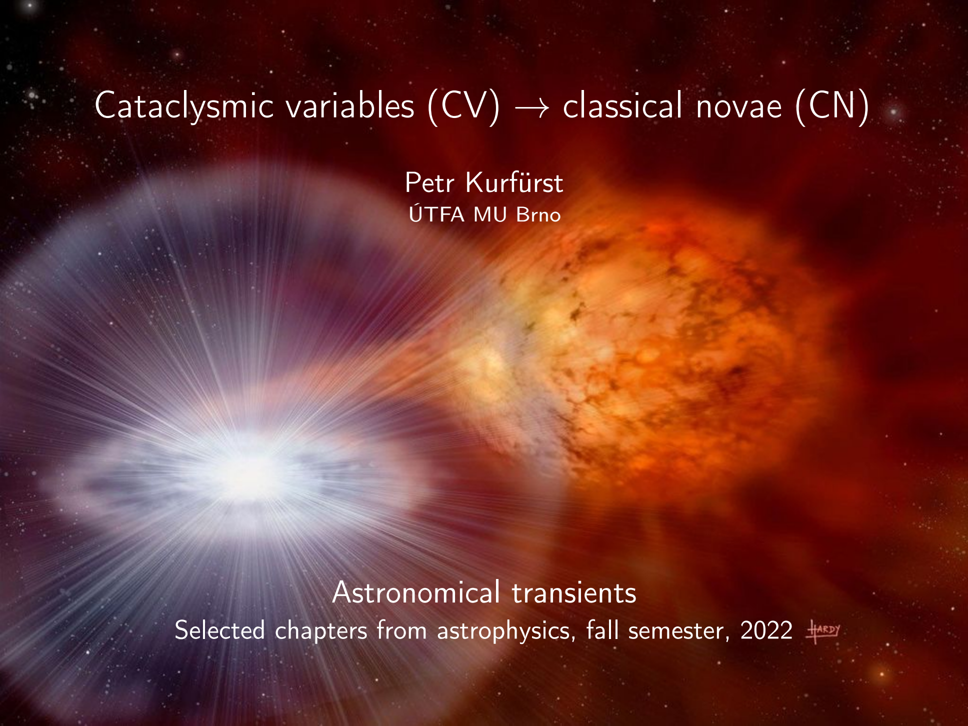


Cataclysmic variables (CV) → classical novae (CN)

Petr Kurfürst
ÚTFA MU Brno

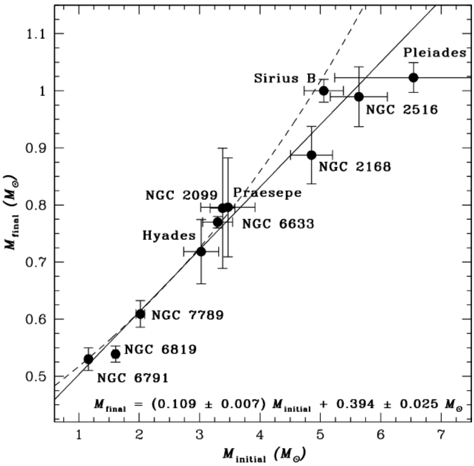
Astronomical transients
Selected chapters from astrophysics, fall semester, 2022

Talk outline

- WDs
- Hydrogen accretion onto WD
- Classical (recurrent (RN)) novae
- Thermal stability of a WD hydrogen surface layer
- He accretion onto WD
- CSM interactions

WD initial/final mass relation ← masses in open clusters

(Adding/removing material to or from WDs)



Credit: Kalirai+ 2018

- WD initial mass relation - typical WD initial/final masses (Hansen+ 2007)
- Most massive WDs are only coming from most massive (relatively) stars

