optically thick wind, carrying orbital angular momentum.

- For mass-transfer rates below ⅛ the lower limit for steady burning they assumed no accreted matter to be retained, and above this all to be retained.

Yungelson et al.(1996) and Yungelson and colleagues (2004) used a similar type of prescription for the > case, but a different one for the < case, which allowed even for very low mass transfer rates in CVs matter to be retained, following the work of Schwartzman, Kovetz, Prialnik (1994).



Time delay distributions for the SD and DD scenarios, calculated
by Förster, Wolf, Podsiadlowsi and Han (2006).

These results roughly confirm those of Yungelson (2004), within factors 1-5.
Very encouraging, since the binary-population-synthesis codes of the
two groups are quite different and were developed independently!
Uncertainties come e.g. from the values of various input parameters such as α_{ce} .

Summary:

Binary Population Synthesis results indicate that:

1. In a population with ages between ~ 200 million and 2 billion years, “Supersoft source” binaries (including the shrouded ones) can produce between 50 (Yungelson 2004) and 90 (Förster et al. 2006) per cent of WD growing to $M_{chandra}$.
2. At other epochs the Double Degenerate mergers appear to dominate the formation rate of degenerate objects with a mass ≥ $M_{chandra}$.

3. Forster et al.(2006) conclude: it is too early to rule out any of the proposed Type Ia scenarios.