X-ray observations of classical novae Theoretical implications

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- Origin of X-ray emission
- Summary of observational results (novae as SSS)

ROSAT, Beppo-SAX, XMM-Newton & Chandra, Swift

- Theoretical models: classical and recurrent novae

V1974 Cyg 1992 – RS Oph

Origin of X-ray emission (I)

- Residual steady H-burning on top of the white dwarf:
  photospheric emission from the hot WD:

  T_{eff}~(2-10)x10^5K (L~10^{38}erg/s) ⟶ ***supersoft X-rays***

  - detected by ROSAT/PSPC in only 3 classical novae, out of 39 observed up to 10 years after explosion:
    GQ Mus (N Mus1983), N Cyg 1992, N LMC 1995
    (Orio et al. 2001). A few more detections with BeppoSAX, Chandra, XMM-Newton, Swift

  - duration related to H-burning turn-off time. "Old" theory: $\tau_{nuc}\approx$100yr; observations: <9 - 12 yr; typically: < 2yr

Origin of X-ray emission (II)

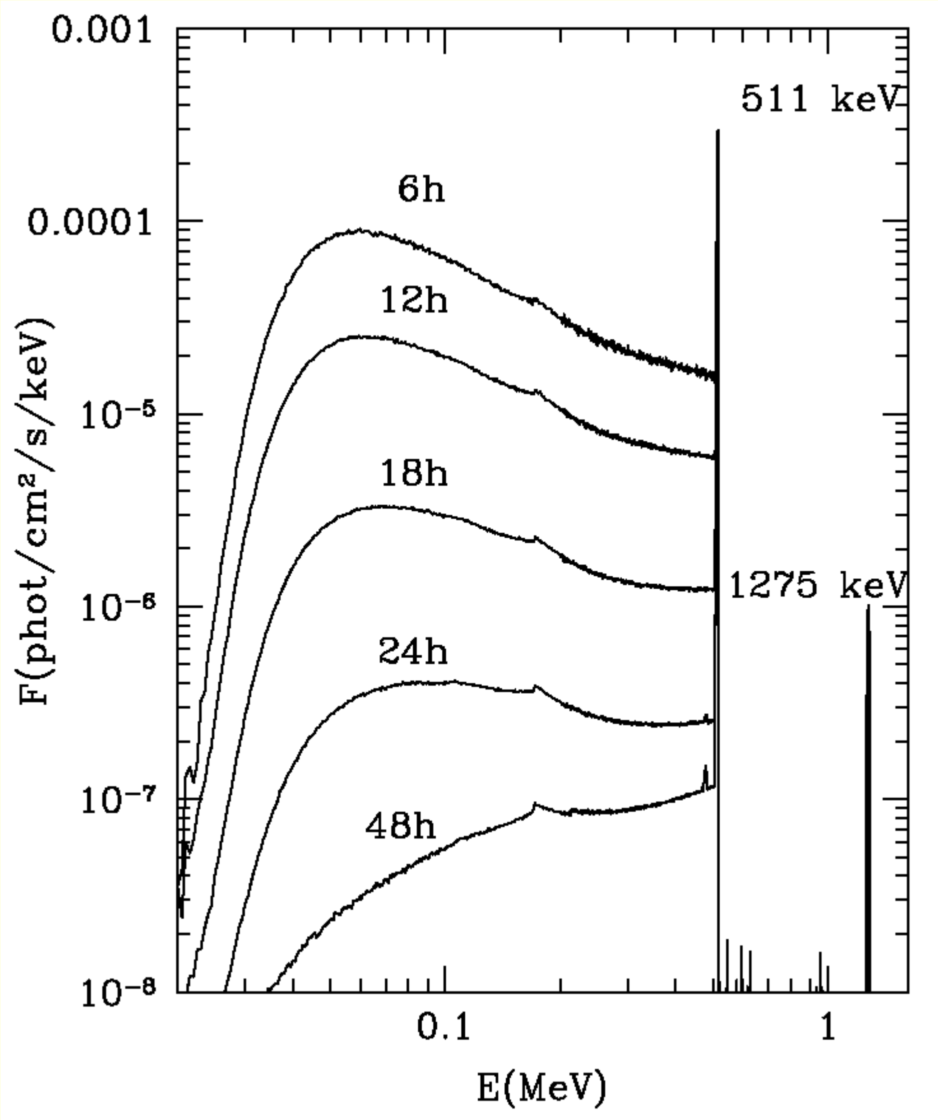
- Internal (external) shocks in the ejecta: thermal plasma emission

  - ➢ detected early after explosion (N Her 1991, N Pup 1991, N Cyg 1992, N Vel 1999, …): internal shocks

- Reestablished accretion: emission “as a CV” (idem)

❖ *Hard (but also soft) X-rays, depending on the thermal plasma T*

Origin of X-ray emission (III)



Compton degradation of γ-rays emitted by classical novae ***CAN NOT*** be responsible of their ***early hard X-ray emission***:

•Cut-off at 20 keV (photoelectric abs.)

•Fast disappearence: 2days (w.r.t T_{max}, i.e., before visual outburst)

Gómez-Gomar,Hernanz,José,Isern, 1998, MNRAS

Observations – Supersoft X-ray emission

- EXOSAT and ROSAT discoveries:

  GQ Mus (1983): 1st detection of X-rays in a nova, EXOSAT (Ögelman et al. 1984). One of the longest supersoft X-ray phases: **9 yr** Ögelman et al.1993; Shanley et al. 1995; Orio et al. 2001; Balman & Krautter 2001

  V1974 Cyg (1992): complete light curve with ROSAT- rise, plateau and decline – **1.5 yr** Krautter et al. 1996, Balman et al. 1998 → later

  N LMC 1995: ROSAT & XMM-Newton – **8 yrs**
  ROSAT discovery Orio &Greiner 1999, **XMM-Newton obs.** Greiner et al. 2003

- BeppoSAX

  V382 Vel (1999): supersoft X-ray flux not constant; model atmosphere not a good fit; emission lines from highly ionized nebula (Orio et al 2002); Chandra grating obs (Burwitz et al., Ness et al.): turn-off **7-9 months**

Observations – Supersoft X-ray emission

Chandra and XMM-Newton: ***grating observations***

V1494 Aql (1999): burst and pulsations Drake et al. 2003;

V4743 Sgr (2002): Ness et al 2003: strong variability –

Rauch: complex spectra

XMM-Newton monitoring campaign: ***V5115 Sgr V5116 Sgr 2005***

Swift: Ness 2007, Osborne

V723 Cas (1985): L and T_{eff} not well determined (BB) Ness et al. 2008 – Still SSS **12 yrs after outburst.** Isn't L a bit small for whole WD emission: $L>5x10^{36}$ erg/s?

V458 Vul (2007), V2491 Cyg (2008): duration SS phase **10 d!**

Ness, Takei, Hachisu

- RS Oph - recurrent nova: Bode (Swift), Nelson & Orio, Ness et al, Drake et al. (XMM & Chandra) – **60 days**
- M31 nova survey → Pietsch

XMM-Newton - AO1 Cycle -Summary

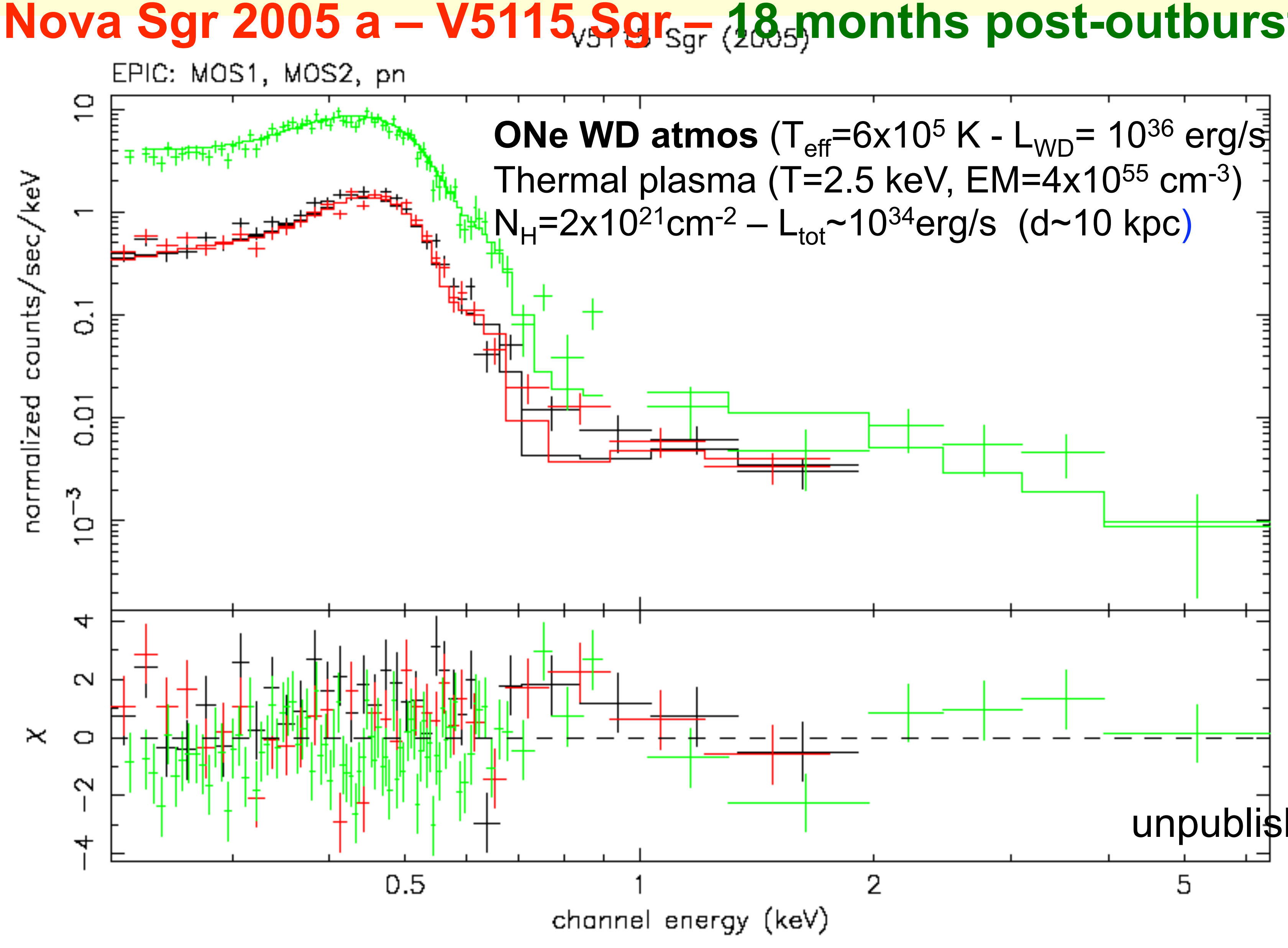
Target	Discovery date	Date of observation – Time after outburst	Detection
N Sco 1997 V1141 Sco	June 5	Oct. 11, 2000 – 1224d, 3.4yr Mar. 24, 2001 – 1388d, 3.8yr Sep. 7, 2001 – 1555d, 4.3yr	NO
N Sgr 1998 V4633 Sgr	March 22	Oct. 11, 2000 – 934d, 2.6yr Mar. 9, 2001 – 1083d, 3.0yr Sep. 7, 2001 – 1265d, 3.5yr	YES *but no SSS*
N Oph 1998 V2487 Oph	June 15	Feb. 25, 2001 – 986d, 2.7 yr Sep. 5, 2001 – 1178d, 3.2 yr Feb. 2002 – 1352d, 3.7yr Sept. 24, 2002 – 1559d, 4.3yr	YES *but no SSS*
N Sco 1998 V1142 Sco	October 21	Oct. 11, 2000 – 721 d, 2.0 yr Mar. 24, 2001 – 885 d, 2.4 yr Sep. 7, 2001 – 1052 d, 2.9 yr	*2.6±0.3* *2.2±0.4* *1.2±0.2* *(10^{-2} cts/s)*
N Mus 1998 LZ Mus	December 29	Dec. 28, 2000 – 730 d, 2.0 yr Jun. 26, 2001 – 910 d, 2.5 yr Dec. 26, 2001 – 1093 d 3.0 yr	NO?