WD initial/final mass relation ← masses from SDSS

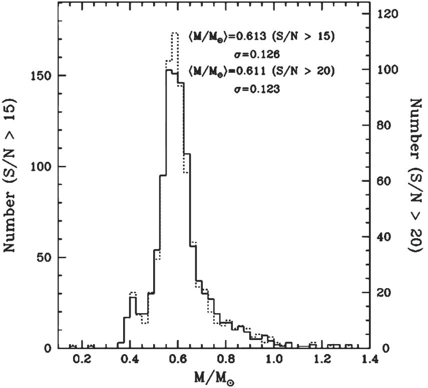


Figure 7. Mass distribution for the DA stars in the SDSS with 40,000 K > $T_{\rm eff}$ > 13,000 K. The distribution shown with a solid line corresponds to our optimal sample of 1089 DA stars with S/N > 15. In comparison, we show as a dashed line the distribution with an alternate cutoff of S/N > 20, scaled to match the former (the number of stars is given on the right-hand scale). The mean mass and standard deviation are given in the figure.

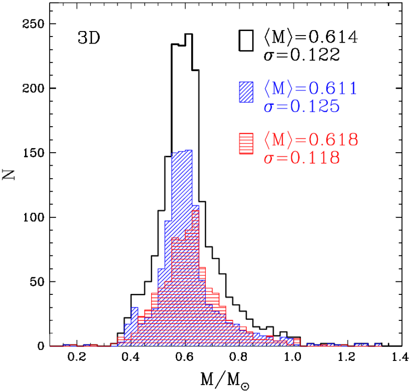


Fig. 14. Similar to Fig. 11 but for the SDSS E06/TB11 sample with $T_{\rm eff}$ < 40 000 K and S/N > 15 (black empty histograms). We also highlight the sub-distributions for 13 000 < $T_{\rm eff}$ (K) < 40 000 (blue histograms, radiative atmospheres) and $T_{\rm eff}$ < 13 000 K (red histograms, convective atmospheres). Binaries and magnetic objects were removed from the distributions.

Credit: Tremblay+ 2011, 2013

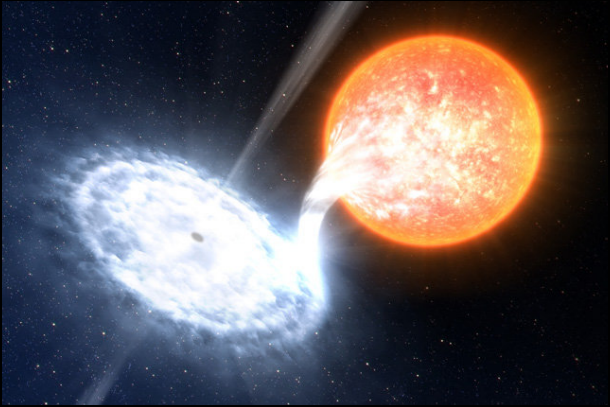
- Only 5 WDs with $M > 1.3\,M_\odot$
- Very rare, origin often speculated to be WD mergers

Accreting WDs

- White dwarfs have typically 'done' burning after the large giant envelope is lost in strong winds and pulses and they simply cool 'forever'.
- Nuclear reactions can be revived, however, when a WD is in a tight binary and given the opportunity to accrete fresh Hydrogen or/and Helium.
- The tightest detected binary system is ZTF J1813+4251, including a sun-like star and white dwarf, co-orbiting every 51 minutes (Burdge+ 2022 - using an algorithm that searched over 1000 images from the ZTF, identifying stars that had brightness variability periods around 1 h)
- Though rare, the resulting thermonuclear outbursts are commonly observed in our galaxy and others.
- Indeed, they are the most frequent type of transients seen in a typical galaxy!

