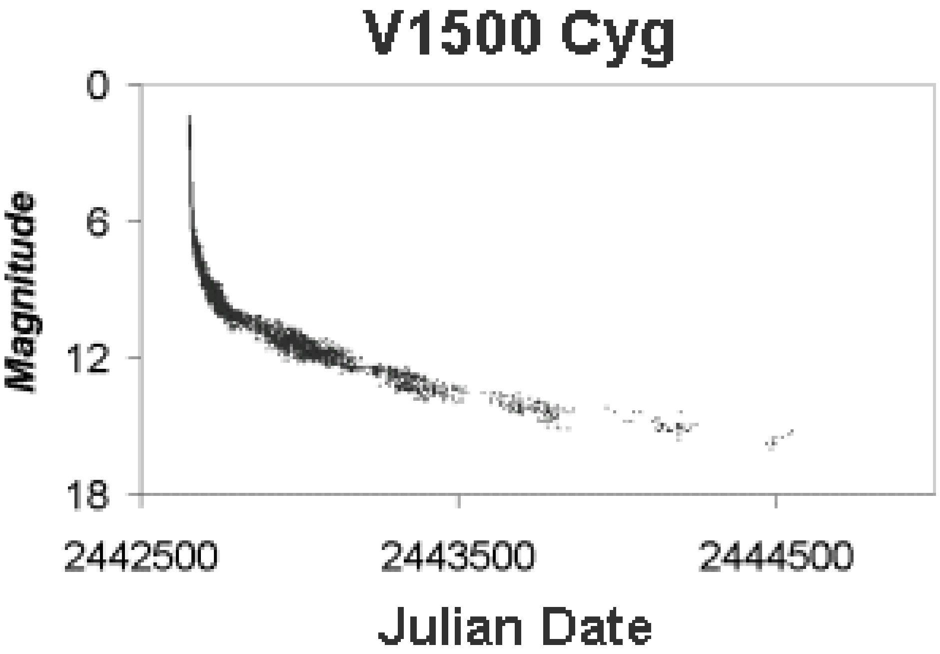
Thermonuclear shell flashes II: on WDs (or: classical novae)

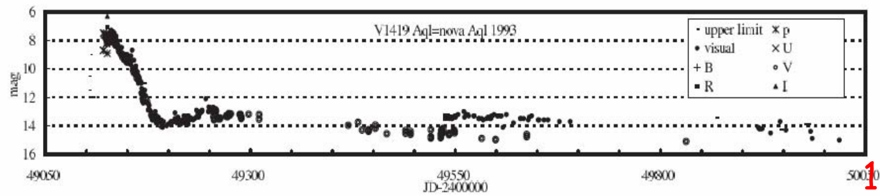
- Observations
- Thermonuclear flash model
- Nova/X-ray burst comparison
- Effects of super-Eddington fluxes
- To grow or not to grow =
  to go supernova Ia or not ..

Nova Cygni 1975

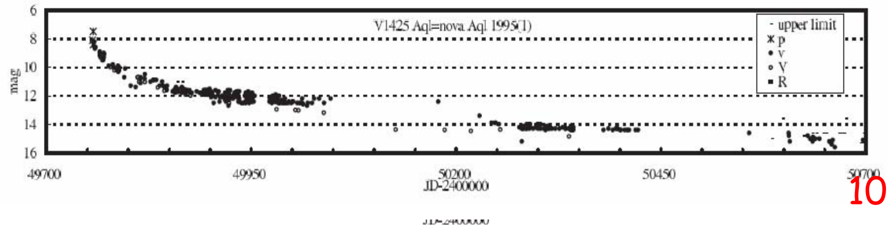
- Nova Cygnus 1975 is the 4th brightest nova in modern times (after Nova Persei 1901 [0.2], Nova Aurigae 1918 [-1.8] and Nova Puppis 1942 [0.3]) V = 2.0 mag). No brighter nova since then
- Descend of 7 mag in 45 days
- V1500 Cyg turned out to be a magnetic CV with an orbital period of 3.3 hr



Examples of classical nova light curves



1000 d



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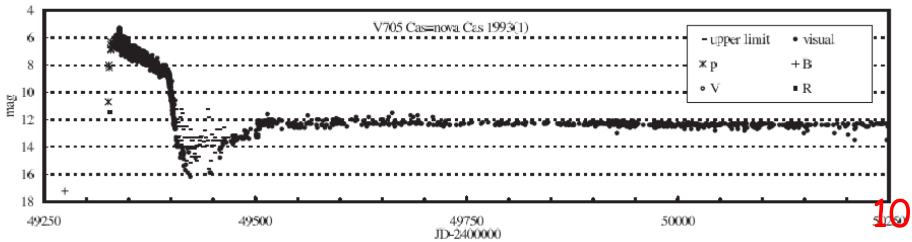

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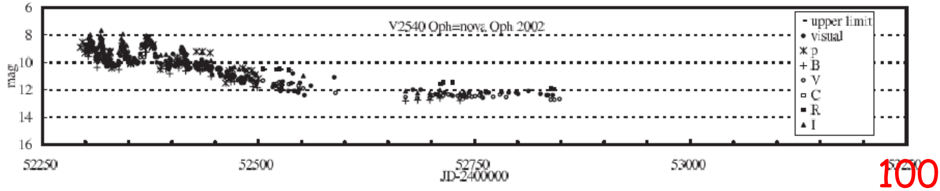

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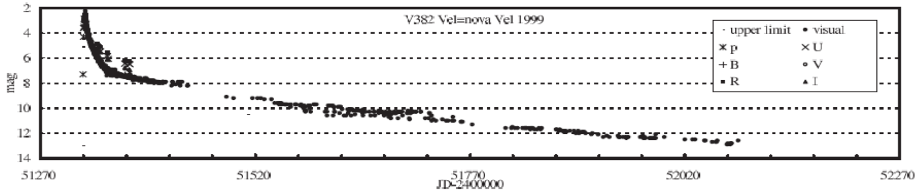