- ***No supersoft*** ***X-ray emission related to residual H-burning detected***
  → ***all novae had already turned-off***
- *3 out of 5 were emitting [thermal plasma (+ BB)] spectrum → ejecta/accretion*

Target	Discovery date	Date of observation – Time after outburst	Detection
N Oph 1998 V2487 Oph	June 15	Mar. 24, 2007 – 8.8yr *AO6 long exposure*	YES *but no SSS*
N Cyg 2005 V2361 Cyg	February 10	May 13, 2006 - 15mo – bkg Oct. 20, 2006 - 20months *AO5*	-- YES *marginal: $(4.0\pm0.8)\times10^{-3}$ cts/s*
N Sgr 2005a V5115 Sgr	March 28	Sep. 27, 2006 – 18months Apr. 4, 2009 – 49 months	YES *supersoft source* YES but no SSS
N Sgr 2005b V5116 Sgr	July 4	Mar. 20, 2007 – 20 months Mar. 13, 2009 – 44 months	YES *supersoft source* YES but no SSS
N Cyg 2006 V2362 Cyg	April 2	May 5, 2007 – 13 months affected by bkg *AO6* Dec. 22, 2008 – 32 months	YES but no SSS YES but no SSS
N Oph 2006a V2575 Oph	February 9	Sep. 4, 2007 – 19 months *AO6*	NO
N Oph 2006b V2576 Oph	April 6	Oct. 3, 2007 – 18months *AO6*	NO

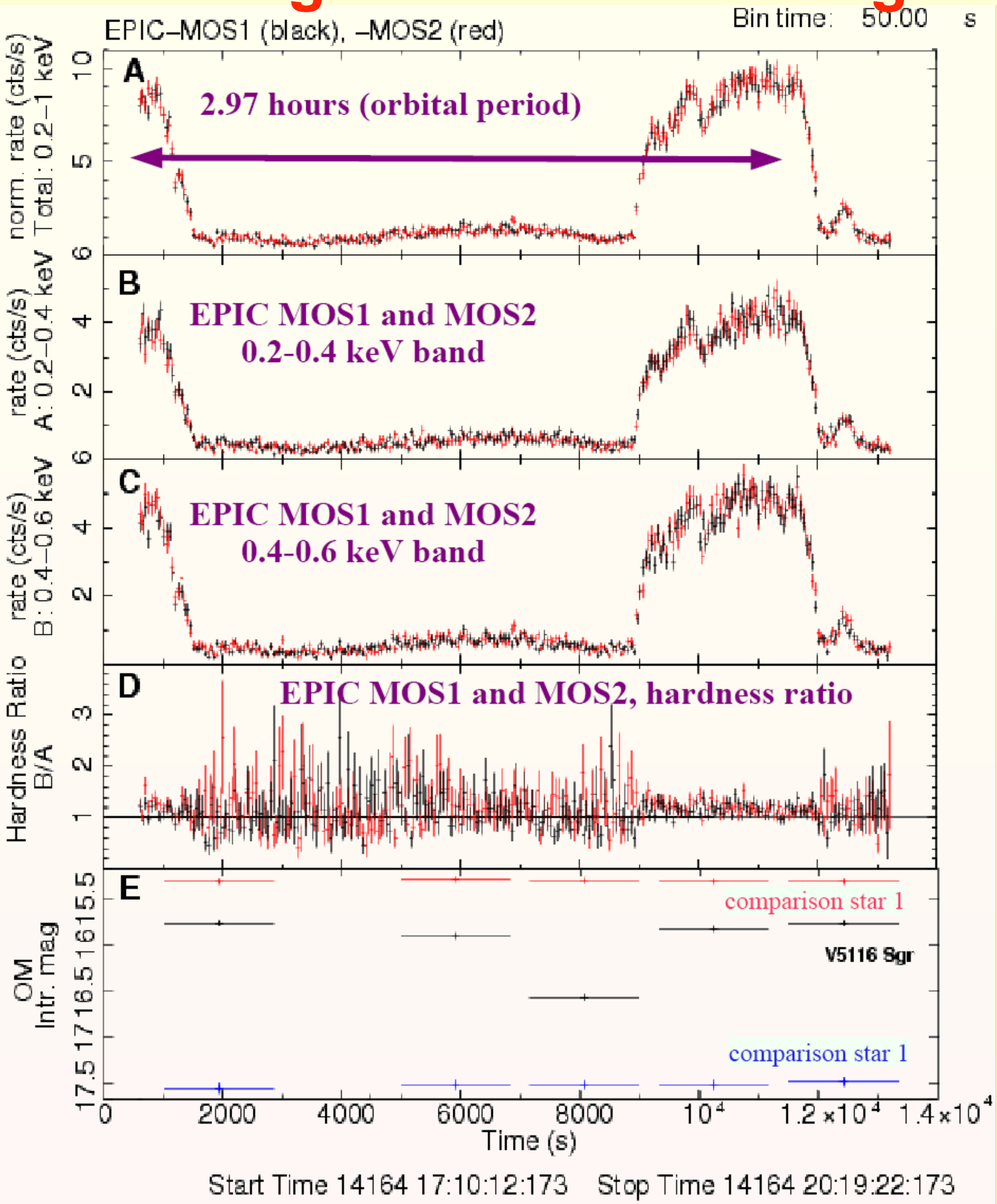
Supersoft X-ray emission related to residual H-burning found in 2 novae from 2005 (V5115 Sgr & V5116 Sgr)→ novae had not turned-off yet

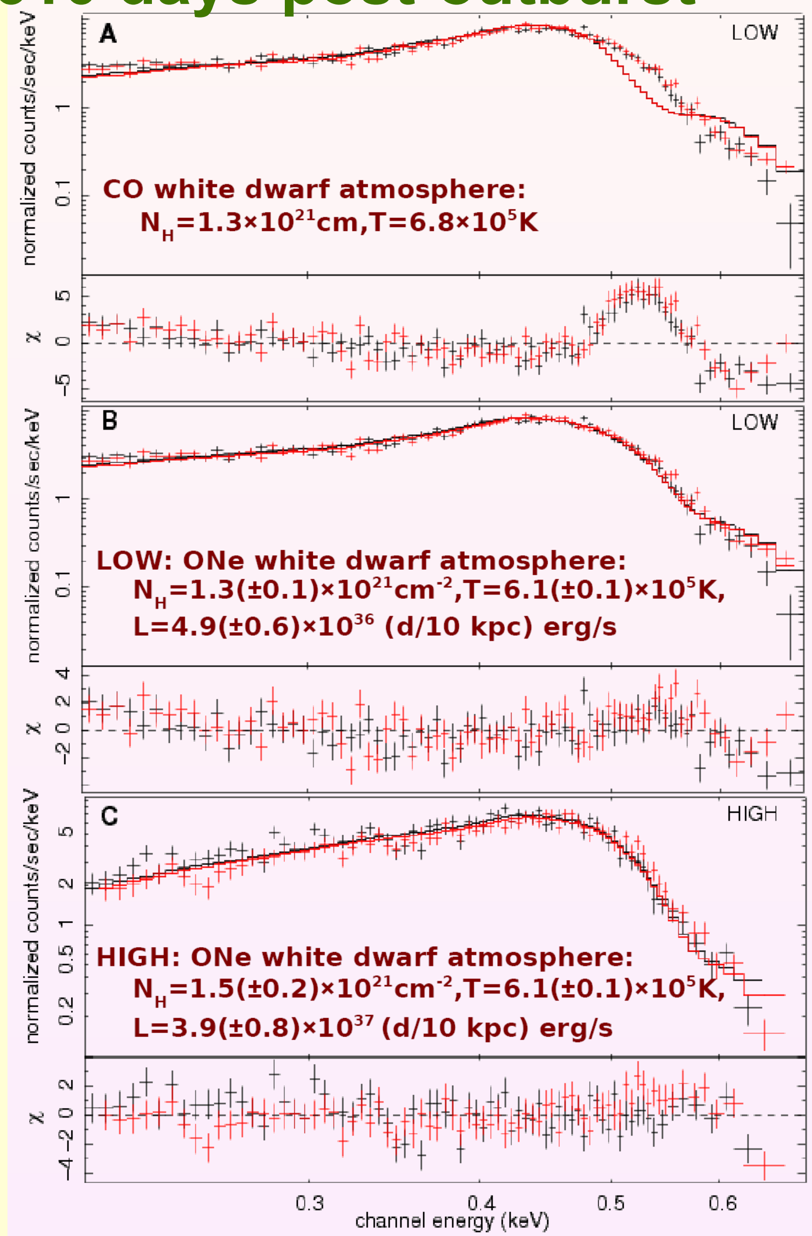
Nova Sgr 2005 a – V5115 Sgr – 18 months post-outburst



Hachisu & Kato (2007): predict H-burning ends day 250-280 – too early

Nova Sgr 2005 b – V5116 Sgr – 610 days post-outburst

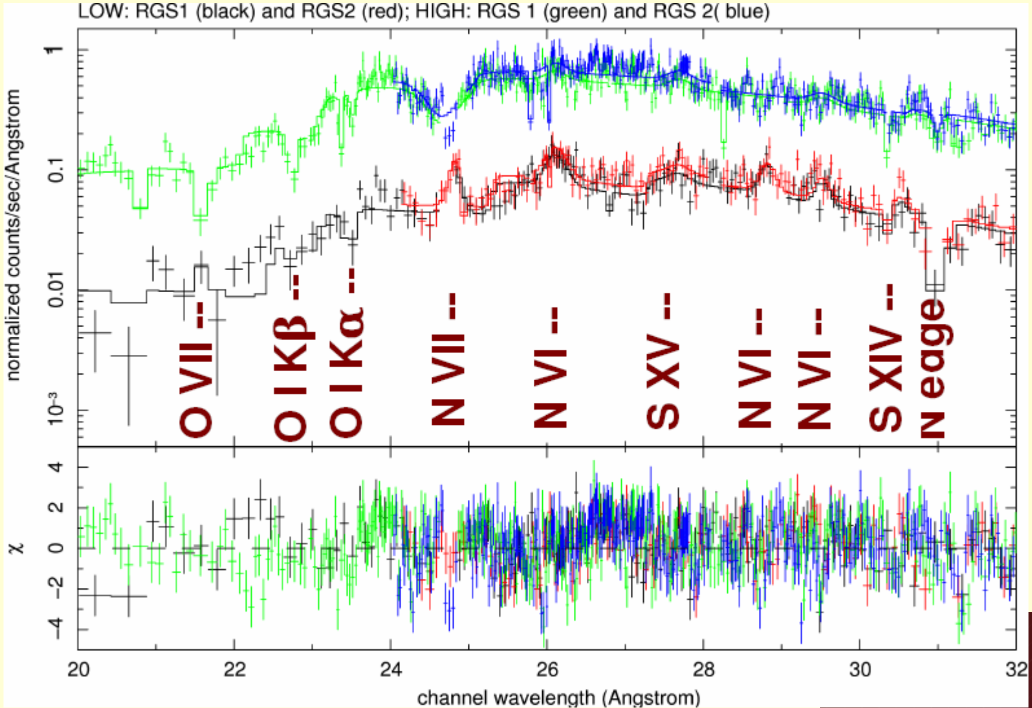




partial eclipse by an asymmetric disk? Sala, Hernanz, Ferri & Greiner, ApJL 2008

→ see poster

Nova Sgr 2005 b – V5116 Sgr – 610 days post-outburst



RGS spectra

→ see poster Sala et al.