Accreting WDs

WD of C/O **donor star** - H/He or pure He



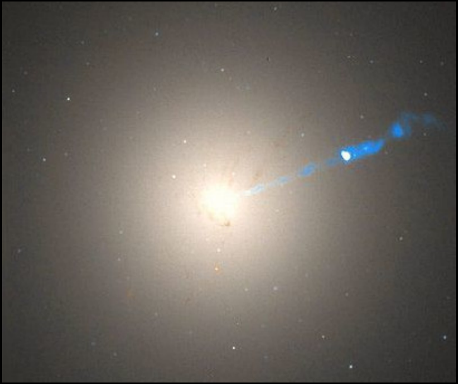
- $< 1\,\%$ of WDs are in binaries where accretion occurs, releasing gravitational energy $GM_1 m_{\rm p}/R_1 \approx$ 100 - 300 keV/nucleon

- Whereas nuclear fusion of H→He or He→C releases energy 1 - 5 MeV/nucleon

- This contrast is further enhanced when the WD stores fuel for >1000 years and burns it rapidly, making these **binaries detectable** in distant galaxies during the thermonuclear event

Accreting WDs

M87 galaxy (Virgo A)



Some numbers:

- Two WDs are 'made' per year in a $10^{11}\,M_\odot$ elliptical galaxy

The observed rates are:

- $\sim$20 Classical Novae (H fuel) per year, implying a WD/MS contact binary birthrate of one every 400 years (Townsley & Bildsten [T&B] 2005)
- One Type Ia SN every 250 years, that is, one in 500 WDs explodes!

- Predicted rates: **Helium Novae** (Eddington-limited) every 250 years, one **large He explosion** every 5000 years, and **WD - WD mergers** every 200 years

H-accreting WDs

Some numbers:

- Basic classification: 3 observed types (Sokoloski, Bildsten & Ho 2001)

	Cataclysmic variables	Supersoft sources	Symbiotics[c]
Orbital period:	Hours	Hours – Days	Years
Mass transfer mechanism:	Stable RLOF[a]	Unstable RLOF	Wind of RLOF
$\dot{M}_{\rm WD}$ $(M_\odot\ {\rm yr}^{-1})^b$:	10^{-10}–10^{-8}	10^{-8}–10^{-6}	10^{-9}–10^{-5}
Observed number:	400–500	≈ 35	≈ 190
Magnetic subclass:	Yes	?	Yes
Outbursts:	TNR[a] & DI[a]	Cause?	Cause?
Disc:	Yes	Yes	Some?
Steady nuclear burning:	No	Yes	Some
Flickering:	Yes	Some	Some

[a] RLOF=Roche lobe overflow; TNR=thermonuclear runaway; DI=disc instability

[b] $\dot{M}_{\rm WD}$ is the time-averaged accretion rate onto the WD

[c] Let's leave it to Jaroslav Merc

- Their "physical nature" differs mainly in mass inflow rate $\dot{M}_{\rm WD}$, outburst mechanisms, and stability of H-shell nuclear burning

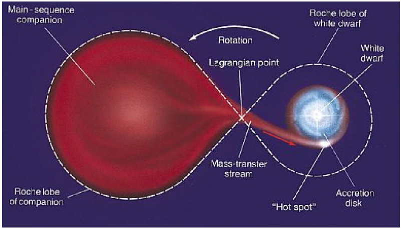
H-accreting WDs

Some numbers:

- Classification according to the light curve development speed:
- fast novae (NA) - rapid brightness increase, followed by a brightness decline of $\sim 3\,\mathrm{mag}$ - within $\sim 100\,\mathrm{days}$ (Ritter & Kolb 2003)
- slow novae (NB) - decline of $\sim 3\,\mathrm{mag}$ - in 150 days or more
- very slow novae (NC) - also known as symbiotic novae, staying at maximum light for a decade or more and then fading very slowly.
- recurrent novae (RNe) - multiple registered nova eruptions - separated by 10-80 years (Bode & Evans 2008)
- dwarf novae - instability in the accretion disk that causes a change in viscosity - heating the whole disc - increase of L

- Extragalactic novae - relatively common in M31 (several dozen novae brighter than about $20\,\mathrm{mag}$ each year) - also in M33 and M81

H-accreting WDs



Some kinematics:

(cf. Paczyński 1971, T&B 2005)

