Mystery of Luminous Supersoft X-Ray Sources in Large Magellanic Cloud and Small Magellanic Cloud

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3. Results: Extreme luminosity, mass-loss rate, nature of the accretor
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Tatranska Lomnica, October 19, 2022

Discovery and the current view of luminous supersoft X-ray sources (SSSs)

Discovery:

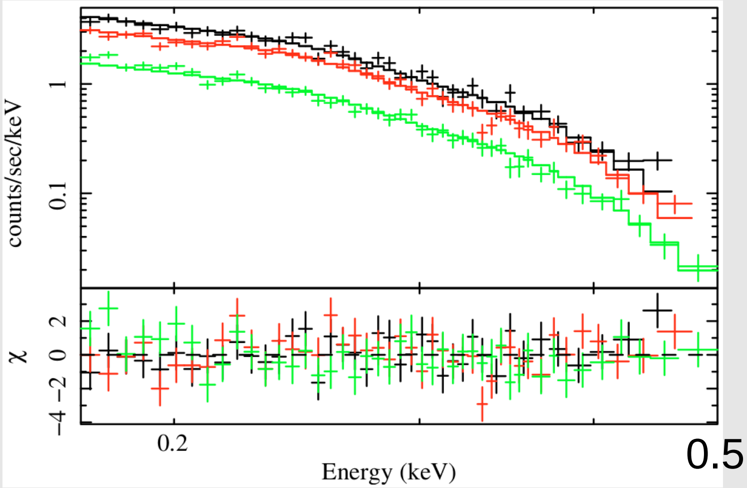
In the 1980s and early 1990s by the Einstein and ROSAT satellites

Basic properties:

- Very soft thermal spectra (E < 0.5 keV, or λ > ~ 25 Å)
- Blackbody temperatures of ~15 – 80 eV (170 – 900 kK)
- Luminosities of 10^{36} – $2\mathrm{x}10^{38}$ erg/s (300 – 50000 L_{Sun})

Current view:

van den Heuvel et al. (1992): Close binaries containing a massive WD radiating close to the Eddington luminosity due to a steady nuclear burning on its surface, when the H-rich material is burned as fast as it is accreted.

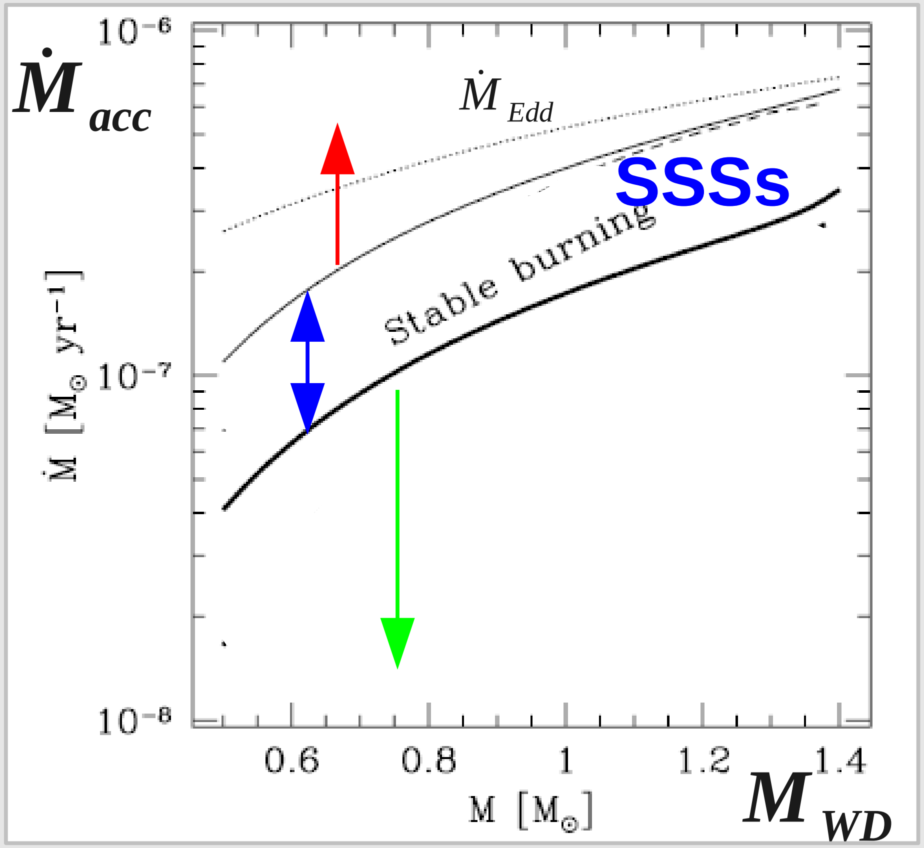


XMM-Newton spectrum of SSS RXJ0058.6-7135 (LIN 333) fitted with a black-body model:
T ~ 313000 K,
L ~ 18000 L(Sun),
Mereghetti et al (2010).