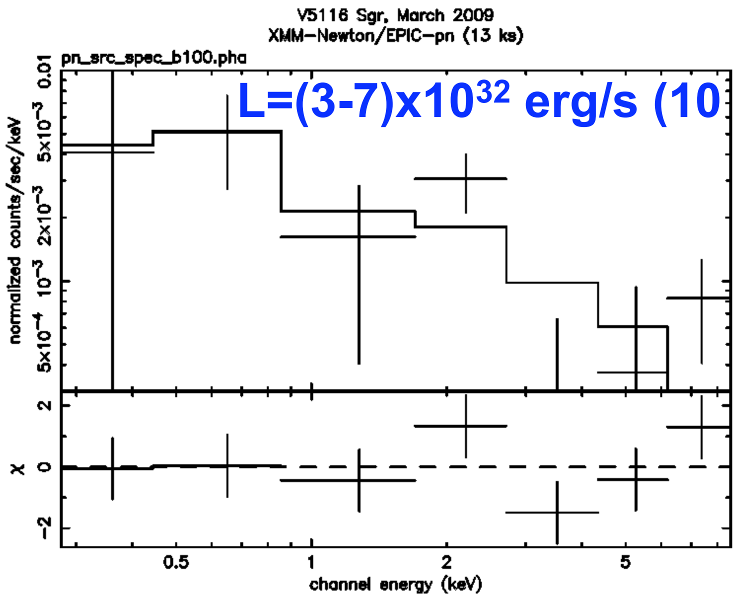
Possibly ISM absorption lines

Emission lines stronger (relative to continuum) during low flux; probably originated at the non-eclipsed material (disk? ejecta?)

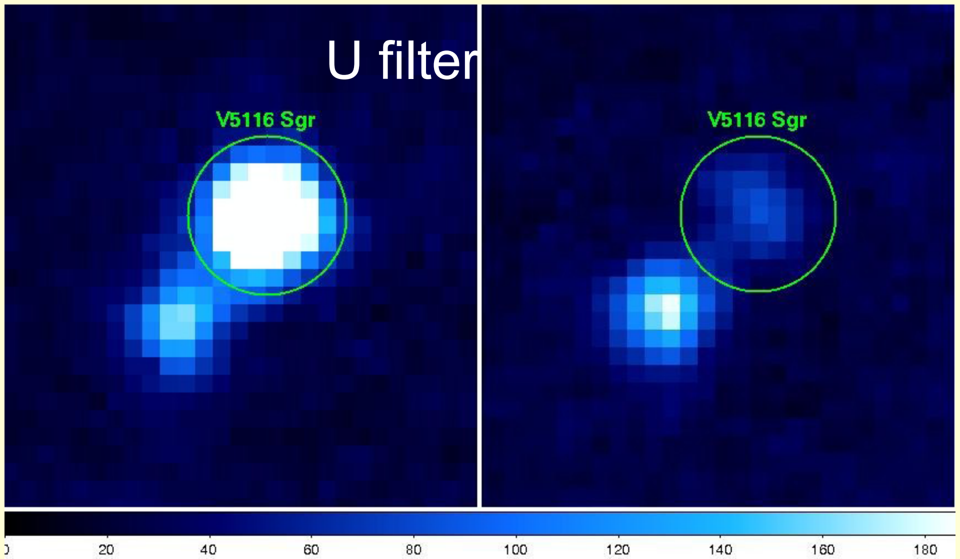
Identification	λ (Å)		FWHM (eV)	Eq. width (eV)
O VII	21.602	High	< 10	$-5.3^{+2.3}_{-6.8}$
		Low	1 (frozen)	> -6
O I Kβ	22.887	High	< 13	$-3.7^{+1.6}_{-6.5}$
		Low	1 (frozen)	> -6
O I Kα	23.507	High	< 14	$-1.6^{+0.7}_{-2.0}$
		Low	1 (frozen)	> -4
N VII	24.78	High	4 ± 2	-6 ± 2
		Low	$1.0 \pm 0.5 (1\sigma)$	$5.2^{+4.5}_{-2.5}$
N VI	26.12	High	2 (frozen)	< 1
		Low	2.0 ± 0.5	4 ± 2
S XV	27.56	High	2 (frozen)	< 1.2
		Low	2 (frozen)	$1^{+1}_{-0.8} (1\sigma)$
N VI	28.79	High	5 (frozen)	< 1.3
		Low	$5 \pm 3 (1\sigma)$	3^{+7}_{-1}
N VI	29.534	High	2 (frozen)	< 1.1
		Low	$2 \pm 1 (1\sigma)$	$2^{+2}_{-1.5}$
S XIV	30.47	High	1 (frozen)	< 0.4
		Low	1 (frozen)	$1.4^{+0.7}_{-1} (1\sigma)$

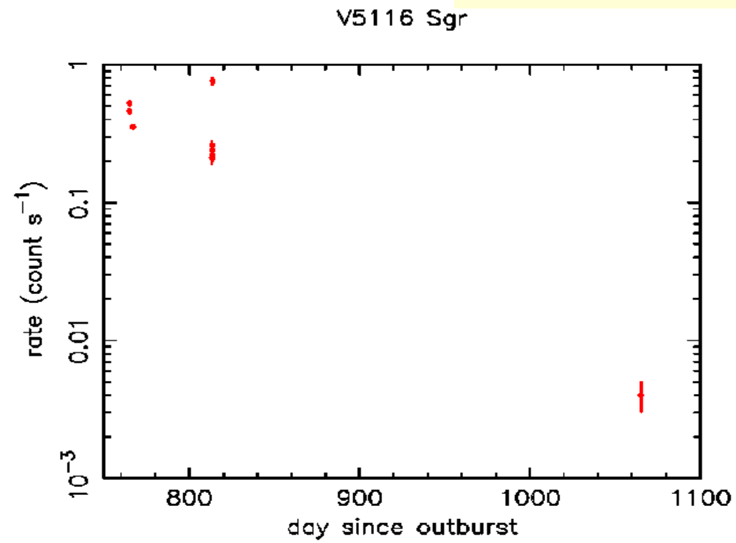
XMM-Newton RGS X-ray spectra

Nova Sgr 2005 b – V5116 Sgr: new obs. March 2009
1348 days post-outburst



L=(3-7)x10^{32} erg/s (10 kpc)





Swift/XRT light light curve

SSS turn-off: **2 - 3 years** post-outburst

compatible with Hachisu & Kato (2007) prediction

SUMMARY of XMM-Newton campaign

- 11 novae have been observed between 3 months and 5 years after outburst (9 years)
- 4 non detected and 2 detected marginally
- Only 2, V5115 Sgr 2005a and V51116 Sgr 2005b, were still bright in supersoft X-rays, revealing remaining H-nuclear burning – one of them with a puzzling temporal behavior

- V2487 Oph 1998, clearly shows recovery of accretion in a magnetic CV (most probably an intermediate polar)
- V4633 Sgr 1998 shows either hot ejecta or accretion (or both)
- V2362 Cyg 2006: mainly hard X-rays (ejecta or accretion)

Different behaviours in X-rays of post-outburst novae (1-4 years old), as seen with XMM-Newton:

- supersoft, still burning H (not very often) - V5115 & V5116 Sgr(2005)

➡ WD properties: M_{wd}, M_{env}, *chem. comp., turnoff*

➡ If absent, shows that $M_{ejected} > M_{accreted}$: ***$M_{wd}$ decreases***

-soft and hard X-rays, reaching E~10 keV

- *ejecta* (heated by shocks) - V4633 Sgr 1998: T and n distribution, chemical composition
- "cataclysmic-like" emission *accretion* - V2487 Oph 1998: accretion disk/stream, (magnetic field, periodicities)

Hydrodynamical models of nova explosions

INITIAL PARAMETERS AND MAIN CHARACTERISTICS OF ONe NOVA MODELS

Parameter	ONe1	ONe2	ONe3	ONe4	ONe5	ONe6	ONe7
M_{wd} ($M_\odot$)	1.00	1.15	1.15	1.15	1.25	1.35	1.35
Mixing (%)	50	25	50	75	50	50	75
ΔM_{env} (10^{-5} $M_\odot$)	6.4	3.2	3.2	3.5	2.2	0.54	0.58
t_{acc} (10^5 yr)	3.3	1.9	1.9	2.1	1.3	0.31	0.33
t_{rise} (10^6 s)	20	46	13	11	6.8	2.5	2.1
$\epsilon_{nuc,max}$ (10^{16} ergs g^{-1} s^{-1})	0.29	0.36	0.76	2.4	2.1	19	14
T_{max} (10^8 K)	1.98	2.21	2.19	2.48	2.44	3.24	3.32
t_{max} (s)	768	828	540	305	380	150	108
ΔM_{ejec} (10^{-5} $M_\odot$)	4.7	2.3	1.9	2.6	1.4	0.44	0.34
v_{ejec} (km s^{-1})	1600	2100	2400	2500	3100	4100	6000
K (10^{45} ergs)	1.3	1.1	1.2	1.9	1.4	0.9	1.3

		ONe2	ONe3	ONe4
H mass fraction	X	0.53	0.35	0.18
Global metallicity	Z	0.27	0.50	0.74
M_{env}-M_{ejec} (10^{-5} $M_\odot$)	M_{rem}	0.9	1.3	0.9
Luminosity (10^4 $L_\odot$)	$L_{plateau}$	4.3	4.9	5.4
time (turn-off) (yrs)	τ_{nuc}	***8.9***	***7.4***	***2.4***

José & Hernanz, ApJ 1998

too long

$$\tau_{nuc} = 400 \left(\frac{M_H}{10^{-4}\ M_\odot} \right) \left(\frac{L}{2 \times 10^4\ L_\odot} \right)^{-1} \text{yr}$$