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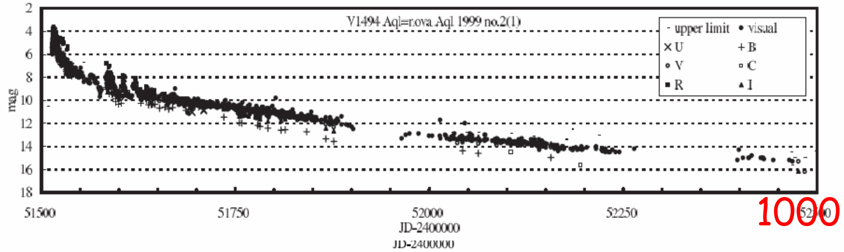

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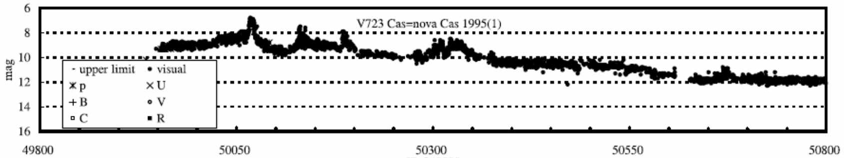

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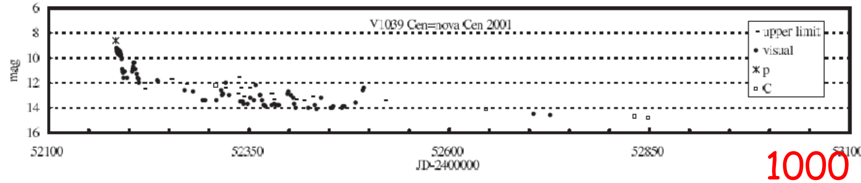

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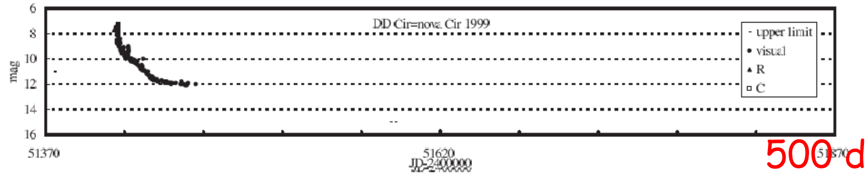
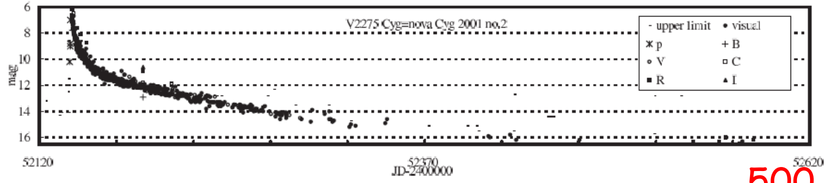


500 d

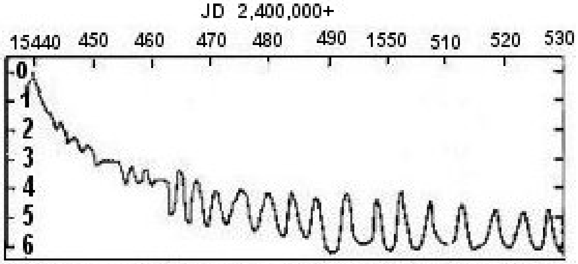


500 d

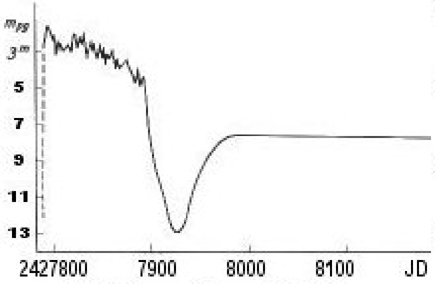
Kyota et al. 2004

Classical novae characteristics

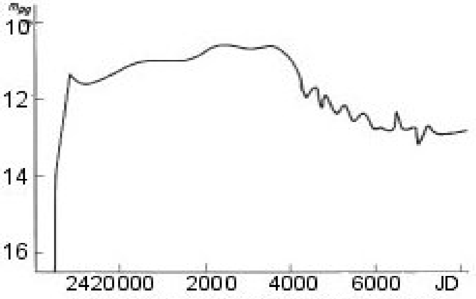
- Fast ($t_2 < 10$ d) , slow ($10 < t_2 < 25$) and very slow novae ($t_2 > 25$ days) (t_2 time needed to faint 2 magnitudes)
- Peak brightness: $m_V \approx 4\text{-}12$ mag
- Peak luminosity: $M_V \approx -6/-11$
- Delta V ≈ 7-16 → L_{max} / L_{min} up to 10^6
- Rise time few days days
- Decay time weeks to decades
- Recurrent novae → recurrence observed and thus less than ~100 yr
- Light curves and spectra very diverse because of shedding of matter (→ reprocessing of light in circumstellar environment)
- Most discoveries done by amateurs
- Thus far ~250 discovered, 10 recurrent



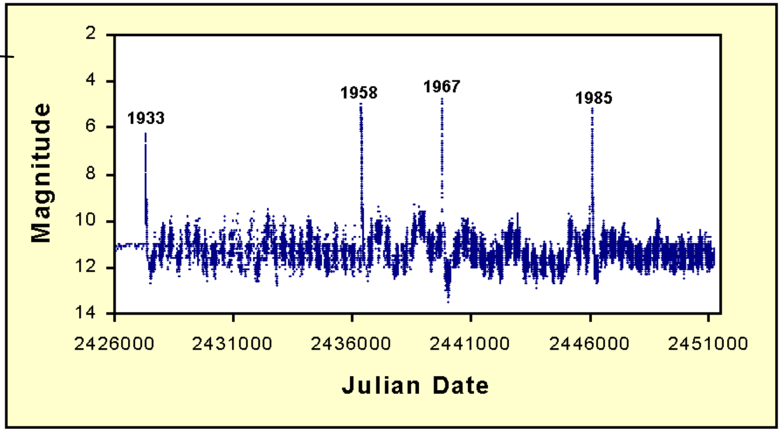
Light Curve of GK Persei from Feb 24, 1901 to May 25, 1901