Discovery and the current view of luminous supersoft X-ray sources (SSSs)

Interpretation is based on the energy output from nuclearly burning accreting WDs

$$L_{WD} = L_{acc.} + L_{nucl.} = G\frac{M_{WD}\dot{M}_{acc}}{R_{WD}} + \eta X \dot{M}_{acc} \quad \left(\eta = 6.3\times10^{18}\,\mathrm{erg/g},\ \ X\equiv0.7\right)$$



Shen & Bildsten (2007)

Accreting WD increases its mass:

(i) at low rates up to ΔM → P_{crit} :

ignition of a **nova outburst**

(ii) at high rates of ~10^{-7} M_{Sun}/year:

stable H-burning in a shell

(iii) if rates >~10^{-7} M_{Sun} /year:

Z And-type outbursts

(iv) if P >~ P_{deg} (M_{WD} > ~1.4 M_{sun}):

collapse & ignition of C+O

→ **supernova Ia explosion**

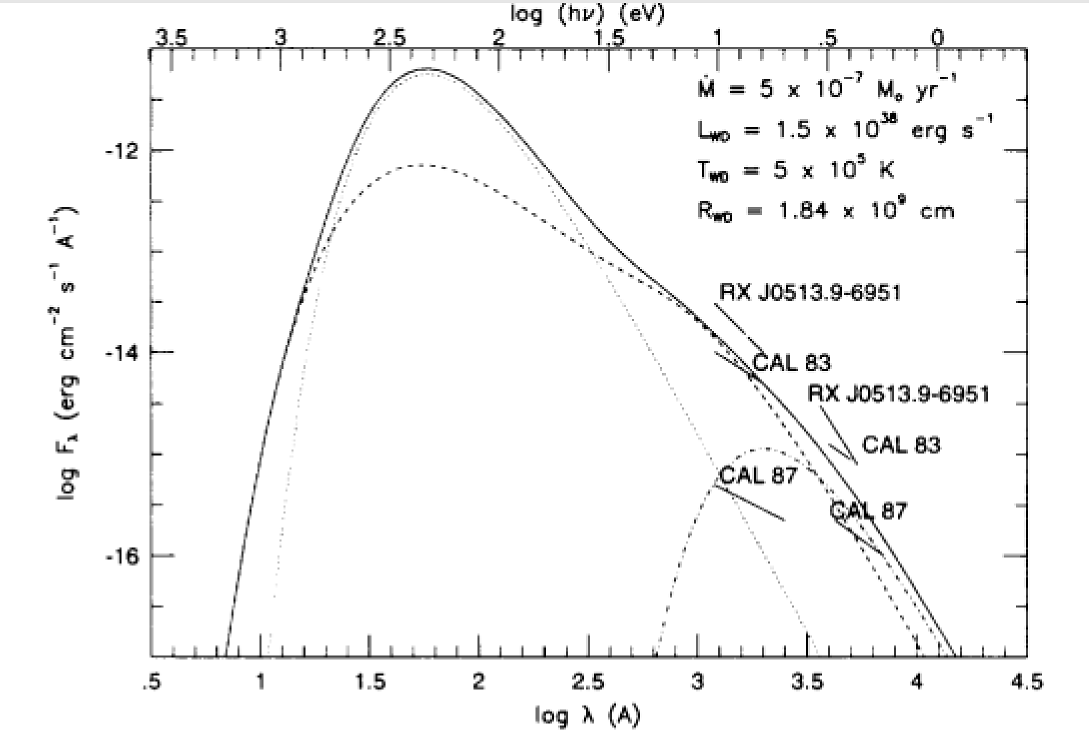
Multiwavelength modeling the global SED: Supersoft X-ray – near-IR spectrum

Current view:

Burning massive WD supersoft X-ray domain

\+

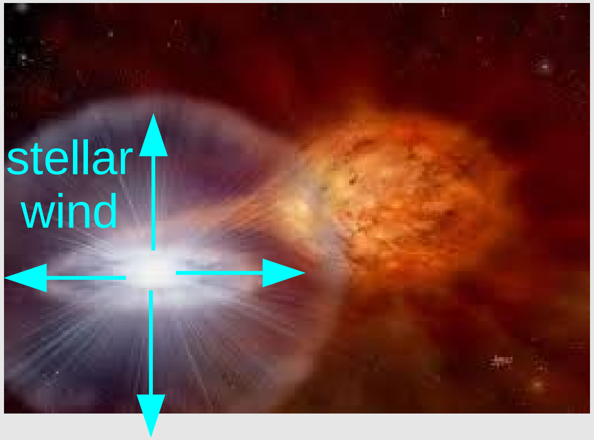
fraction of its radiation reprocessed by the flared disk & reflected by the companion UV/optical + near-IR domain

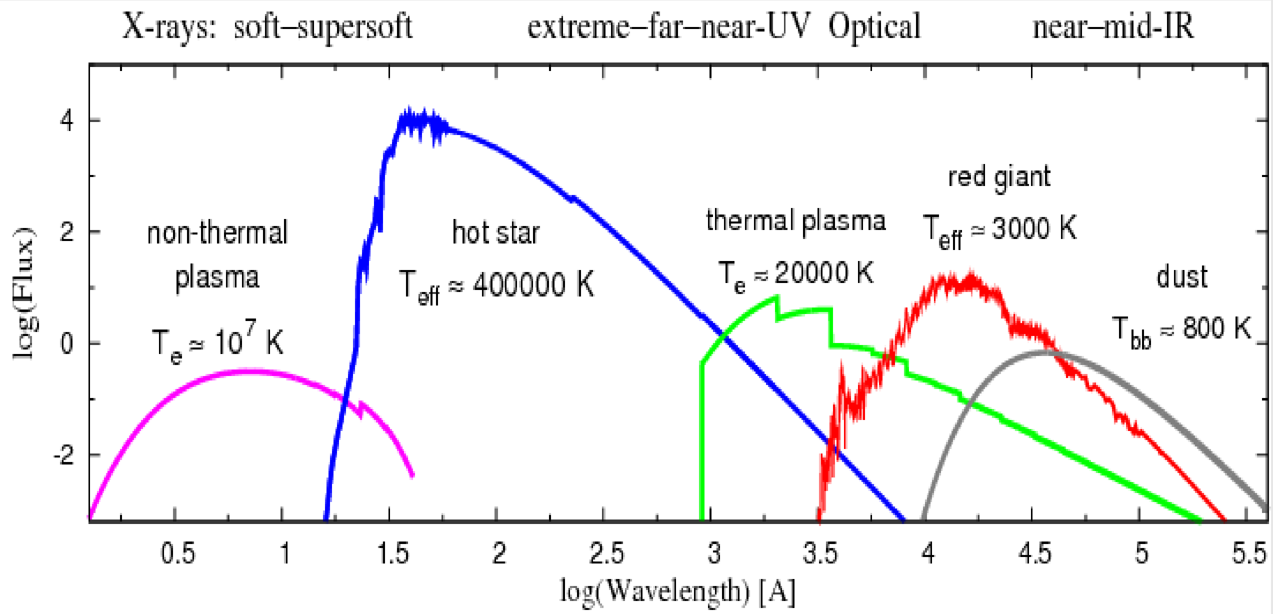


Model of the X-ray – near-IR spectral energy distribution (SED) of luminous SSSs by Popham & Di Stefano (1996). The steady-burning WD (dotted line) and the flared disk reprocessing a fraction of its radiation into the UV/optical/near-IR domain (dashed line). The donor star with a contribution in the near-IR (dash-dotted line). The resulting combined spectrum is given by the solid line.

Multiwavelength modeling the global SED: Supersoft X-ray – near-IR spectrum

New approach:
Burning WD
supersoft X-ray domain
+
fraction of its radiation reprocessed by the stellar wind from the WD:
Nebular component of rad.
UV/optical + near-IR domain





$$F(\lambda) = F_{WD}(\lambda) + F_N(\lambda) + F_G(\lambda) + F_D(\lambda)$$

Model of the X-ray – near-IR SED of luminous SSSs is given by the superposition the hard radiation from the burning WD (blue line) and its fraction converted to longer wavelengths by the WD's wind in the form of the nebular radiation (green line). Other components, from a red giant (red line) and/or dust (gray line) are present for the so-called symbiotic X-ray binaries.