- Radius of a low-mass MS binary companion with filled RL is

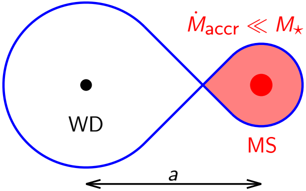
$$R_2 = 0.46a\left(\frac{M_2}{M_{\rm WD}+M_2}\right)^{1/3}, \quad \text{with} \quad \omega_{\rm orb}^2 = G\,\frac{M_{\rm WD}+M_2}{a^3}$$

- Relation between such a low-mass MS star average density and the orbital period:

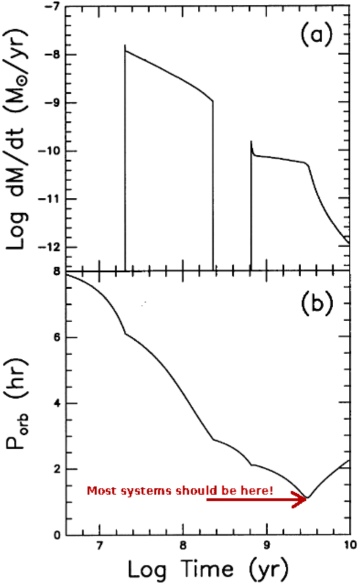
$$P_{\rm orb} = 10.6\,{\rm hr}\left(\frac{{\rm g\,cm}^{-3}}{\langle\rho\rangle}\right)^{1/2}, \quad \text{where} \quad \langle\rho\rangle = \frac{3M_2}{4\pi R_2^3}$$

- Orbital period of a CV with the above MS donor star is

$$P_{\rm orb} = 9\,{\rm hr}\sqrt{\frac{M_\odot}{M_2}\left(\frac{R_2}{R_\odot}\right)^3}$$



H-accreting WDs



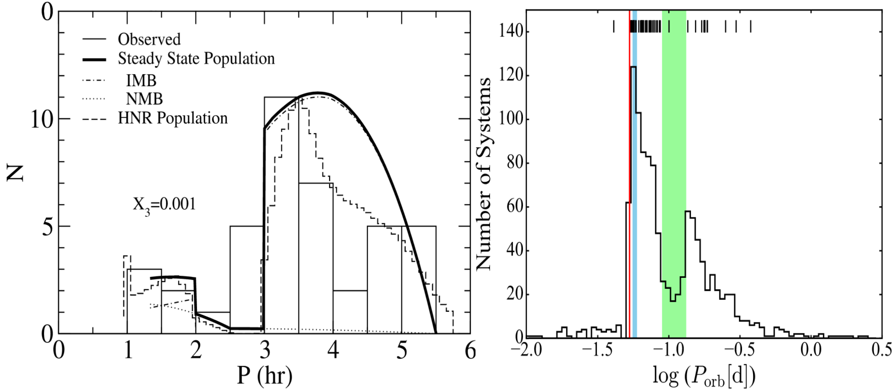
Credit: Howell+ 2001

Cataclysmic variables:

- ∼1 in 100 WDs end up in a CV, local space density is 1 per 40 pc^3
- Optically variable objects with strong emission lines; at low accretion rates, the disk is thermally unstable, leading to **dwarf novae outbursts**
- Very uncertain whether the WD mass increases or decreases, but it is clear that 0.3 − 0.6 solar masses is put on the WD over its "lifetime"
- **Figure**: evolution of a single CV with init $M_2 = 0.9\,M_\odot$; $M_{\mathrm{WD}} = 1.1\,M_\odot$; the system first comes into RL contact at $P_{\mathrm{orb}} = 6\,\mathrm{h}$ and evolves through the period gap to the min P_{orb} and back to longer periods by 10^{10} yr

H-accreting WDs

(Credit: Townsley & Bildsten 2005, Pala+ 2017)