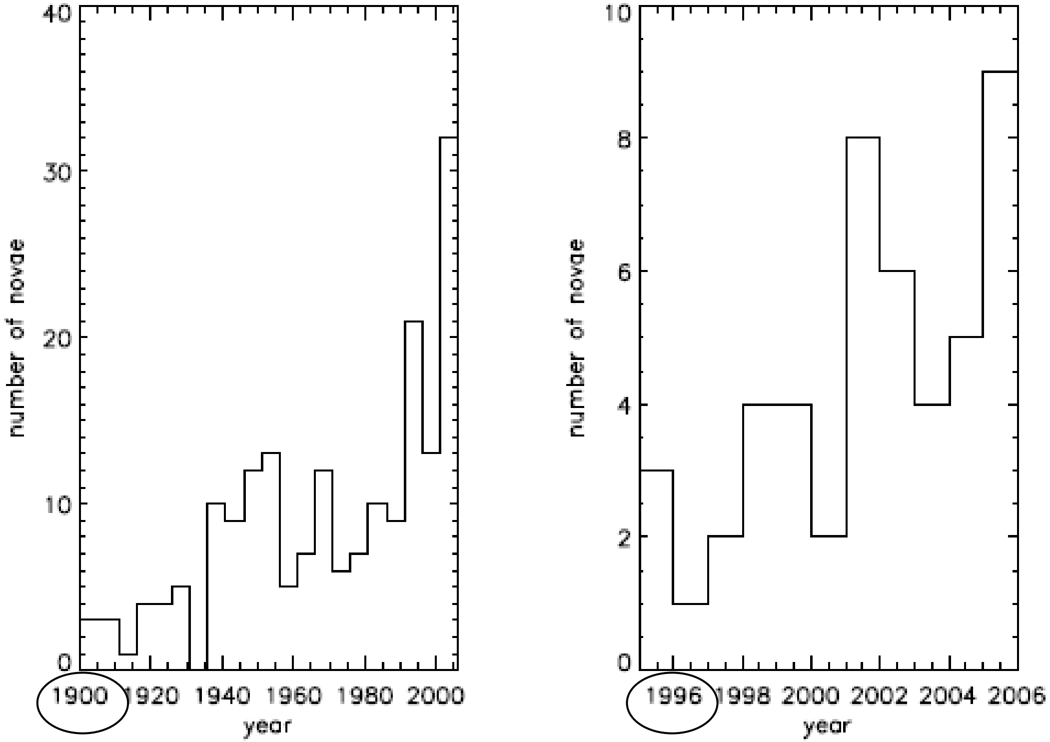
Light Curve of Nova DQ Her from Dec 28, 1934 to Feb 1, 1936



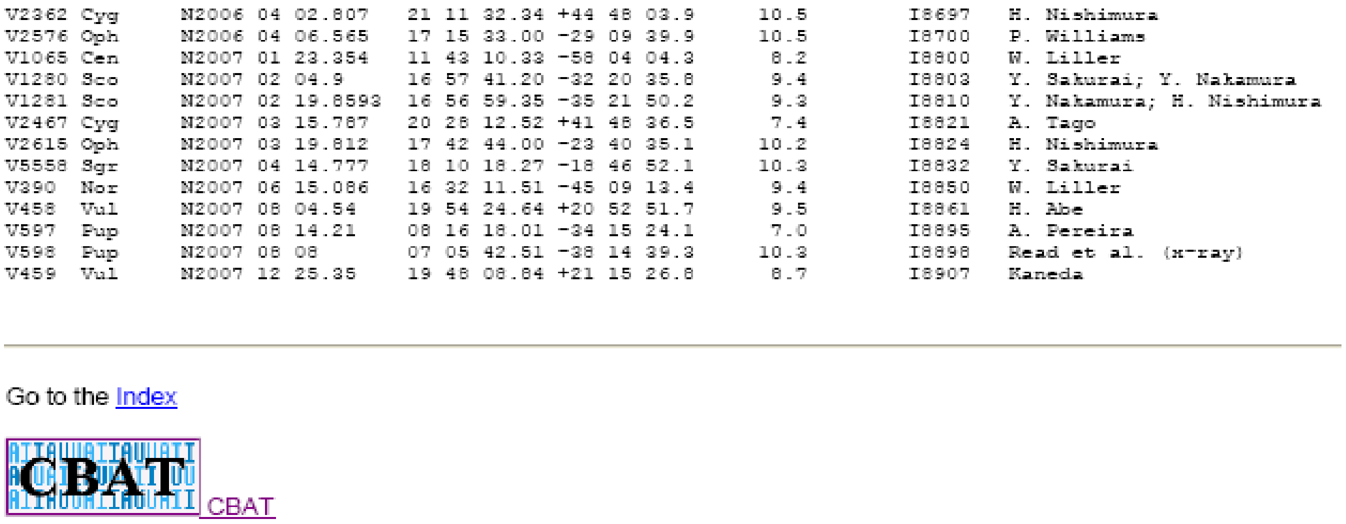
Light Curve of Nova RT Ser from the beginning of 1908 to July 16, 1935



Nova discovery rates



→ On average 5 per year



V2362 Cyg	N2006 04 02.807	21 11 32.34	+44 48 03.9	10.5	I8697	H. Nishimura
V2576 Oph	N2006 04 06.565	17 15 33.00	-29 09 39.9	10.5	I8700	P. Williams
V1065 Cen	N2007 01 23.354	11 43 10.33	-58 04 04.3	8.2	I8800	W. Liller
V1280 Sco	N2007 02 04.9	16 57 41.20	-32 20 35.8	9.4	I8803	Y. Sakurai; Y. Nakamura
V1281 Sco	N2007 02 19.8593	16 56 59.35	-35 21 50.2	9.3	I8810	Y. Nakamura; H. Nishimura
V2467 Cyg	N2007 03 15.787	20 28 12.52	+41 48 36.5	7.4	I8821	A. Tago
V2615 Oph	N2007 03 19.812	17 42 44.00	-23 40 35.1	10.2	I8824	H. Nishimura
V5558 Sgr	N2007 04 14.777	18 10 18.27	-18 46 52.1	10.3	I8832	Y. Sakurai
V390 Nor	N2007 06 15.086	16 32 11.51	-45 09 13.4	9.4	I8850	W. Liller
V458 Vul	N2007 08 04.54	19 54 24.64	+20 52 51.7	9.5	I8861	H. Abe
V597 Pup	N2007 08 14.21	08 16 18.01	-34 15 24.1	7.0	I8895	A. Pereira
V598 Pup	N2007 08 08	07 05 42.51	-38 14 39.3	10.3	I8898	Read et al. (x-ray)
V459 Vul	N2007 12 25.35	19 48 08.84	+21 15 26.8	8.7	I8907	Kaneda