Starrfield 1998

WD envelope models with steady H-burning (no accretion)

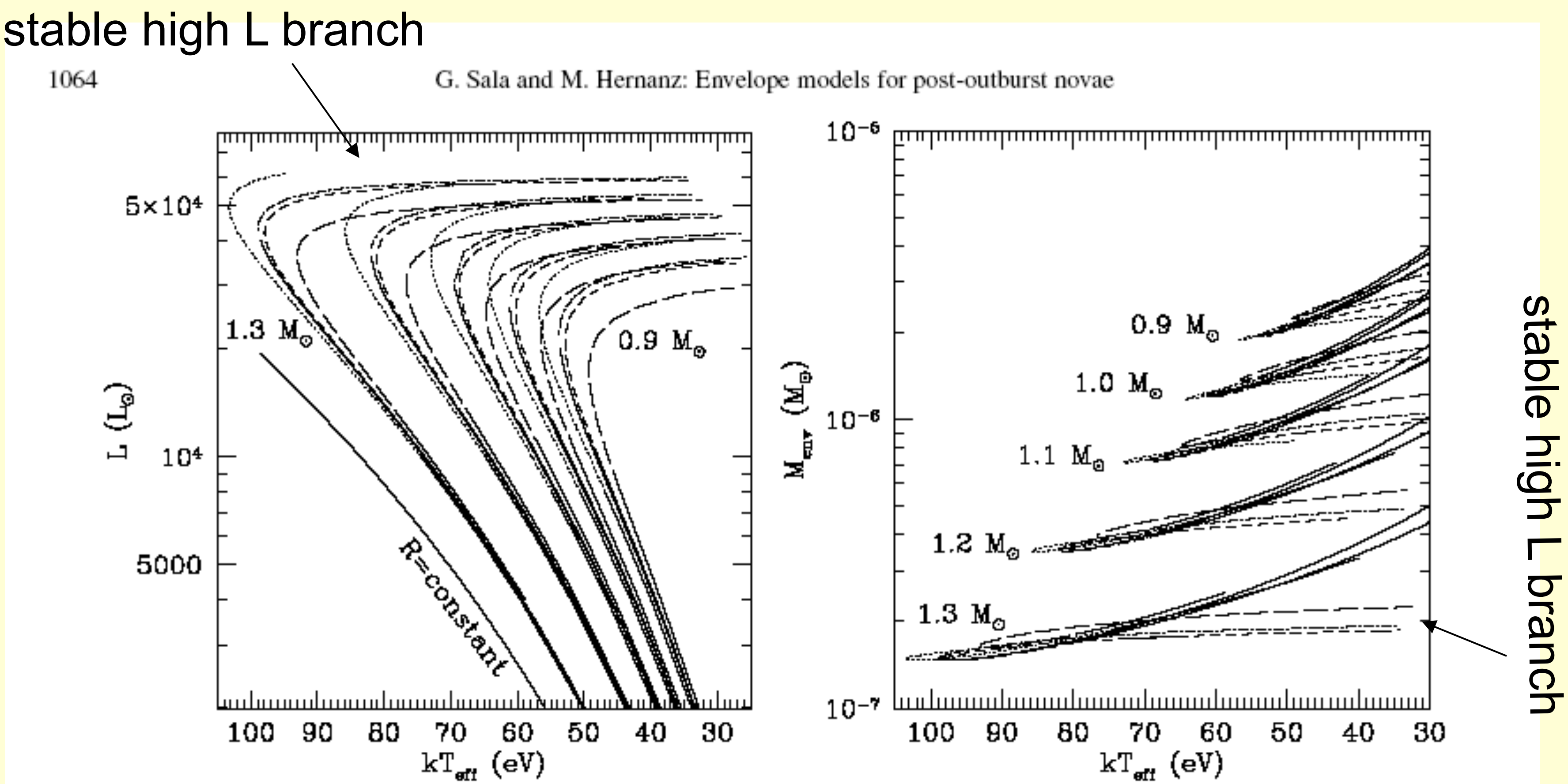


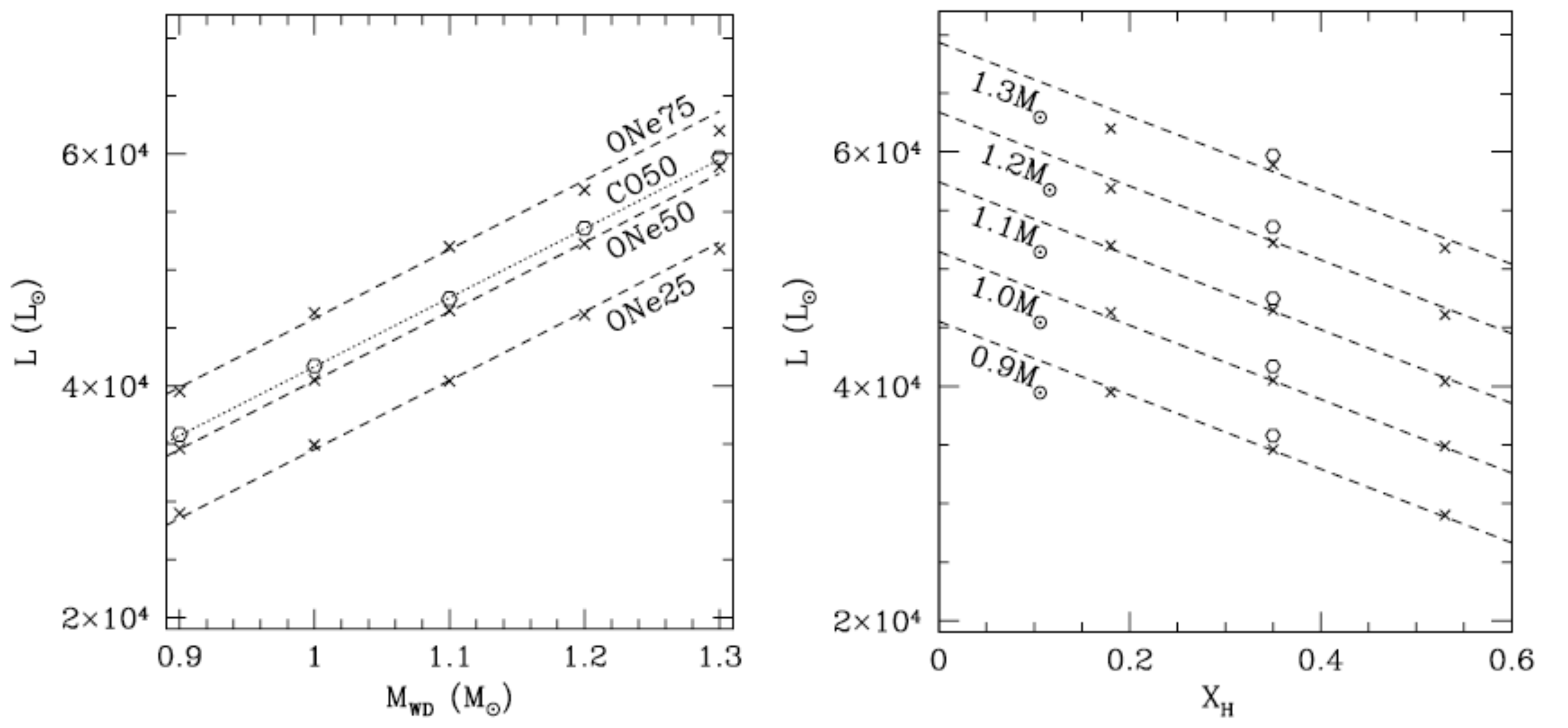
Fig. 1. Total luminosity (*left panel*) and envelope mass (*right panel*) versus effective temperature for our white dwarf envelope models: ONe75 (dotted line), ONe50 (short dash), ONe25 (long dash), and CO50 (short dash–dot). Effective temperature is given in eV, $kT_{\rm eff}$ (eV) = $8.617 \times 10^{-5} T_{\rm eff}$ (K) Solid lines indicate envelopes without convective regions. Five series of models are plotted for each chemical composition, corresponding to total masses 0.9, 1.0, 1.1, 1.2, and 1.3 $M_\odot$. A line indicating the luminosity-effective temperature relation for constant photospheric radius is over-plotted in left panel for comparison.

Sala & Hernanz, A&A 2005

Model	M_c ($M_\odot$)	$L^{plateau}$ ($10^4\ L_\odot$)	kT_{eff}^{max} (eV)	T_{eff}^{max} (10^5 K)	M_{env}^{max} ($10^{-6}\ M_\odot$)	M_{env}^{min} ($10^{-6}\ M_\odot$)	$\Delta\ t_{10\ eV}^{(a)}$ (days)
	0.9	3.9	57	6.6	2.3	1.9	47
ONe75	1.0	4.4	64	7.4	1.4	1.2	24
(X = 0.18)	1.1	5.2	73	8.5	0.84	0.71	12
	1.2	5.7	86	9.9	0.40	0.35	4.6
	1.3	6.2	103	11.9	0.16	0.15	1.1
	0.9	3.5	53	6.1	2.7	1.5	160
ONe50	1.0	4.1	60	7.0	1.7	1.2	78
(X = 0.35)	1.1	4.7	69	8.0	0.99	0.72	37
	1.2	5.2	81	9.4	0.45	0.35	14
	1.3	5.6	98	11.4	0.19	0.15	4.9
	0.9	2.9	49	5.7	3.0	2.2	430
ONe25	1.0	3.5	56	6.5	2.1	1.4	210
(X = 0.53)	1.1	4.0	64	7.5	1.20	0.81	98
	1.2	4.6	77	8.9	0.60	0.39	36
	1.3	5.2	93	10.8	0.22	0.16	12
	0.9	3.6	54	6.2	2.9	1.9	230
CO50	1.0	4.2	61	7.1	1.8	1.2	90
(X = 0.35)	1.1	4.7	70	8.1	1.0	0.72	48
	1.2	5.4	82	9.5	0.49	0.35	19
	1.3	6.0	99	14.7	0.19	0.15	6

[a] Time needed for the envelope to evolve from $kT_{eff} \simeq kT_{eff}^{max} - 10$ eV to kT_{eff}^{max}.