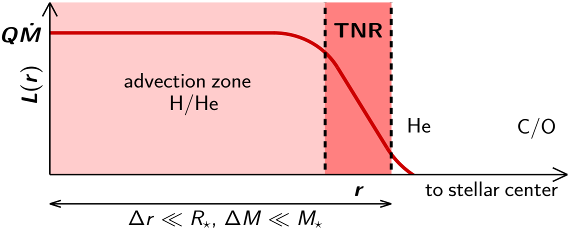
- Left panel: Normal distribution of CNe orbital periods of 9 systems with $P_{\rm orb} < 6\,{\rm hr}$
- Right panel: Orbital period distribution of 1144 semidetached binaries containing a WD and a RL filling low-mass secondary; the green band highlights the period gap ($2.15\,{\rm h} \lesssim P_{\rm orb} \lesssim 3.18\,{\rm h}$)

Accreting WDs

- Things yet to be explained:
- Why is the burning thermally unstable (first approximation analytical solution - **a bit more math**)?
- How does a thermally unstable model evolve?
- What is the rate of the events from a given binary?
- How do we underststnd their outcomes? (not quite well... considering)
- Do we have any good predictions that are testable? (I will highlight supersoft sources from stable burning after the flash)

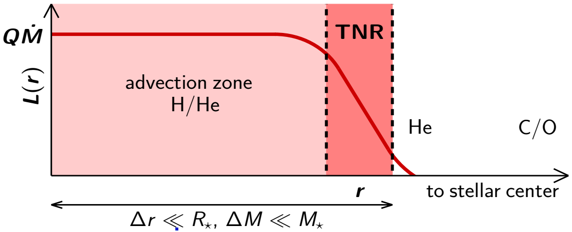
Thermally stable × unstable WD surface layer?

(cf. K. Shen & L. Bildsten 2007, LB's talk at 35 HUJI WS, Agrawal+ 2021)



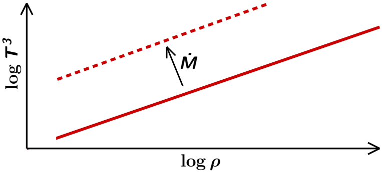
- steady state luminosity $L = Q\dot{M} + L_{\rm core}$, with specific nuclear energy release Q, and accretion rate (mass overflow) $\dot{M}$
- typical values: $Q \sim 5\times10^{18}\,{\rm erg\,g^{-1}}$ for H/He → He, $Q \sim 1\times10^{18}\,{\rm erg\,g^{-1}}$ for He → C
- heat transfer in advection zone: $L(r) = -4\pi r^2 \left[\frac{1}{3}\frac{c}{\kappa\rho}\frac{\rm d}{{\rm d}r}\,aT^4\right]$ (1)
- outer envelope in a steady state HEq: ${\rm d}P/{\rm d}r = -\rho(r)g$
- $\frac{{\rm d}P_{\rm rad}}{{\rm d}P} = \frac{\kappa L(r)}{4\pi G M(r) c} = \frac{L(r)}{L_{\rm Edd}(r)}$, with $\kappa \equiv \kappa_{\rm es} = {\rm constant}$ (2)

Thermally stable × unstable WD surface layer?



- Eddington L: $L_{\rm Edd} = Q\dot{M}_{\rm Edd}$, steady state: $L \ll L_{\rm Edd} \rightarrow P \approx P_g$
- $\dot{M}_{\rm Edd} \sim 4.3 \times 10^{-7} \frac{M_\odot}{\rm yr} \left(\frac{M}{M_\odot}\right)$ for H/He $\rightarrow$ He;

  $\sim 5 \times 10^{-6} \frac{M_\odot}{\rm yr} \left(\frac{M}{M_\odot}\right)$ for He $\rightarrow$ C

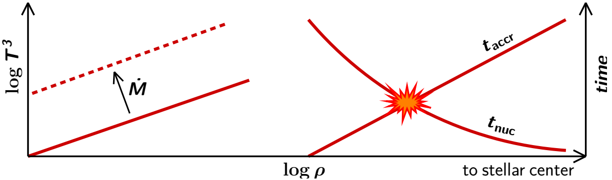


- "Radiative-zero" solution (Eq. (2)):

  $$\frac{aT^4}{3} \approx \frac{L(r)}{L_{\rm Edd}(r)} \frac{\rho k T}{\mu m_{\rm p}} \Rightarrow T^3 \propto \rho \quad (3)$$
- This profile **survives** until we reach **high enough ρ and T to burn**

Thermally stable × unstable WD surface layer?