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CBAT

Classical novae

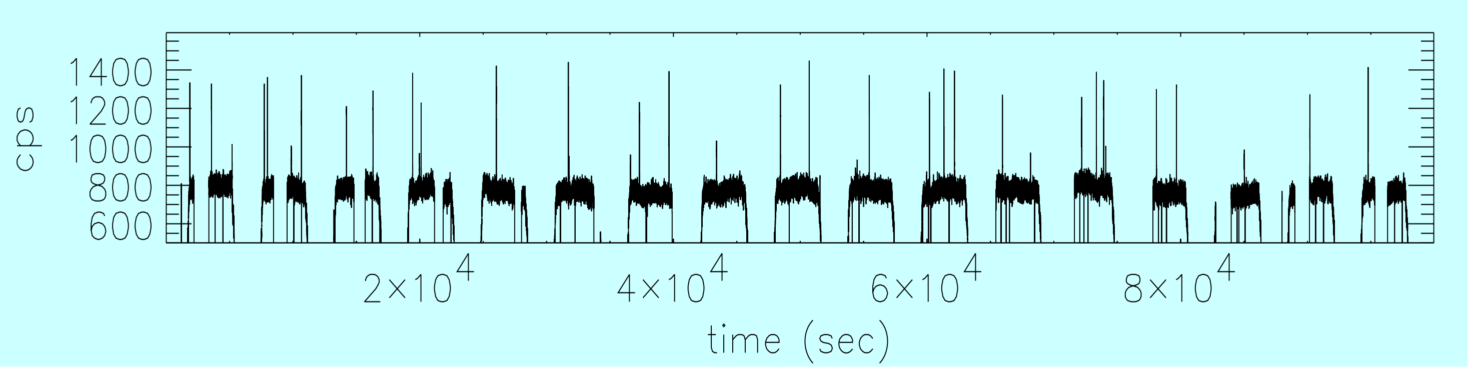
- Accretion at levels of 10^{-10} / 10^{-9} $M_\odot$/yr in CVs with P_{orb} between 1 and 10 hrs
- White dwarf is heated by compressional heating
- Envelope electron-degenerate → pressure not a function of temperature
- Heating and pressure build-up ignites accreted hydrogen layer, first through pp, then through CNO cycle. T not high enough for helium burning (3α)
- Burning of freshly accreted material can continue for some time (~100 d) due to high T
- Nuclear network moderate: ~100 isotopes up to $A \approx 40$, $T_{peak} \approx 10^8$ K. All nuclear reaction rates based on experimental data. This is a significant contrast to X-ray bursts (500 isotopes, 1000s of reactions, incomplete experimental data)

Comparison Novae / X-ray bursts

	Novae	X-ray burst	Ratio
Galactic rate per year	40	10^4	10^3
R (km)	10^4	10	10^3
$g_{surface}$ (cm s^{-2})	10^{11}	10^{14}	10^3
Recurrence time	decades to megayears	hours to weeks	10^3
Duration	weeks to years	Minute to hours	10^3
Fluence (ergs)	10^{41-46}	10^{39-42}	10^4
Peak luminosity	Always Eddington	Up to Eddington	
T_{peak} (K) of burning	10^8	10^9	
kT_{eff} (keV)	0.05	2	$\sqrt{10^3}$
Isotopes	10^2 ($A<40$)	10^3 ($A<100$)	
Alpha	~0.01	~100	10^4
Mass burned ($M_\odot$)	10^{-4}	10^{-12}	10^8
Density (g cm^{-3})	10^4	10^6	10^2

X-ray bursts are far more frequent..

One day in the Galactic bulge → tens of X-ray bursts!



Critical envelope mass, recurrence time

$$P_{\mathrm{crit}} \sim 10^{19}\mathrm{Nm}^{-2}$$

$R \propto M^{-1/3}$

$$P = \frac{F}{A} = \frac{GMM_{\mathrm{env}}}{R^2}\frac{1}{4\pi R^2} \propto \frac{MM_{\mathrm{env}}}{R^4} \propto \frac{MM_{\mathrm{env}}}{M^{-4/3}} = M^{7/3}M_{\mathrm{env}}$$

$$\Longrightarrow M_{\mathrm{env}} \propto \frac{P_{\mathrm{crit}}}{M^{7/3}} \qquad M\uparrow \Longrightarrow M_{\mathrm{env}}\downarrow$$

$$M \sim 0.6M_\odot \Longrightarrow M_{\mathrm{crit}} = 5\times10^{-3}M_\odot$$
$$M \sim 1.3M_\odot \Longrightarrow M_{\mathrm{crit}} = 3\times10^{-5}M_\odot$$

$$\tau_{\mathrm{rec}} = \frac{< M_{\mathrm{crit}} >}{< \dot{M} >} \simeq 10^3\cdots10^6\mathrm{y}$$

$\dot{M} \simeq 10^{-11}\cdots10^{-9}M_\odot\mathrm{yr}^{-1}$

$$N_{\mathrm{CN}} \simeq \frac{M_{2,i}}{< M_{\mathrm{crit}} >} \simeq 10^2\cdots10^4$$