Sala & Hernanz, A&A 2005



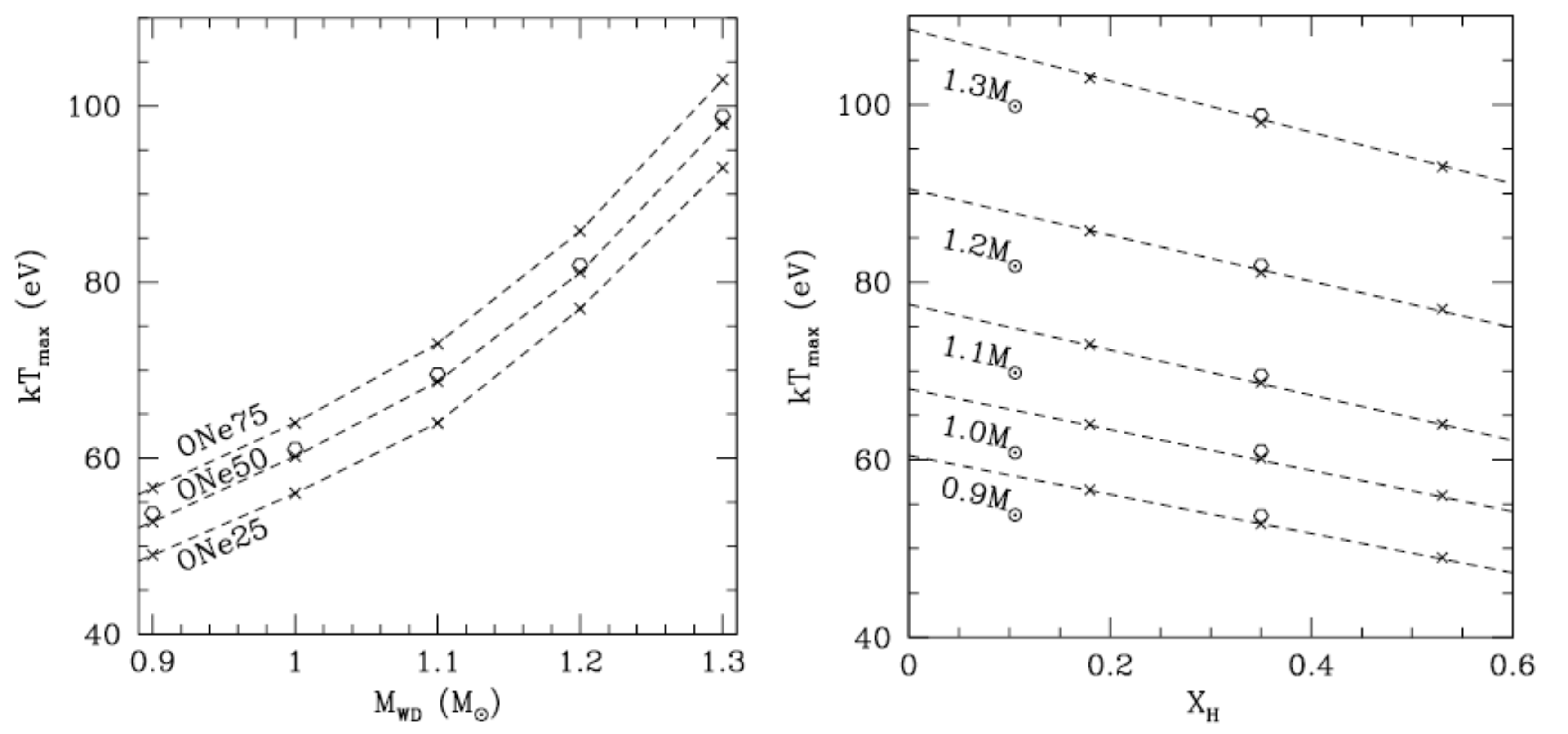
➡ $L_{plateau}$ depends on M_{wd} but also on H content

$$L_{\rm ONe}^{\rm plateau}(L_\odot) \simeq 5.95 \times 10^4 \left(\frac{M_{\rm c}}{M_\odot} - 0.536 X_{\rm H} - 0.14\right)$$

1.15 $M_\odot$ - ONe 50%

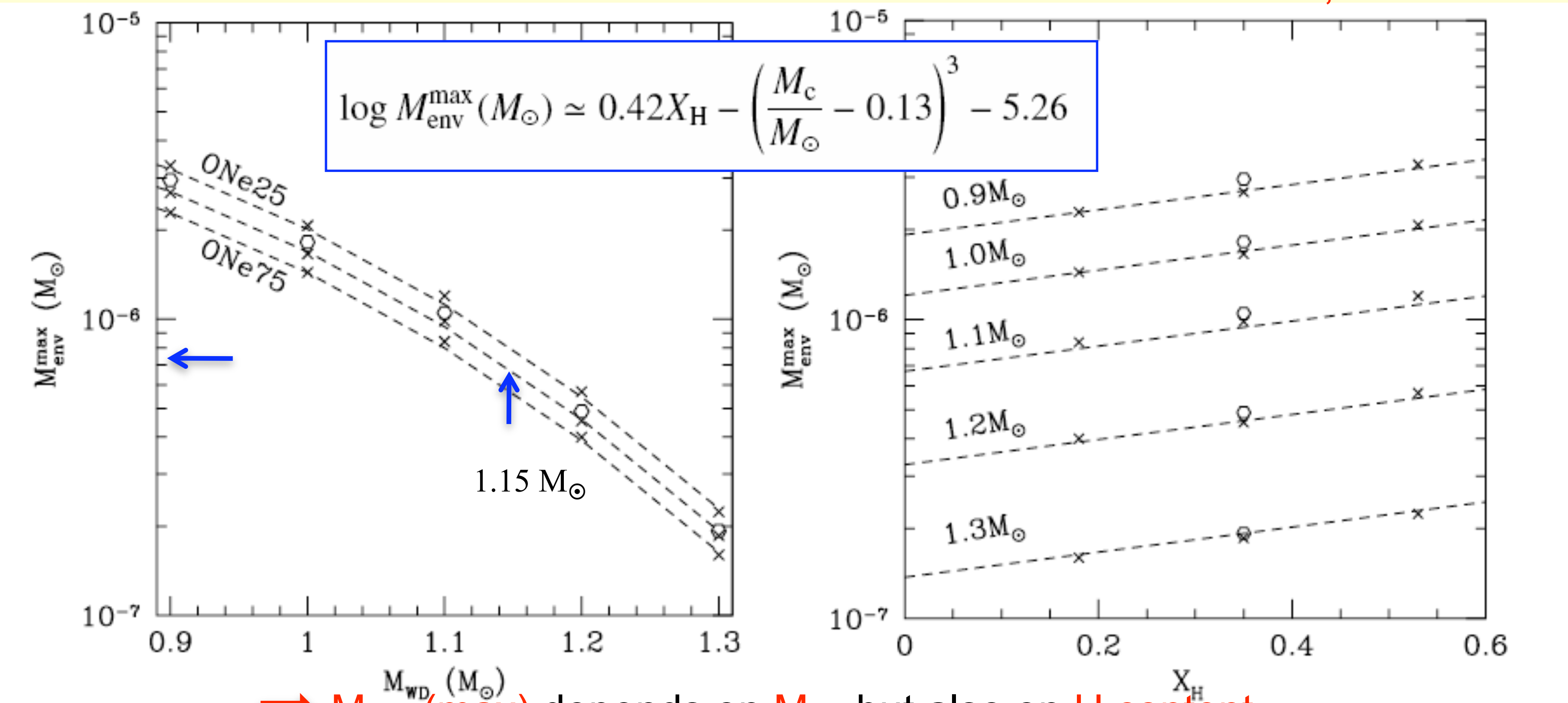
L = 4.9x10^{-4} $L_\odot$

Sala & Hernanz, A&A 2005



➡ T_{eff} (max) depends on M_{wd} but also on H content

Sala & Hernanz, A&A 2005



$$\log M_{\rm env}^{\rm max}(M_\odot) \simeq 0.42 X_{\rm H} - \left(\frac{M_{\rm c}}{M_\odot} - 0.13\right)^3 - 5.26$$

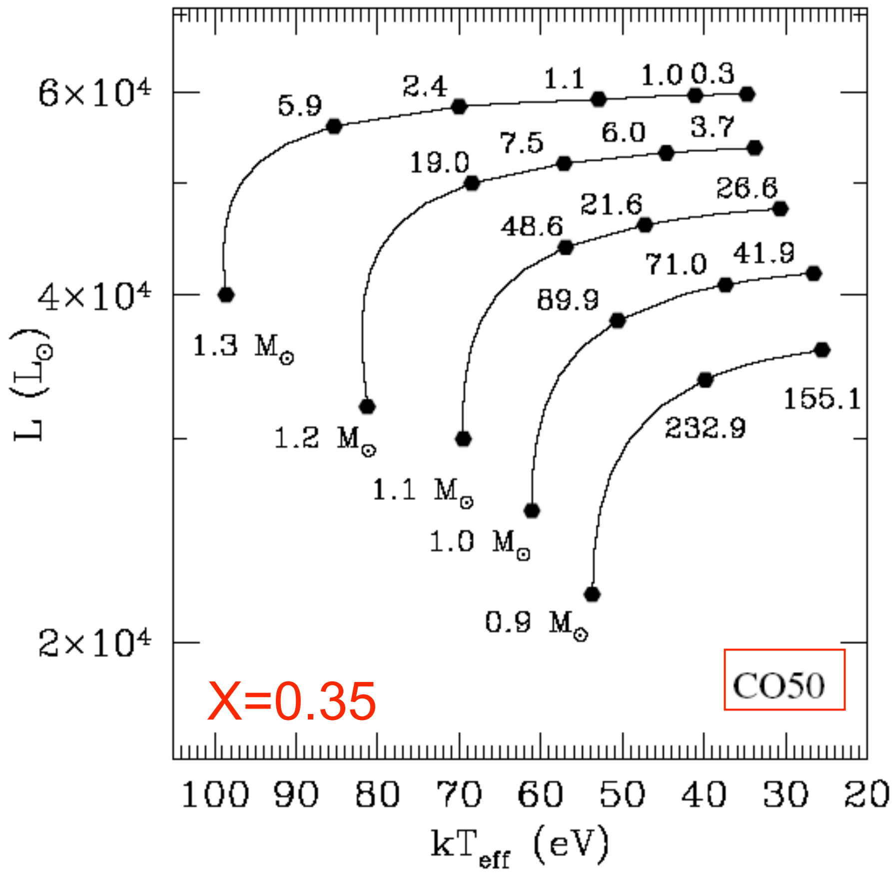
➡ M_{env} (max) depends on M_{wd} but also on H content