Multiwavelength modeling the global SED: Supersoft X-ray – near-IR spectrum

! fluxes from both sides of the SSS spectrum are needed !

$$\boxed{F(\lambda) = \theta_{WD}^2 \pi B_\lambda(T_{BB}) e^{\sigma_X(\lambda) N_H} + k_N \times \epsilon(\lambda, T_e)}$$

$$\underline{\textit{fitting parameters:}\ \theta_{WD},\ T_{BB},\ N_H,\ k_N,\ T_e}$$

$$\theta_{WD} = \frac{R_{WD}^{eff}}{d} - \textit{angular radius of the WD pseudophotosphere}$$

$$N_H - \textit{ISM} + \textit{CSM column density of } H^0$$

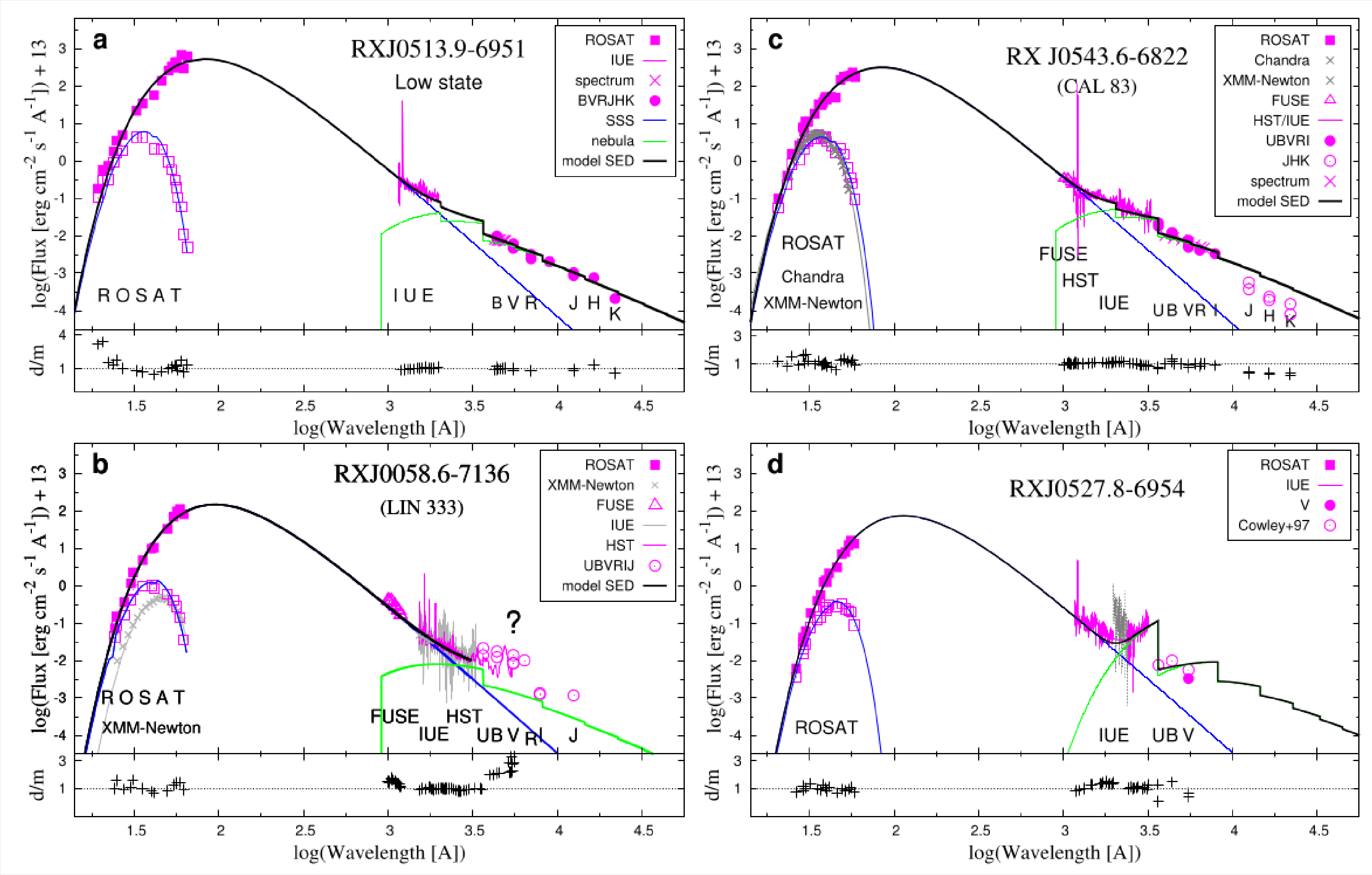
$$\sigma_X(\lambda) - \textit{total cross-section for photoelectric absorption} / H$$