$M_{2,i} \sim 0.1\cdots0.5M_\odot$

Temperature vs accretion rate → Ignition mass vs accretion rate

- Heating due to compressional heating; source gravitational energy

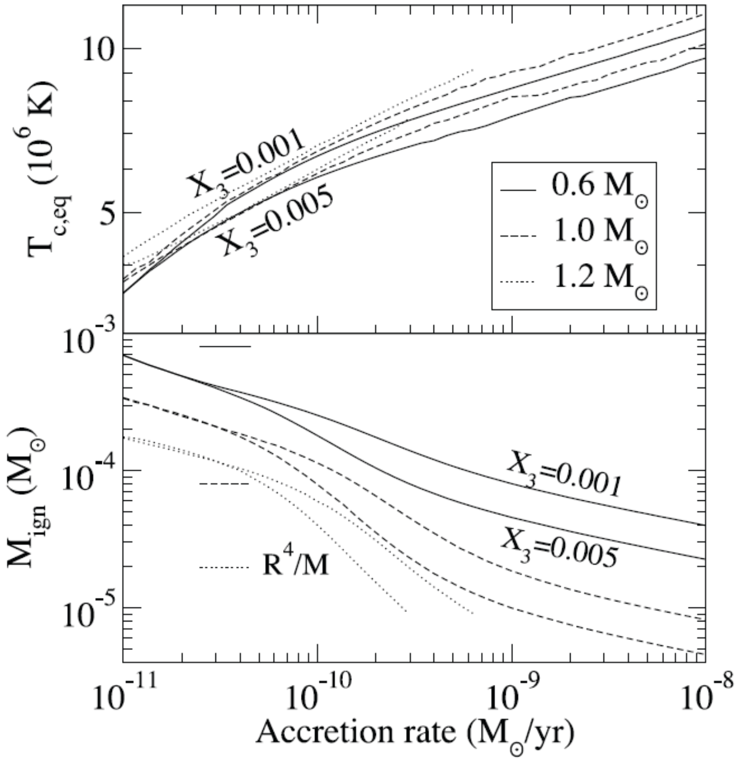
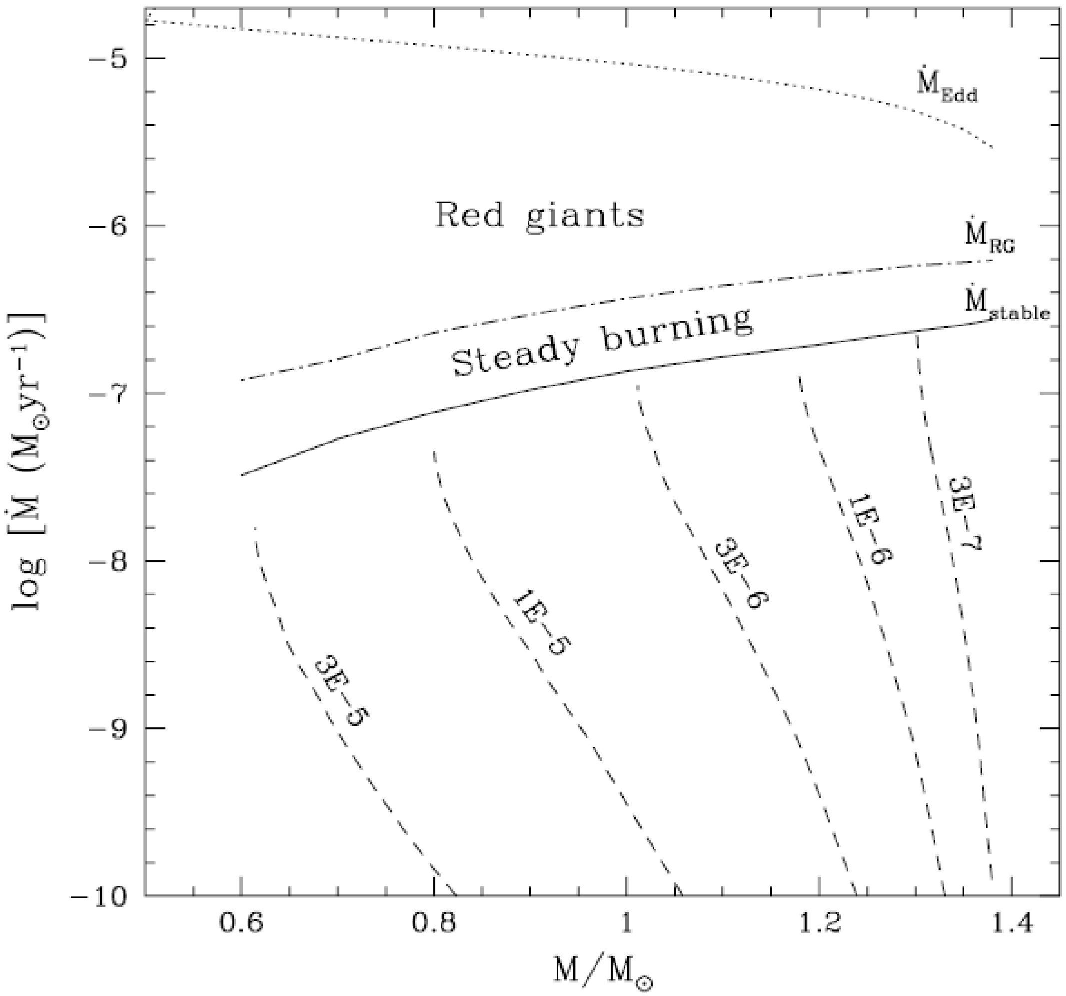


FIG. 8.—Equilibrium core temperature and mass of the accreted layer at CN ignition, M_{ign}, as a function of the time-averaged accretion rate $\langle \dot{M} \rangle$. Curves are shown for three WD masses M and two different mass fractions of ^{3}He at each value of M.

Townsley & Bildsten 2004

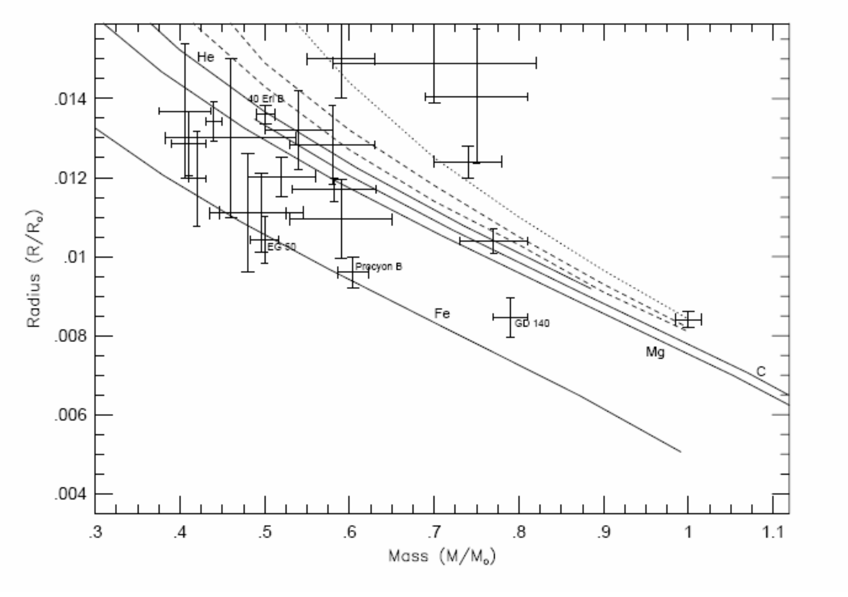
Stable and unstable burning on WD



Note that Eddington limit on WDs is 10^3 times higher than on NSs in terms of M-dot, but similar in terms of L. Reason: bigger WD → only ~0.1 MeV/nucleon grav energy release in WD instead of 200 MeV/nucleon as in NS