- **We introduce the following timescales:**
  - accretion time: $t_{\mathrm{accr}} = \dfrac{\Delta M}{\dot{M}}$ → time to accrete the ΔM layer
  - nuclear burning time: $t_{\mathrm{nuc}} = \dfrac{Q}{\epsilon(\rho, T)}$ → time to deplete the fuel
  - $\epsilon(\rho, T)$ is the nuclear energy generation rate [$\mathrm{erg\,g^{-1}\,s^{-1}}$]



  - gas layer undergoes compression for some time → until it is dense and hot enough for nuclear fusion ignition
  - further compression is now of the "ash" (basically He)

Thermally stable × unstable WD surface layer?

- comparability of t_{accr} and t_{nuc} at TN burning: $\dfrac{\Delta M}{\dot{M}} = \dfrac{Q}{\epsilon\left(\rho, T\right)}$ (4)
- pressure at TN layer: $P = \dfrac{F}{S} = \dfrac{g\Delta M}{4\pi R^2} = \dfrac{GM\Delta M}{4\pi R^4}$
- is this solution stable to thermal perturbations?
- from the 1st LTD: $T\dfrac{\mathrm{d}s}{\mathrm{d}t} = \epsilon\left(\rho, T\right) - \dfrac{\mathrm{d}L(r)}{\mathrm{d}M(r)} = \epsilon_{\mathrm{nuc}} - \dfrac{1}{\rho}\boldsymbol{\nabla}\cdot\boldsymbol{F}$ (5)
- putting in thermal perturbation: will T rise or drop? Assume a constant pressure perturbation dP (relevant assumption in a thin limit)
  $$c_p\frac{\mathrm{d}T}{\mathrm{d}t} = \epsilon_{\mathrm{nuc}} - \frac{1}{\rho}\boldsymbol{\nabla}\cdot\boldsymbol{F} \quad \text{(RHS = steady state: } \epsilon_{\mathrm{nuc}} - \epsilon_{\mathrm{cool}}\text{)} \tag{6}$$
- one zone model: from TB $dP/g = -\rho\,\mathrm{d}r$, that is,
  $$\epsilon_{\mathrm{cool}} = -\frac{1}{\rho}\frac{\mathrm{d}}{\mathrm{d}r}\left[\frac{c}{\kappa\rho}\frac{\mathrm{d}}{\mathrm{d}r}\left(\tfrac{1}{3}aT^4\right)\right] = -g^2\frac{\mathrm{d}}{\mathrm{d}P}\left[\frac{c}{\kappa}\frac{\mathrm{d}}{\mathrm{d}P}\left(\tfrac{1}{3}aT^4\right)\right] \propto T^4 \tag{7}$$
  (P is better coordinate than ρ - it does not change so much)

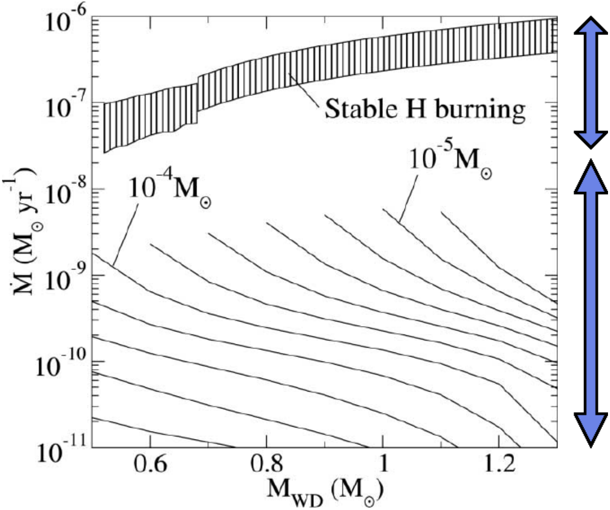
Thermally stable × unstable WD surface layer?