$$k_N - \textit{observed emission measure}$$

$$T_e - \textit{electron temperature}$$

$$\underline{R_{WD}^{eff} = \theta_{WD} \times d, \quad L_{WD} = 4\pi d^2 \theta_{WD}^2 T_{BB}^4, \quad EM = 4\pi d^2 \times k_N}$$

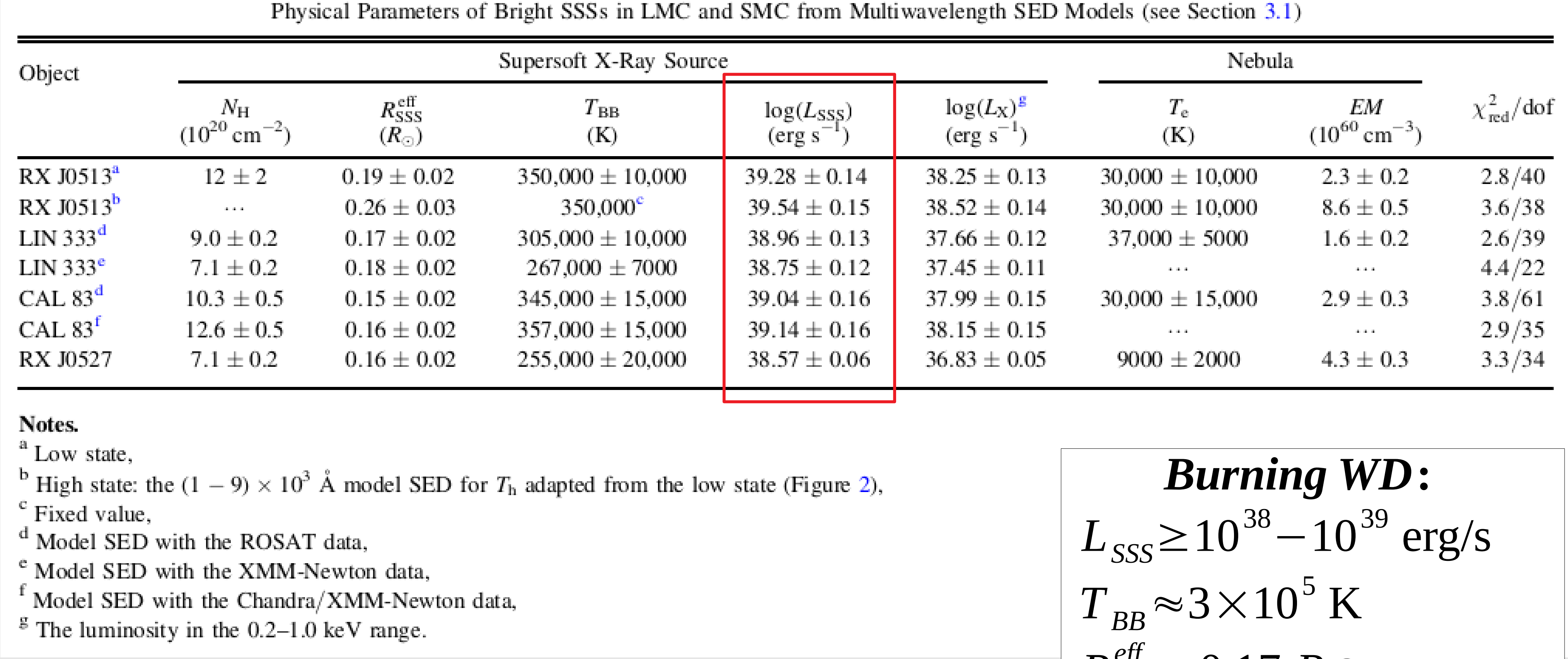
Results: X-ray – near-IR SED models of the brightest SSSs



A comparison of the measured (in magenta) and modeled SEDs (heavy black line) of our targets with corresponding data-to-model ratios (d/m). Filled/open squares are the unabsorbed/observed X-ray fluxes. The blue and green lines denote components of radiation from the SSS and the nebula, respectively.