Matter expulsion

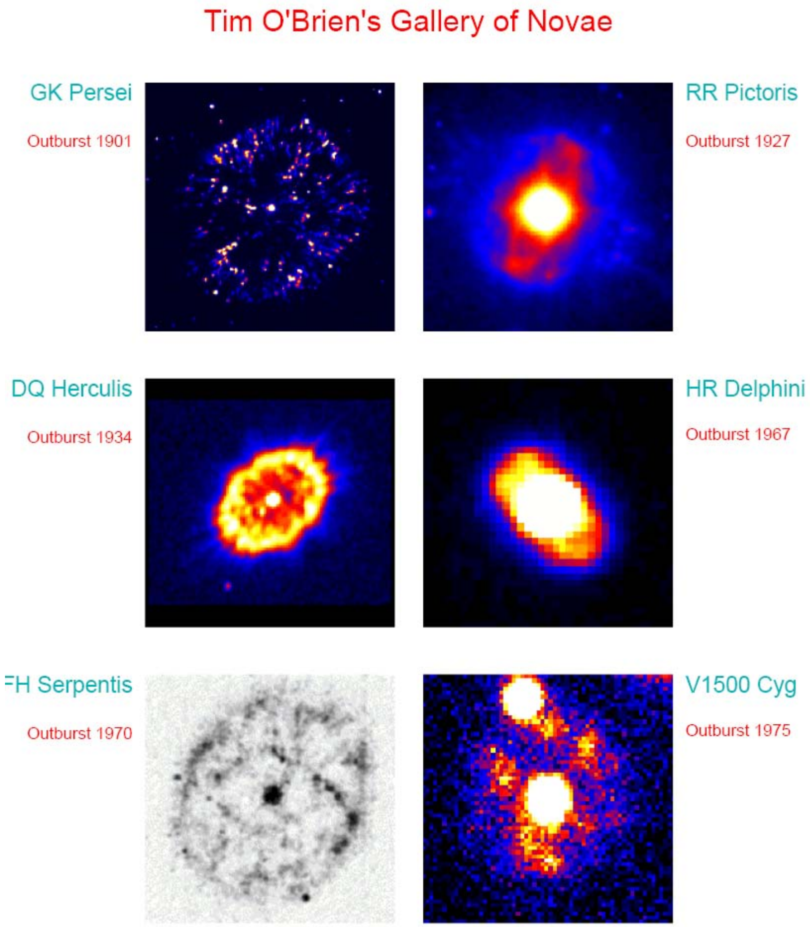
- GM/R between 0.04 and 0.2 MeV/nucleon
- Nuclear energy 7 MeV/nucleon → there is plenty of energy to expel each nucleon, but expulsion will only occur if the Eddington limit is reached → Question: how fast does burning need to be before Eddington limit is reached?
- Eddington limit is 8.1 x 10^{43} $(M_{WD}/M_{\odot})$ MeV/s
- The Eddington limit can be reached if 1.2x 10^{43} $(M_{WD}/M_{\odot})$ nucleons/s are burned and energy is radiated
- For a fuel mass of 10^{-5} $M_{\odot}$ = 1.2 x X x 10^{52} H-nucleons the burning time should be less than 20 yrs to keep flux at Edd.
- Classical novae last shorter → always super Eddintgon



Provencal et al. 2004

Nova remnants

- Most accreted mass expelled, after being enriched through mixing with deeper layers in WD
- Sometimes odd abundances in remnants → excavation of CO or ONe WD proposed (meaning that WD mass decreases through classical novae!)
- A lot of H is found in ejecta (up to 50%) → not all H is burnt
- ISM pollution: ~30 CNs/yr/Gal X 10 Gyr X 10^{-5} $M_\odot$ ≈ 10^{7} $M_\odot$ → not important, except:
- Some isotopes (^{13}C, ^{15}O, ^{17}Ne) 1000x overabundant → may be important



Light curve evolution

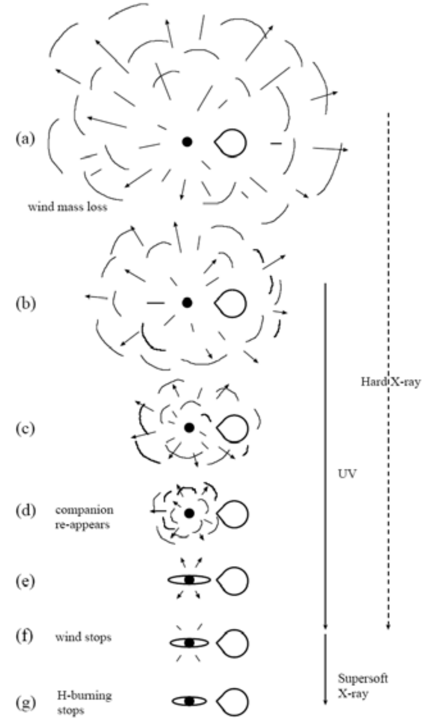


FIG. 1.— Evolution of nova outbursts: (*a*) after a nova explosion sets in, the photosphere expands greatly up to $\gtrsim 100\ R_\odot$, and the companion star is engulfed deep inside the photosphere; (*b*) after the maximum expansion, the photospheric radius shrinks with time and free-free emission dominates the flux at relatively longer wavelengths; (*c*) a large part of the envelope matter is blown in the wind and the photosphere moves further inside; (*d*) the companion eventually emerges from the WD photosphere and an accretion disk may appear or reestablished again; (*e*) the photosphere further shrinks to a size of $\lesssim 0.1\ R_\odot$; (*f*) the optically thick wind stops; (*g*) hydrogen nuclear burning stops and the nova enters a cooling phase. Hard X-rays may originate from internal shocks between ejecta (or a bow shock between ejecta and the companion) from stage (*a*) to (*f*) as indicated by a dashed line. The ultraviolet (UV) flux dominates from stage (*b*) to (*f*). Then the supersoft X-ray flux replaces the UV flux from stage (*f*) to (*g*).