- what about perturbing the nuclear burning rate $\epsilon_{\rm nuc} \equiv \epsilon(\rho, T)$?
- we expand $\epsilon_{\rm nuc}$: $\dfrac{\delta\epsilon}{\epsilon} = \dfrac{\partial \ln \epsilon}{\partial \ln \rho}\dfrac{\delta\rho}{\rho} + \dfrac{\partial \ln \epsilon}{\partial \ln T}\dfrac{\delta T}{T}$ (8)
- perturbed quantities $\delta\rho$, δT
- $\dfrac{\partial \ln \epsilon}{\partial \ln \rho} \approx 1$, while $\dfrac{\partial \ln \epsilon}{\partial \ln T} \equiv \nu \approx 10$ for CNO burning at $T = 10^8\,\mathrm{K}$
- total pressure: $P = \dfrac{\rho k T}{\mu m_{\rm p}} + \dfrac{a T^4}{3}$, perturbation $\delta P = 0$
- perturbing this, we get: $\dfrac{\delta\rho}{\rho} = -\dfrac{\delta T}{T}\left(1 + 4\,\dfrac{P_{\rm rad}}{P_{\rm gas}}\right)$, so if (9)
  - $P_{\rm rad} = 0$, then $\delta \ln \rho$ and $\delta \ln T$ are (clearly) anticorrelated
  - $P_{\rm rad}$ becomes important, then $\delta \ln \rho / \delta \ln T$ grows up, and the density decline is going to shut off the burning (this is why nuclear burning can be stabilized in a WD case)

Thermally stable × unstable WD surface layer?

- recalling the equation $c_p \frac{\mathrm{d}T}{\mathrm{d}t} = \epsilon_{\mathrm{nuc}} - \epsilon_{\mathrm{cool}}$, its perturbations are:
- LHS: $c_p \frac{\mathrm{d}}{\mathrm{d}t}(T_0 + \delta T) = c_p \frac{\mathrm{d}}{\mathrm{d}t} \delta T$, where T_0 is a fiducial T (10)
- RHS: $= \epsilon_{\mathrm{nuc}} - \epsilon_0 \left(\frac{T}{T_0} \right)^4$, where ϵ_0 is the "stable" rate,
- that is, using Eq. (8): $\epsilon_0 \frac{\delta T}{T_0} \left(\nu - 1 - 4 \frac{P_{\mathrm{rad}}}{P_{\mathrm{gas}}} \right) - 4\epsilon_0 \frac{\delta T}{T_0}$, (11)
- If $\epsilon_{\mathrm{nuc}} > \epsilon_{\mathrm{cool}}$, the solution is unstable: $\nu > 1 + 4 \left(1 + \frac{P_{\mathrm{rad}}}{P_{\mathrm{gas}}} \right)$
- From this condition, we can constrain the (narrow) stabilizing luminosity zone: $\frac{P_{\mathrm{rad}}}{P} = \frac{\dot{M}}{\dot{M}_{\mathrm{Edd}}} = \frac{L}{L_{\mathrm{Edd}}} = \frac{5}{9}$
- This can be achieved either by high **"core" luminosity L_{core}** or by high **accretion rate $\dot{M}/\dot{M}_{\mathrm{Edd}}$**

Thermally stable × unstable WD surface layer?