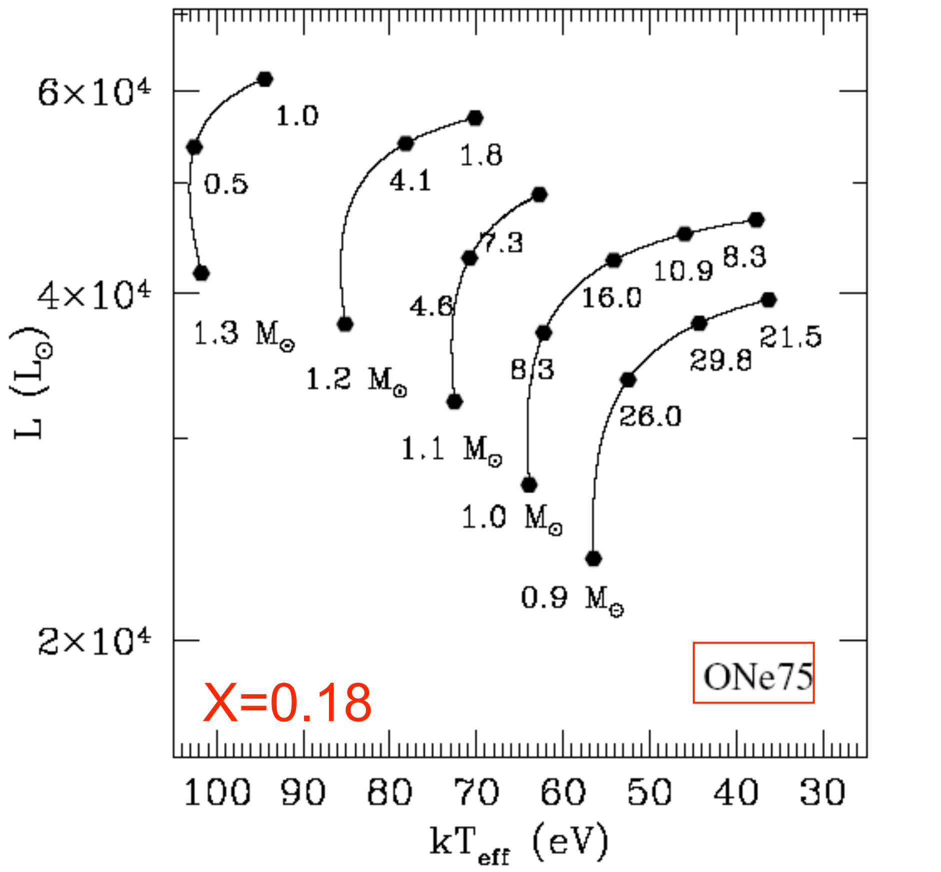
Example: 1.15 $M_\odot$ - ONe 50%

L = 4.9×10^{-4} $L_\odot$ - M_{env} = 7×10^{-7} $M_\odot$ (steady bur.) << 1.3×10^{-5} $M_\odot$ (hydro models JH98)

- ***turn-off time ≈ τ_{nuc} = 0.4 yr << 7.4 yr in better agreement with observations***

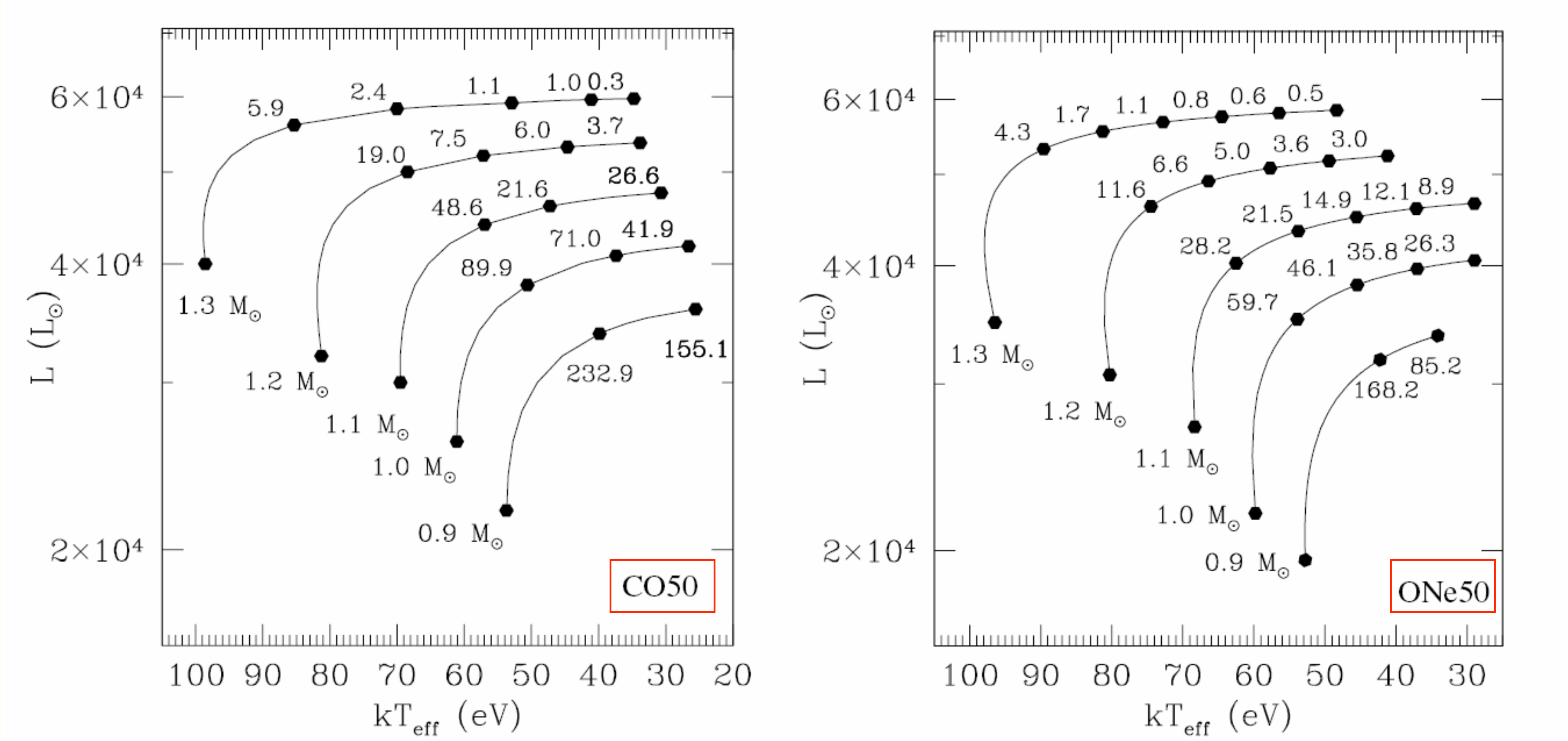
❖ remnant H-rich envelope masses should be significantly reduced after outburst Tuchmann & Truran (1998)





Quasi-static temporal evolution

$$\Delta t = \epsilon \frac{\Delta M_{\rm env} X_{\rm H}}{L}$$



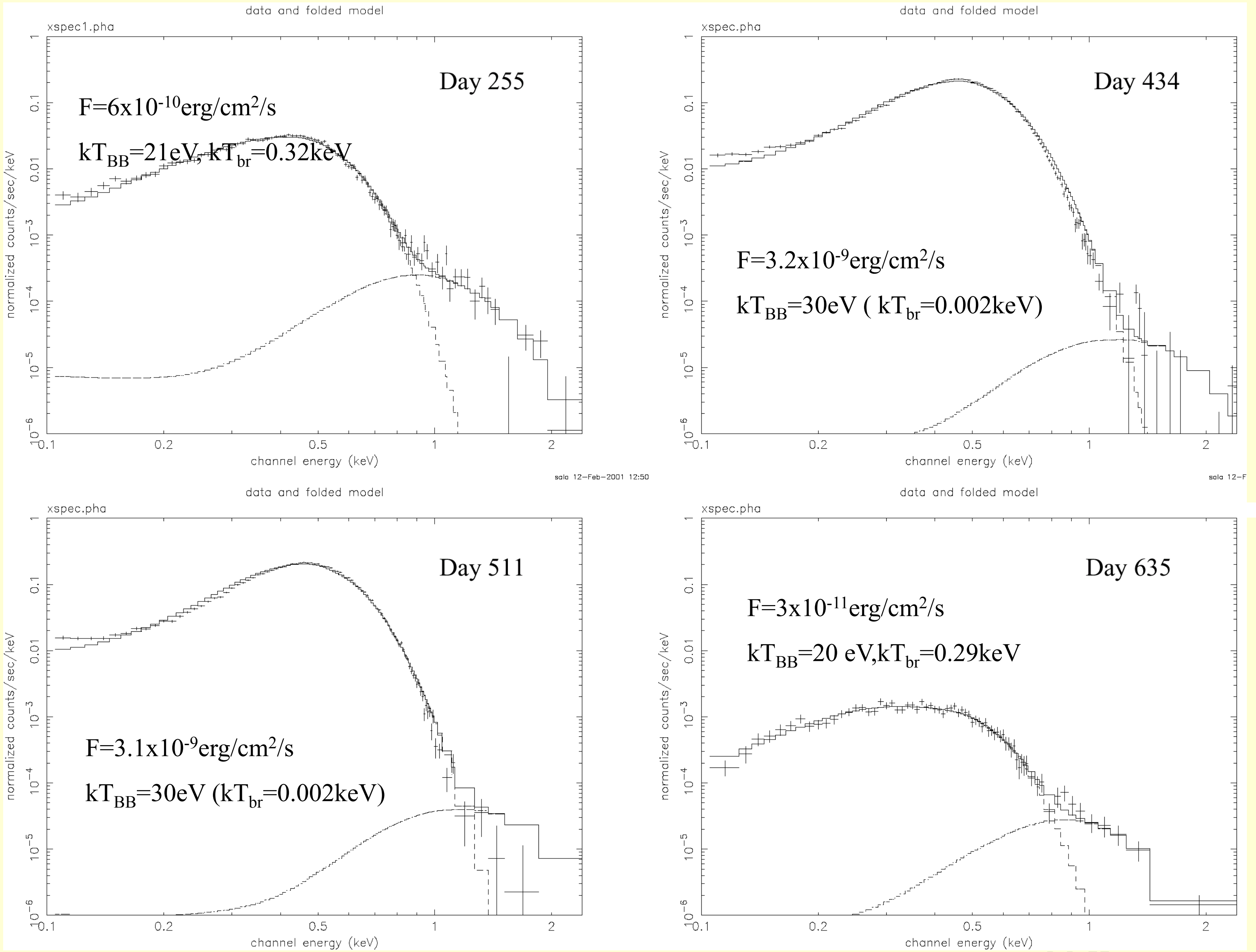
Quasi-static temporal evolution

$$\Delta t = \epsilon \frac{\Delta M_{\rm env} X_{\rm H}}{L}$$

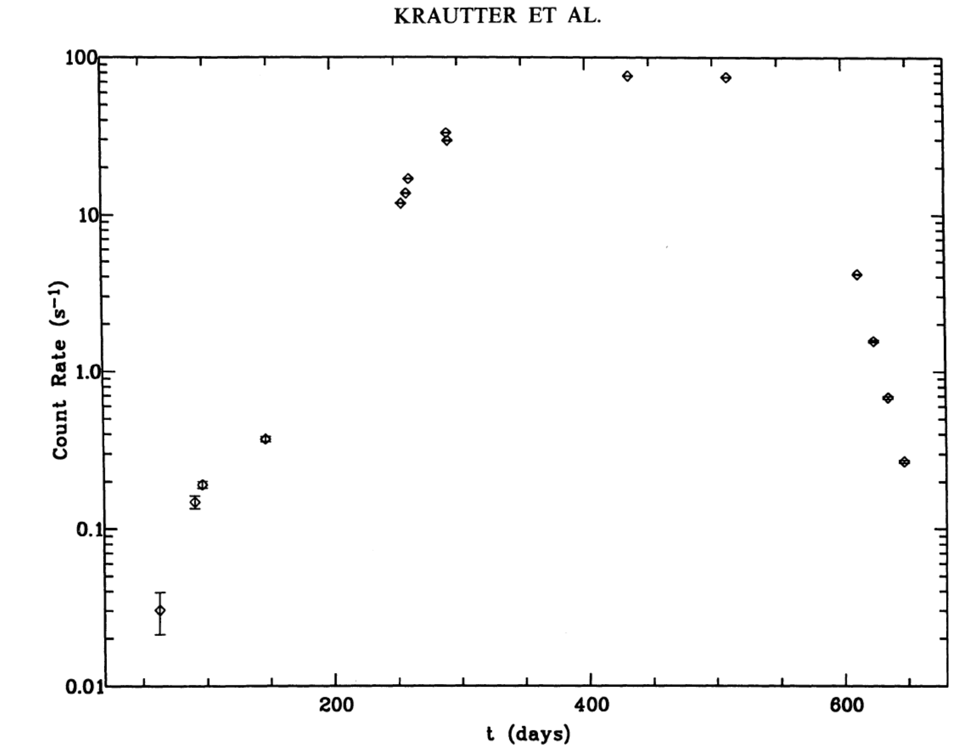
Constraints on models from ROSAT observations of V1974 Cyg 1992:

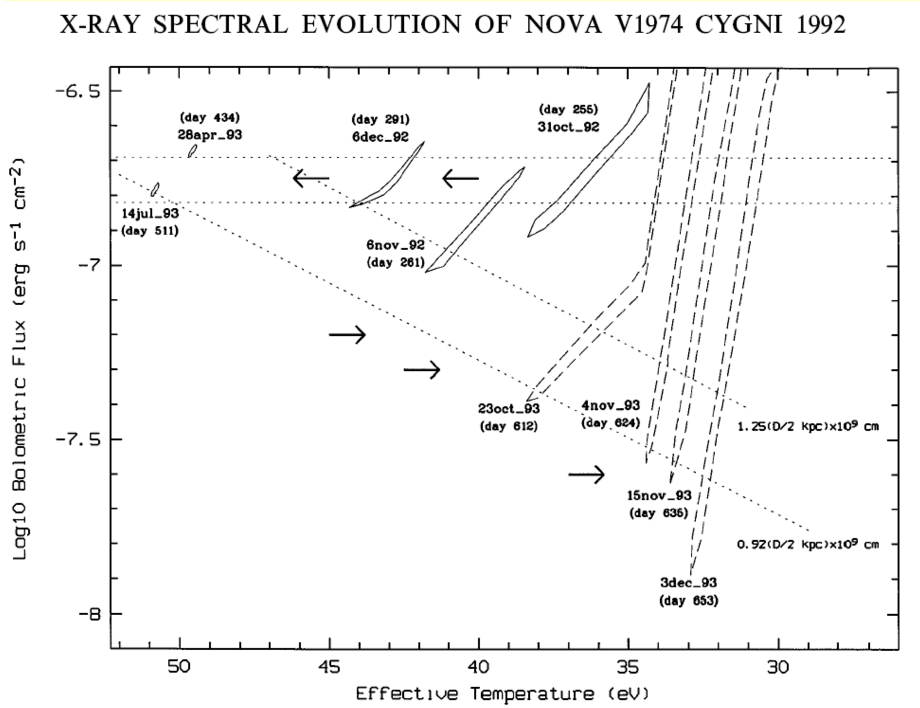
supersoft source during various months

Nova Cyg 1992. ROSAT observations



V1974 Cyg: ROSAT's soft X-ray light curve





rise: until day 147

plateau: 18 months

BB fits not good – too large L

Krautter et al. 1996, ApJ

ONe WD atmospheres

MacDonald & Vennes

Balman et al. 1998, ApJ

Table 1. ROSAT observational results for V1974 Cyg.

	Day after outburst	$K^{a,b}$ 10^{-25}	$R^{c}_{\rm photos}$ (10^9 cm)	$kT^{b}_{\rm eff}$ (eV)
A	255	0.6–2.4	1.8–3.7	34.3–38.3
B	261	0.3–0.9	1.3–2.3	38.4–41.8
C	291	0.4–0.8	1.5–2.1	41.2–44.3
D	434	0.32–0.36	1.3–1.4	49.4–49.7
E	511	0.22–0.26	1.1–1.2	50.6–51.0

[a] Normalization constant of the white dwarf atmosphere model, $K = (R/D)^2$, where R and D are the photospheric radius and the distance to the source.

[b] Results from Balman et al. (1998).

[c] Photospheric radius for a distance of 2.5 kpc.

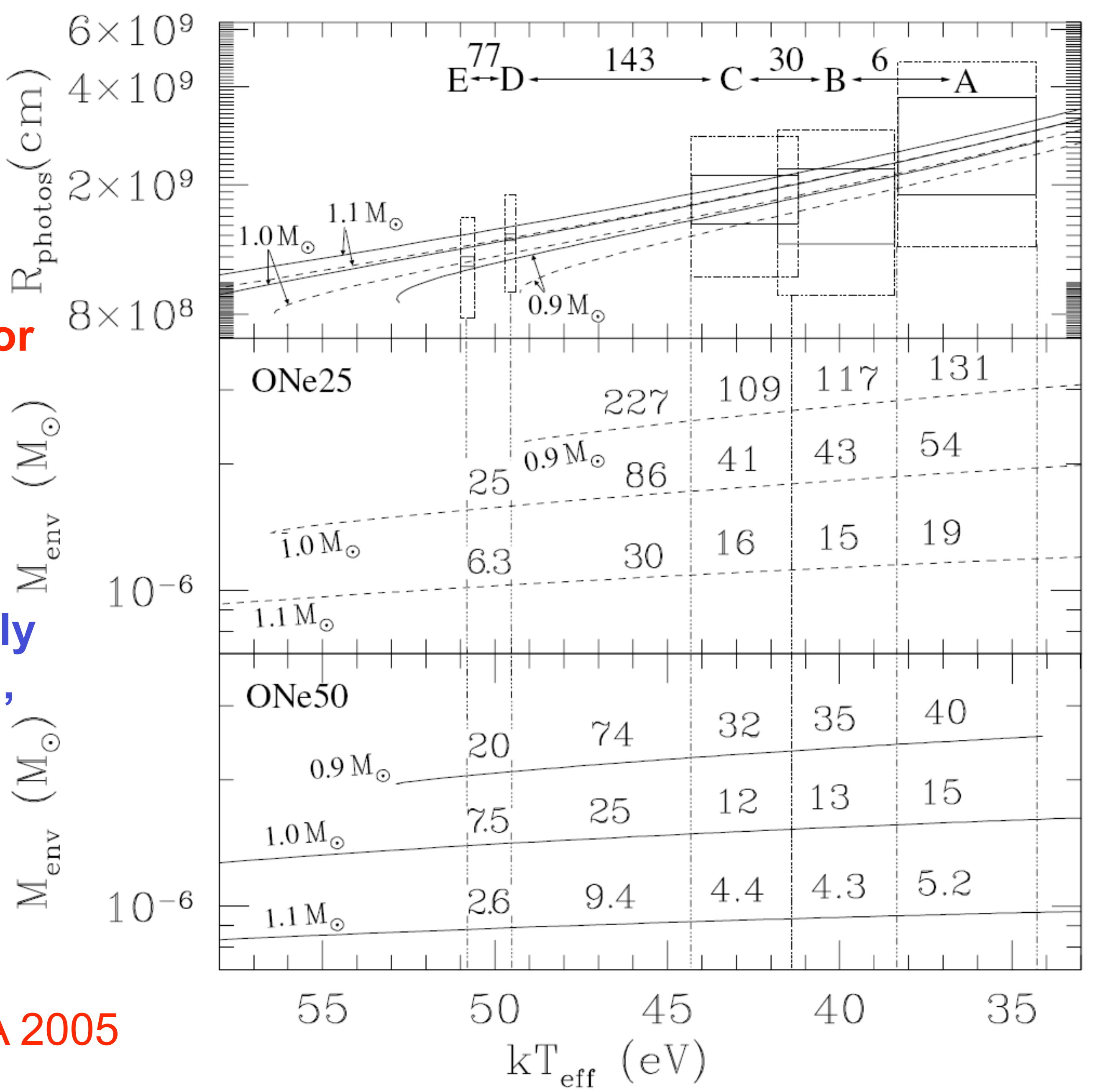
Balman et al. 1998, ApJ

Comparison model-observation:

evolution of T_{eff} & R (or L) with time

- **IMPORTANT:**

T_{eff} max. would directly constrain M_{wd}-chem., independently of distance



Sala & Hernanz, A&A 2005

Models that best explain the supersoft X-ray emission of V1974 Cyg 1992 and its evolution

- M_{wd}=0.9 $M_{\odot}$, 50% mixing with CO core (but V 1974Cyg 1992 was a neon nova!)

or

- M_{wd}=1.0 $M_{\odot}$, 25% mixing with ONe core

[in goog agreement with models of the optical and UV light curve (Kato & Hachisu, 2006)]

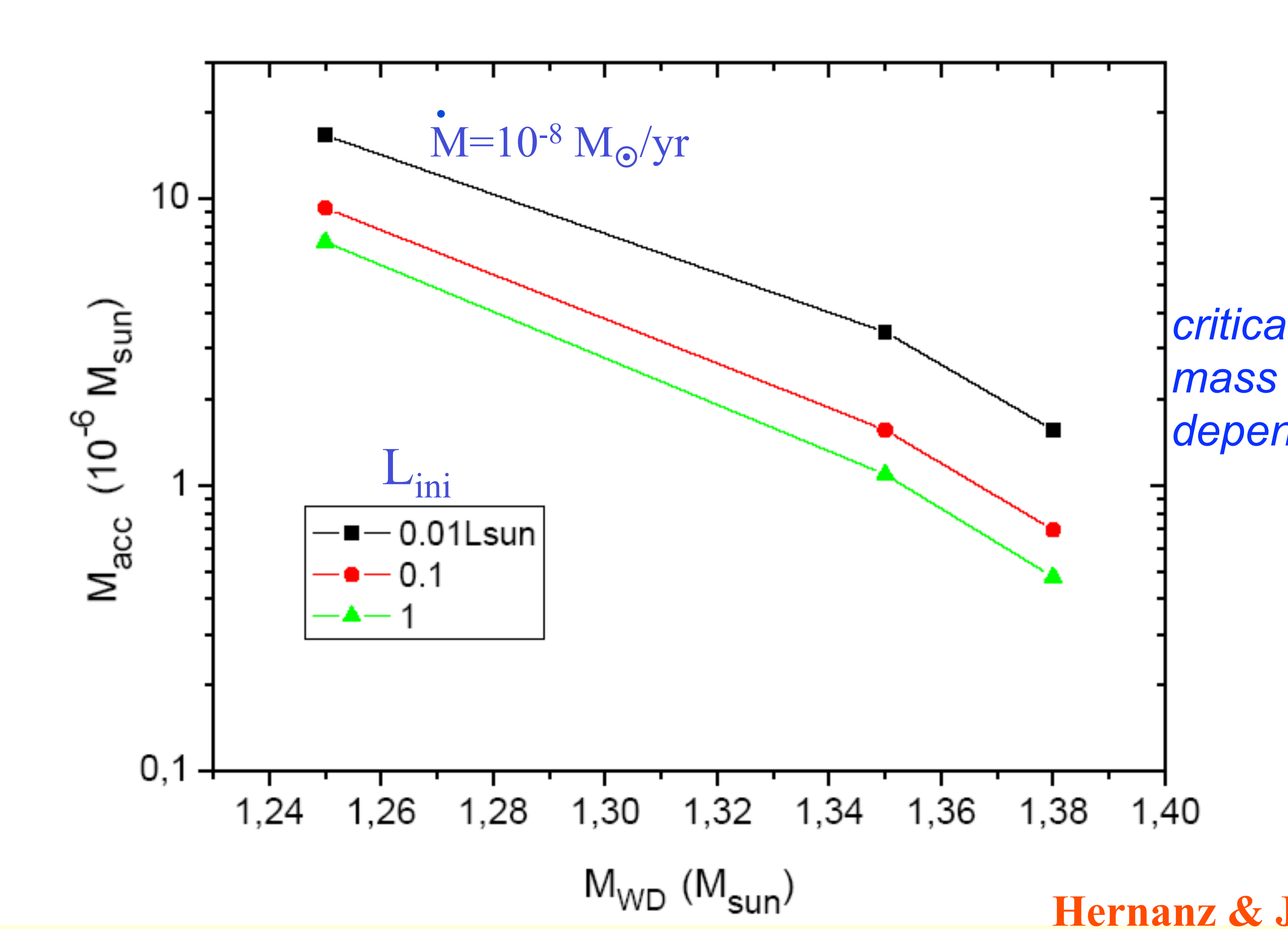
- M_{env}~$2x10^{-6}$ $M_{\odot}$

Models of recurrent novae – TNR on accreting WDs

Search combinations of initial conditions leading to short recurrence periods:

- $P_{rec} = \Delta M_{acc} / (dM/dt) = 21$ years
    - ΔM_{acc}: required accreted mass on top of the WD to power the outburst through a TNR
    - *M_{wd}^{ini}? Accretion rate? L_{wd}^{ini}?*
- Accretion rate: related to mass loss from the red giant wind
- effective dM/dt onto the WD: $2 \times 10^{-7} - 10^{-8}\ M_{\odot}/yr$

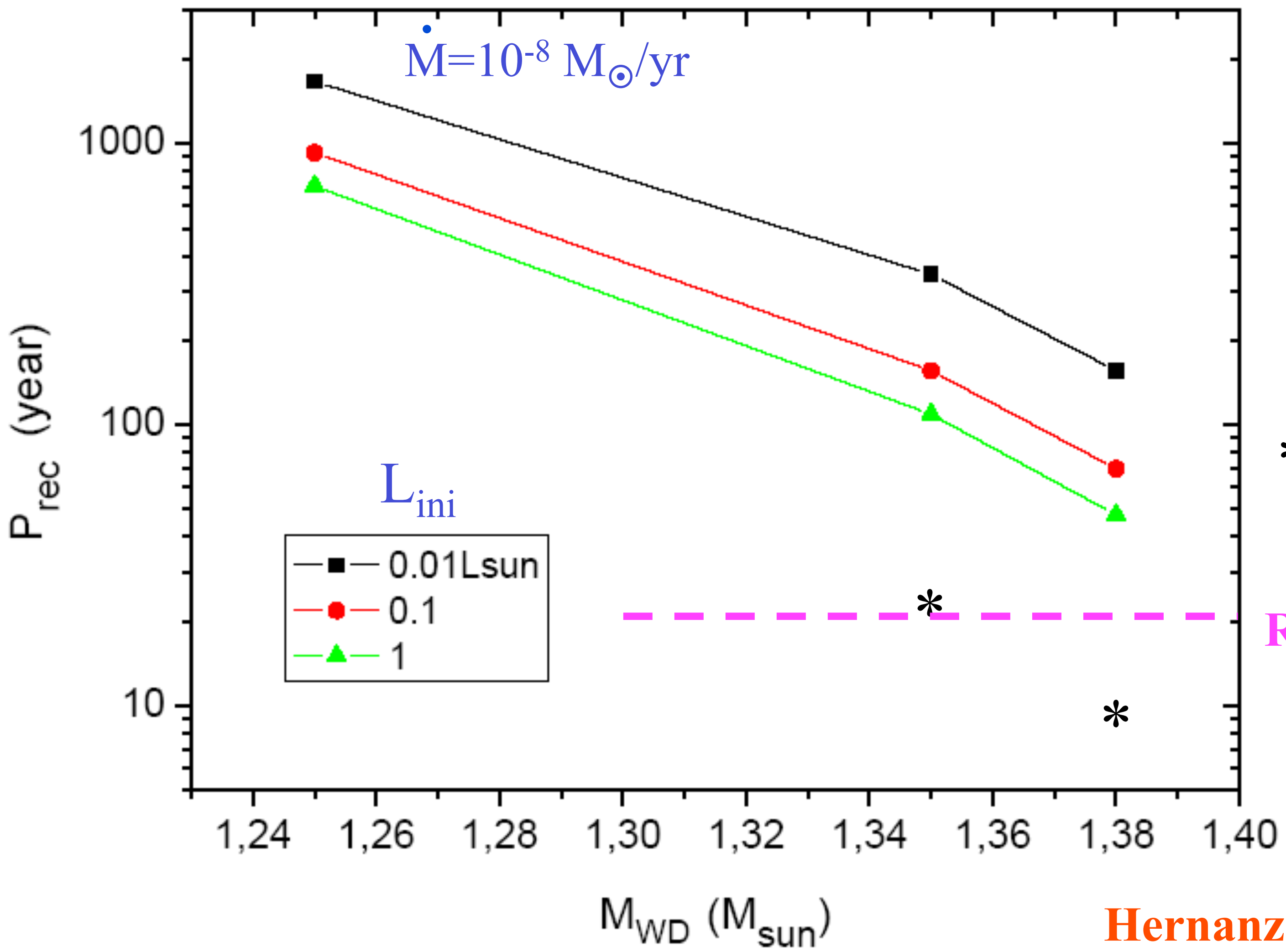
Accreted masses to reach H-ignition conditions



critical accreted mass does not depend only on M_{wd}

Hernanz & José 2008

Recurrence Periods



* $\dot{M}=2\ 10^{-7}\ M_\odot/yr$

& $L=10^{-2}\ L_\odot$

RS Oph: P_{rec}=21 yr

Hernanz & José 2008

Models for the RS Oph outburst

M_{wd} = 1.35-1.38 $M_{\odot}$ - dM/dt= 2 10^{-7} $M_{\odot}$/yr - L= 10^{-2} $L_{\odot}$

M_{wd} ($M_{\odot}$) - ONe	1.35	1.38
T_{peak}(10^8K)	2.8	3.1
M_{acc} ($M_{\odot}$)	4.7 10^{-6}	2.0 10^{-6}
M_{ejec} ($M_{\odot}$)	*3.0 10^{-6}*	*1.3 10^{-6}*
t_{TOT}	*24 yr*	*10.4 yr*
ΔM_{wd} ($M_{\odot}$)	1.7 10^{-6}	0.7 10^{-6}
	36% of M_{acc}	35% of M_{acc}
Δt (to $M_{Chandra}$)	*6.9 10^5 yr*	*2.9 10^5 yr*

No mixing; solar accretion

- *M_{wd} increases* ***BUT ONe WDs do not explode as SNIa***

Hernanz & José 2008

Supersoft X-ray light curve of the recurrent nova RS Oph (Swift observations, Bode et al. 2006)

M_{wd}=1.35 $M_{\odot}$

M_{env}= 4x10^{-6} $M_{\odot}$

Kato & Hachisu, 2007

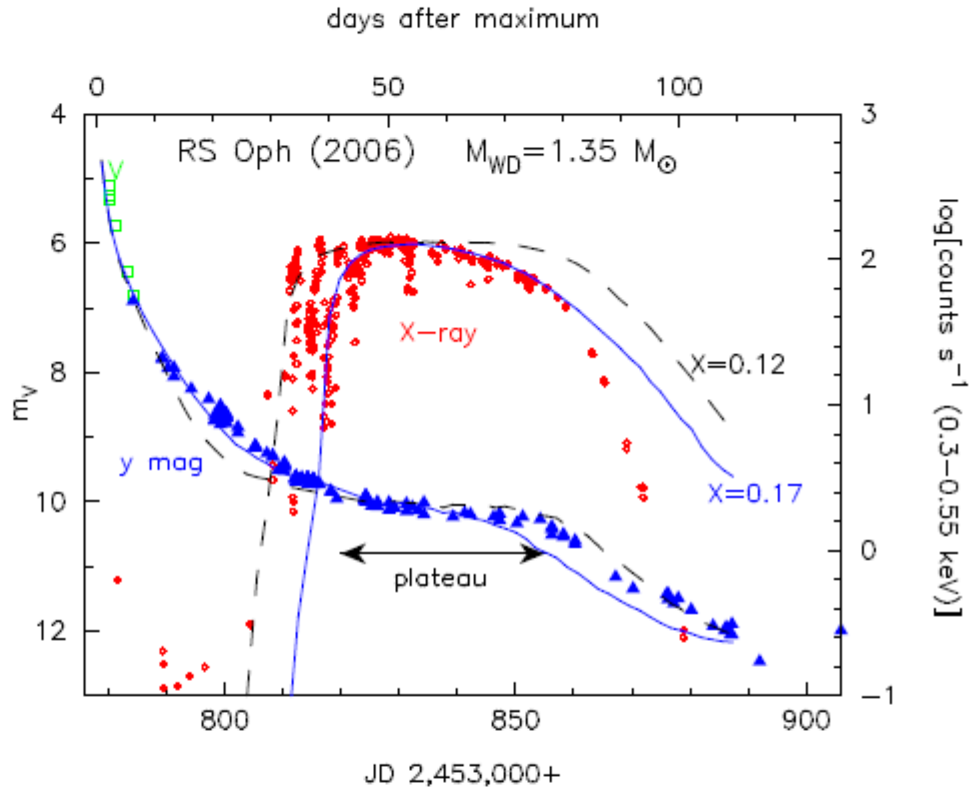


FIG. 3.— Same as those in Fig. 2, but together with the visual light curves. Hydrogen content in the envelope is $X = 0.12$ (*dashed lines*) and $X = 0.17$ (*solid lines*). These two models predict visual light curves as shown in the figure. Here we assume a 0.7 $M_{\odot}$ red giant with a radius of 35 $R_{\odot}$ for the companion, an irradiated disk with a radius of 47 $R_{\odot}$ around the white dwarf, a binary orbital period of 455.72 days, and a binary inclination angle of $i = 33°$ (Hachisu et al. 2006).

Summary

• Variety of behaviours of post-outburst novae: still need more observations.

• Grating spectra are very rich, but still lack of emission models (e.g. WD atmospheres) to interpret them. Blackbodies give wrong L and T_{eff} & emission is often a mixture of photospheric and ejecta

• WD Mass and envelope chemical composition (mainly H content) determine duration of SS X-ray phase

• Duration of SS X-ray phase observed indicates in general M_{env} < M_{acc}-M_{eject} from hydro models → mass loss (wind and/or others?)

• Recurrent novae: very short duration of SS phase compatible with small M_{env}. Challenging for theory: narrow parameter range: M_{wd} extremely large & accretion rate large.

→ main caveat for RNe as SNIa scenario: not CO WDs but ONe