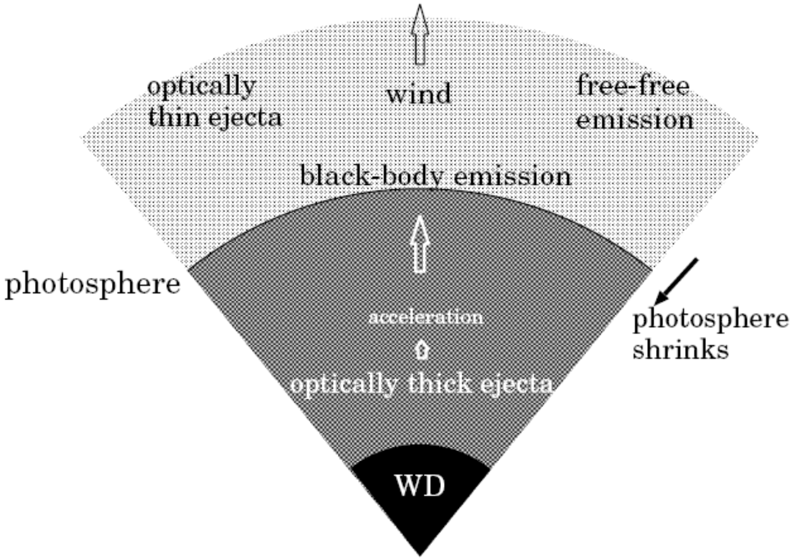
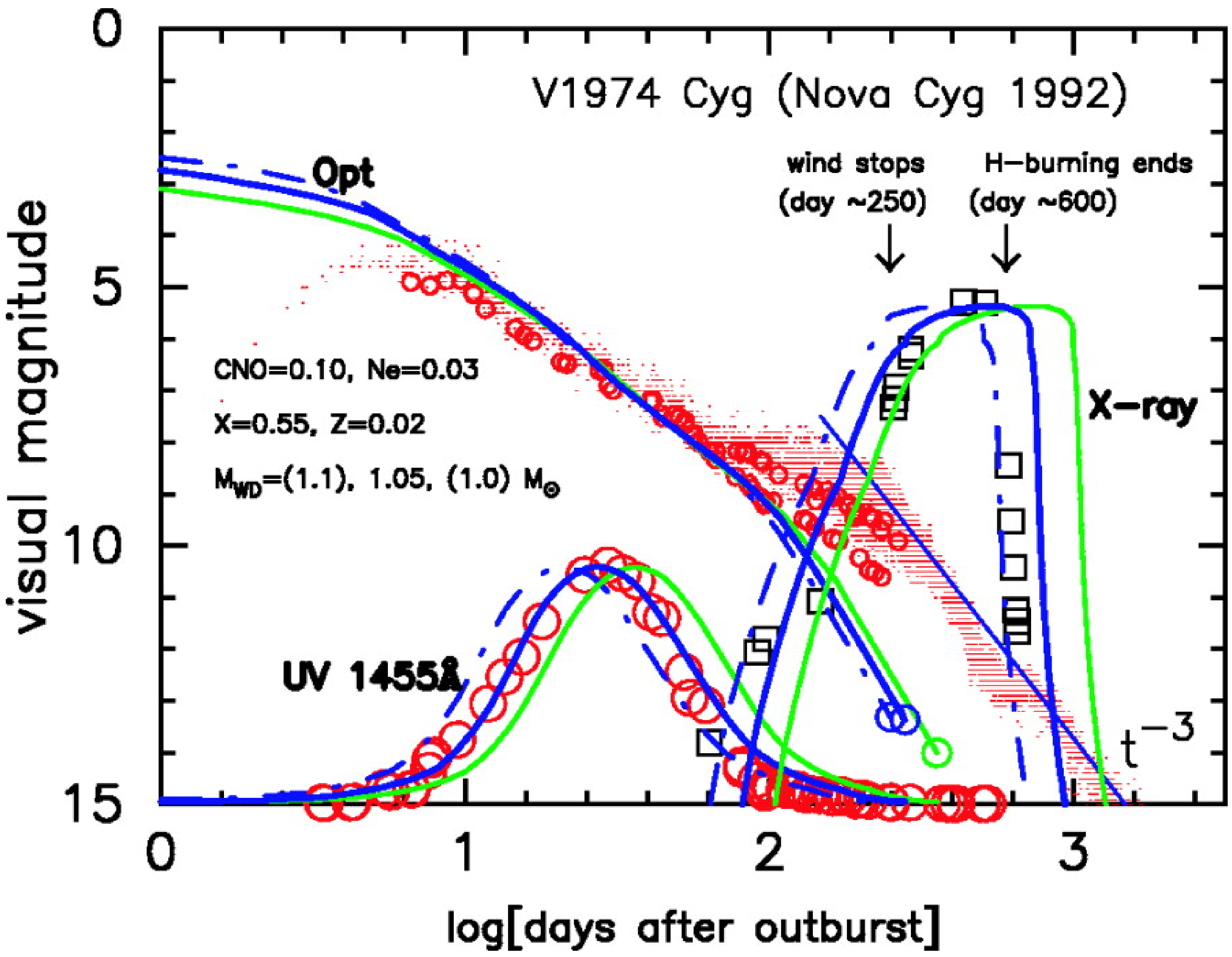


FIG. 2.— A schematic configuration of our nova ejection model: A large part of the initial envelope mass is ejected by the winds, which are accelerated deep inside the photosphere. After the optical maximum, that is, after the maximum expansion of the photosphere, the photosphere begins to shrink whereas the ejecta are expanding. The optically thin layer emits free-free radiation at relatively longer wavelengths while blackbody radiation from the photosphere dominates at shorter wavelengths.