The global SED models satisfactorily fit the measured multiband fluxes.

Problem of the high luminosity



Physical Parameters of Bright SSSs in LMC and SMC from Multiwavelength SED Models (see Section 3.1)

Object	Supersoft X-Ray Source					Nebula		
	N_H (10^{20} cm^{-2})	R_{SSS}^{eff} ($R_\odot$)	T_{BB} (K)	$\log(L_{SSS})$ (erg s^{-1})	$\log(L_X)$[g] (erg s^{-1})	T_e (K)	EM (10^{60} cm^{-3})	χ^2_{red}/dof
RX J0513[a]	12 ± 2	0.19 ± 0.02	350,000 ± 10,000	39.28 ± 0.14	38.25 ± 0.13	30,000 ± 10,000	2.3 ± 0.2	2.8/40
RX J0513[b]	…	0.26 ± 0.03	350,000[c]	39.54 ± 0.15	38.52 ± 0.14	30,000 ± 10,000	8.6 ± 0.5	3.6/38
LIN 333[d]	9.0 ± 0.2	0.17 ± 0.02	305,000 ± 10,000	38.96 ± 0.13	37.66 ± 0.12	37,000 ± 5000	1.6 ± 0.2	2.6/39
LIN 333[e]	7.1 ± 0.2	0.18 ± 0.02	267,000 ± 7000	38.75 ± 0.12	37.45 ± 0.11	…	…	4.4/22
CAL 83[d]	10.3 ± 0.5	0.15 ± 0.02	345,000 ± 15,000	39.04 ± 0.16	37.99 ± 0.15	30,000 ± 15,000	2.9 ± 0.3	3.8/61
CAL 83[f]	12.6 ± 0.5	0.16 ± 0.02	357,000 ± 15,000	39.14 ± 0.16	38.15 ± 0.15	…	…	2.9/35
RX J0527	7.1 ± 0.2	0.16 ± 0.02	255,000 ± 20,000	38.57 ± 0.06	36.83 ± 0.05	9000 ± 2000	4.3 ± 0.3	3.3/34

Notes.

[a] Low state,

[b] High state: the $(1-9)\times10^3$ Å model SED for T_h adapted from the low state (Figure 2),

[c] Fixed value,

[d] Model SED with the ROSAT data,

[e] Model SED with the XMM-Newton data,

[f] Model SED with the Chandra/XMM-Newton data,

[g] The luminosity in the 0.2–1.0 keV range.

$$\boldsymbol{Mystery}: \quad L \gg L_{Edd} \sim 1.3 \times \left(\frac{M_{WD}}{M_\odot}\right) \sim 1.8 \times 10^{38}\ erg/s$$

In spite of the super-Eddington luminosity for 1.4 M_{Sun} compact object, the accretor has to be a WD (the soft X-ray spectrum profile + small jet's velocity).