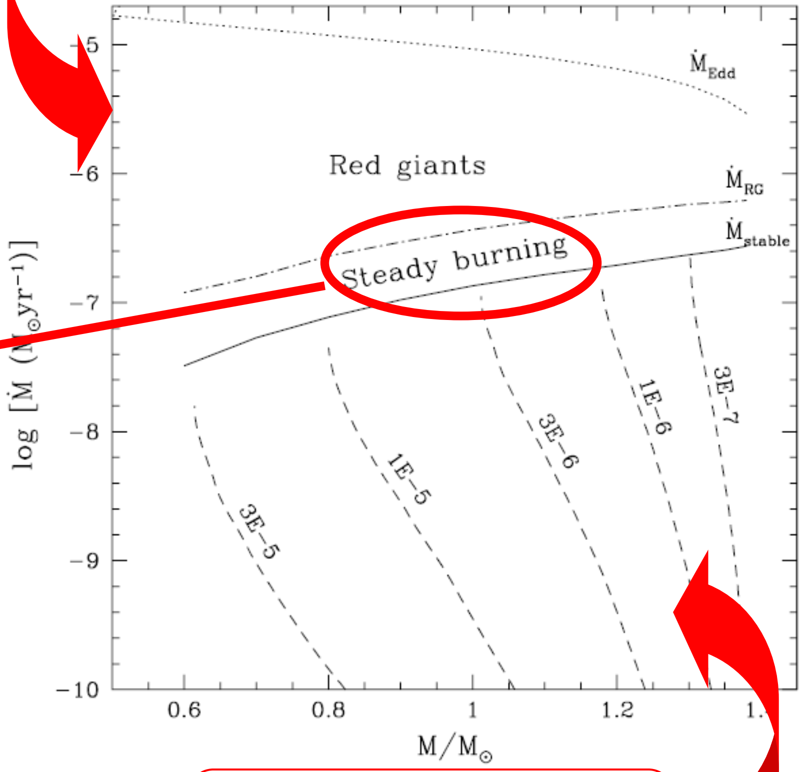
Hachisu & Kato 2007

Light curve @ 3 different wavelengths



Can we get a SN Ia?

- Can Chandrasekhar limit of 1.4 $M_\odot$ be surpassed through accretion?
- What is needed in this 'single degenerate' channel?
  - WD
  - Heavy enough donor star, also leaving some room for non-conservative mass transfer
  - Transferred mass must be burned continuously instead of through novae, in order for it to be retained by the WD → stringent limits on M-dot → limits on donor (more massive, somewhat evolved)
- Candidate growing WDs: High M-dot (10^{38} erg/s), high T (tens of eVs) → Super Soft Sources (SSS)

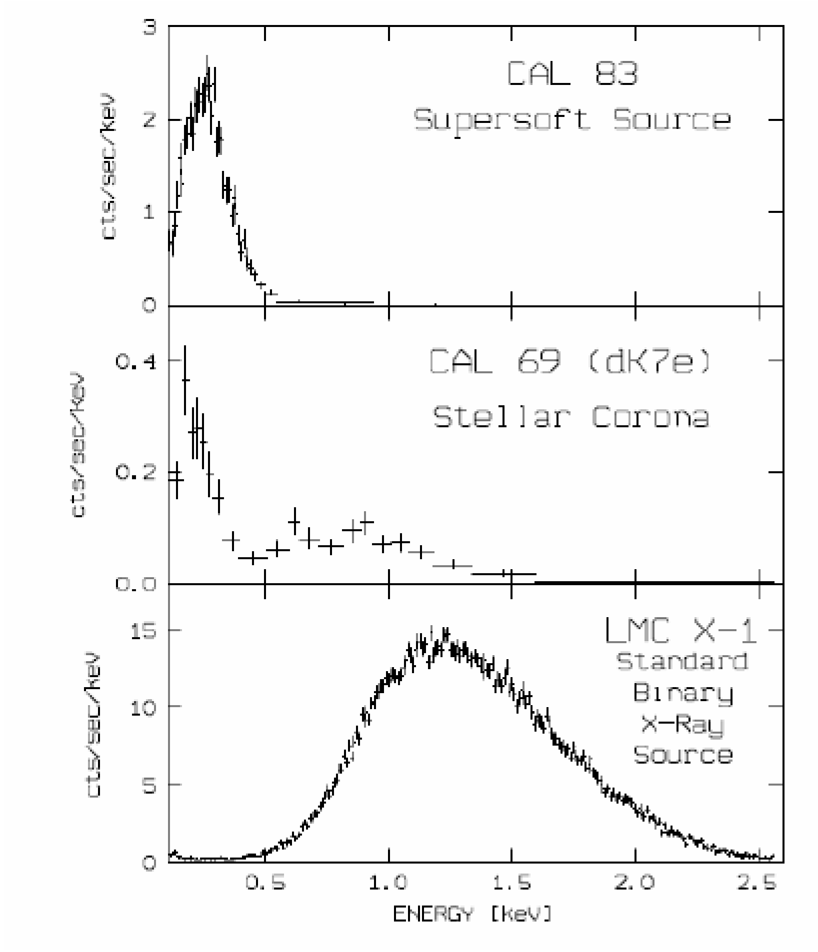


Accreted matter lost in RG winds

Accreted matter lost in novae

Super Soft Sources (10^{38} erg/s; tens of eVs)

- 18 in Galaxy and MCs
- 3 types
  - CVs with $M_{donor} > 1.5\ M_\odot$
  - CVs with $M_{donor} < 1.5\ M_\odot$
  - Symbiotics (supergiant+WD)
- 10^3 predicted, but many extincted by interstellar dust → look in other galaxies
- SSSs not seen in large numbers in external galaxies (~10 instead of 10^3)
- → unlikely SN IA channel, at least if they are SSSs
- BUT: community not unanimous about this yet! To be continued..



Standard candle?

- There is a relationship between peak luminosity and nova duration: higher peak luminosity goes with faster novae. This can be understood through M_{WD} dependency
  - All novae are Eddington limited
  - L_{edd} (:) M^{WD}
  - M_{ign} (:) $M_{WD}^{-7/3}$
- Potential for use as standard candle and as distance indicator out to Virgo cluster (20 Mpc)

Thermonuclear shell flashes summary

- Occur on compact non-singular objects
- Need degenerate environment to keep pressure up to sustain nuclear burning
- Ignition mass dependent on M-dot, M and X
- Peak temperature dependent on X
- 4 important nuclear reaction chains: proton-proton chain (pp) , CNO cycle, triple alpha and rapid proton capture (rp). Latter two only in NSs
- Mass expulsion: from <1% (NS) to ≥100% (WD)
- Light curve complications in WDs due to mass expulsion
- Stable hydrogen burning present in both NSs and WDs at similar accretion luminosities. The WD cases ('Super Soft Sources') are candidate SN Ia progenitors
- Agreement on general physics, NOT on details such as on accretion-induced Type Ia SNe.