$$\boldsymbol{Burning\ WD}:$$

$$L_{SSS} \geq 10^{38} - 10^{39}\ \mathrm{erg/s}$$

$$T_{BB} \approx 3\times10^5\ \mathrm{K}$$

$$R_{SSS}^{eff} \sim 0.17\ R\odot$$

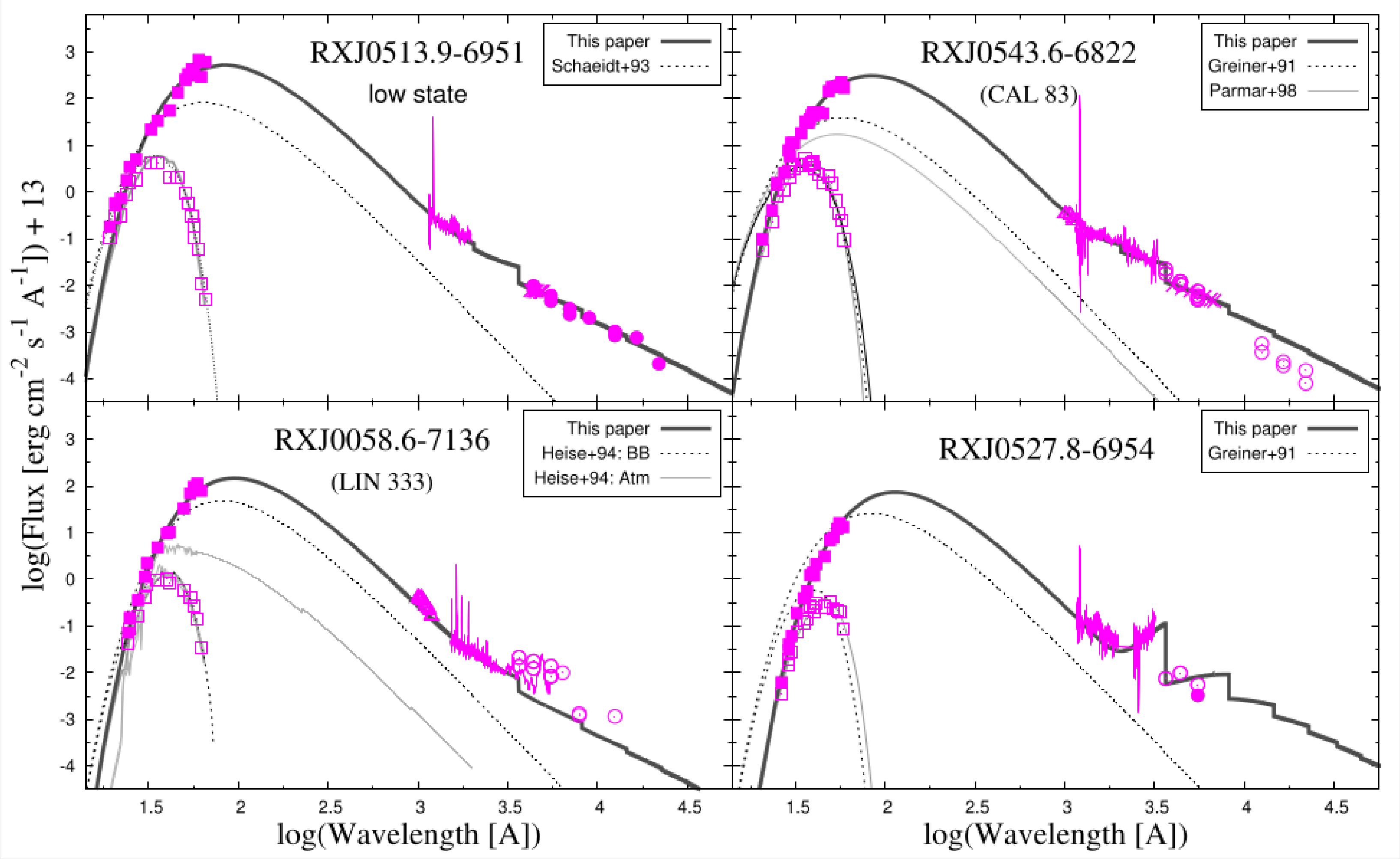
$$N_H = (7-12)\times10^{20}\ \mathrm{cm}^{-2}$$

$$\boldsymbol{Compact\ \ nebula}:$$

$$EM \geq 2\times10^{60}\ \mathrm{cm}^{-3}$$

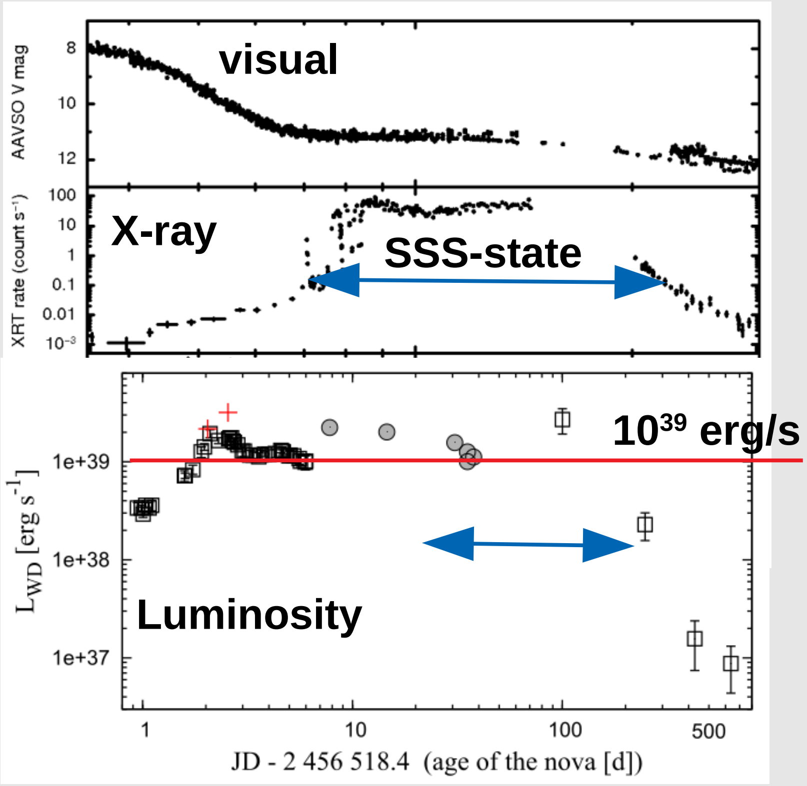
$$\dot{M} \geq 2\times10^{-6}\ M\odot/yr$$

Comparison with previous models



L from multiwavelength modeling (solid lines) >> L from modeling the X-ray data only

Possible explanation of the long-lasting super-Eddington luminosity of the brightest SSSs in LMC and SMC



Example of classical nova V339 Del. Visual and X-ray (*Swift*) light curves. Bottom: super-Eddington luminosity (from Shore et al. 2016; Skopal 2019).

Other examples:

Duration of the SSS state: week(s) – years/decades
GQ Mus: ~10 years; LMC 1995: ~6–8 years;
V723 Cas (1995): > 12 years; …

Theoretical consideration:

- The irradiation of the donor star after the nova outburst can induce a significant enhancement in the mass transfer rate (Kovetz et al. 1988).
- If the accretion resumes immediately at the beginning of the post-nova SSS phase, the SSS lifetime can be substantially lengthened (Kato et al. 2017).

Interpretaion:

Therefore, the brightest SSSs could be (unidentified) optical novae that are in a post-nova SSS state when the residual surface nuclear burning is supported by rapid re-accretion from the donor.

The lifetime of the high luminosity will then depend on the energy output from both the residual burning and the resumed accretion.

Conclusions and Future Work

For the first time, I performed the multiwavelength modeling of the supersoft X-ray–NIR SED for the brightest Magellanic Cloud SSSs. The modeling revealed:

1. Super-Eddington luminosity of 10^{38} – 10^{39} erg/s; temperatures, T_{BB} ~ $3x10^5$ K.
2. A strong nebular component of radiation generated by a compact (unresolved) circumstellar nebula represented by the ionized wind from the SSS.
   The nebular emission corresponds to a wind mass-loss rate >~10^{-6} Mo/yr.

It is suggested that the brightest SSSs in the LMC and SMC could be unidentified classical novae in a post-nova SSS state, whose very high luminosity is sustained by resumed accretion, possibly at super-Eddington rates.

Future work:

For testing the proposed model, and developing its more perfect version:

- A flux-calibrated low-resolution optical/NIR spectrum (λ > 350 nm) should verify the presence of the nebular continuum (e.g., the Balmer jump).
- High-resolution spectra should directly indicate a high-velocity mass outflow.
- Using the photoionization code CLOUDY, calculate emission-line spectrum to confirm the presence of a dense nebula (e.g., a large Balmer decrement).
- In modeling the global SED, to consider the component of radiation from the irradiated accretion disk

Thank you for your attention

Based on:

Augustin Skopal, *Multiwavelength Modeling the SED of Luminous Supersoft X-Ray Sources in Large Magellanic Cloud and Small Magellanic Cloud.* In: The Astronomical Journal, 164:145 (18pp), 2022 October

Data sources:

Made by ROSAT, XMM-Newton, Chandra, FUSE, HST, IUE. Data from: USNO-B Catalog, NOMAD Catalog, 2MASS All-Sky Catalog, IRSF Magellanic Clouds Point Source Catalog, 2MASS 6X Point Source Working Database/Catalog, The SMC Stellar Catalog and Extinction Map, The LMC Stellar Catalog and Extinction Map, Catalogue of Stellar Spectra Classifications, the 3rd release of the DENIS database, the MAST data archive at the Space Telescope Science Institute.

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