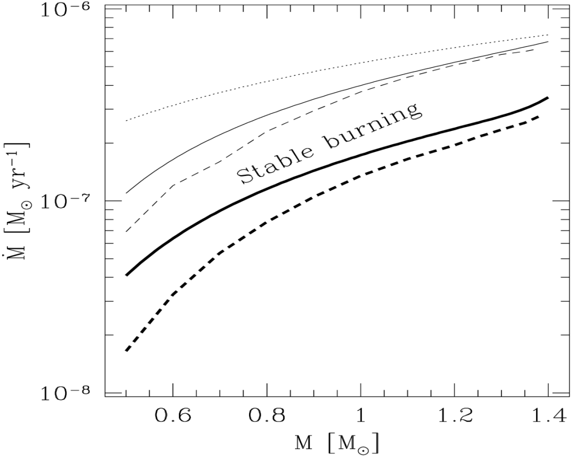


Credit: Townsley & Bildsten 2005

Supersoft sources: H burn stable (van den Heuvel+ 1992) or weakly unstable; accretion rates ∼100 Myrs

Cataclysmic variables: unstable burning leads to Classical Novae; whether the mass stays or leaves is uncertain but WDs are not massive enough (T&B 2005)

Thermally stable × unstable WD surface layer?

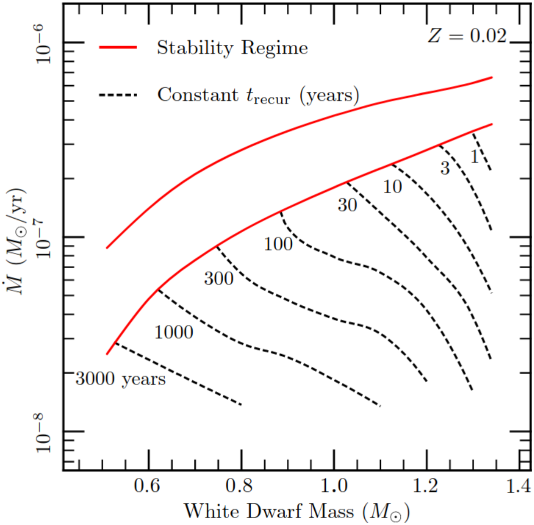


Credit: Shen & Bildsten 2007

- $\dot{M}$ for Z $= 10^{-2}$, no $L_{\rm core}$. No hydrostatic envelope above the stability strip, thermally unstable envelope below this. Numerical equivalent bounds (right panel, dashed lines), nuclear $\dot{M}_{\rm Edd}$ (dotted line).

Thermally stable × unstable WD surface layer?

Classical novae from unstable TN burning of accumulated matter



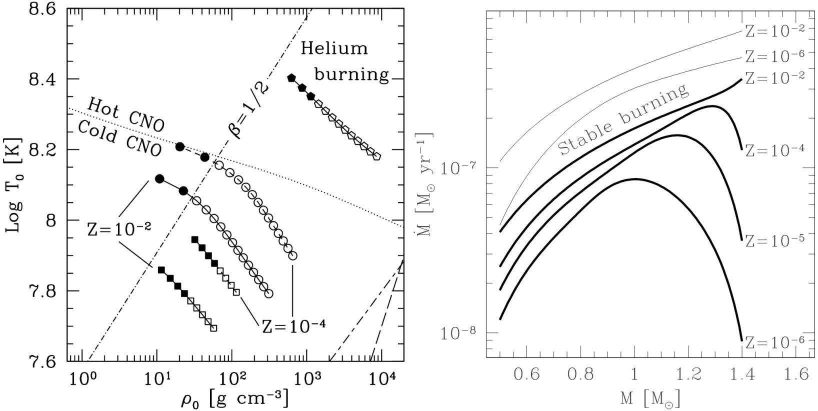
Credit: Wolf+ 2013

Accretion of H/He at low rates leads to a limit cycle of accumulation followed by thermonuclear instability

Reccurence times depend on **WD mass** and **accretion rate**

Stable burning can occur at high $\dot{M}$ rates due to radiation pressure stabilization

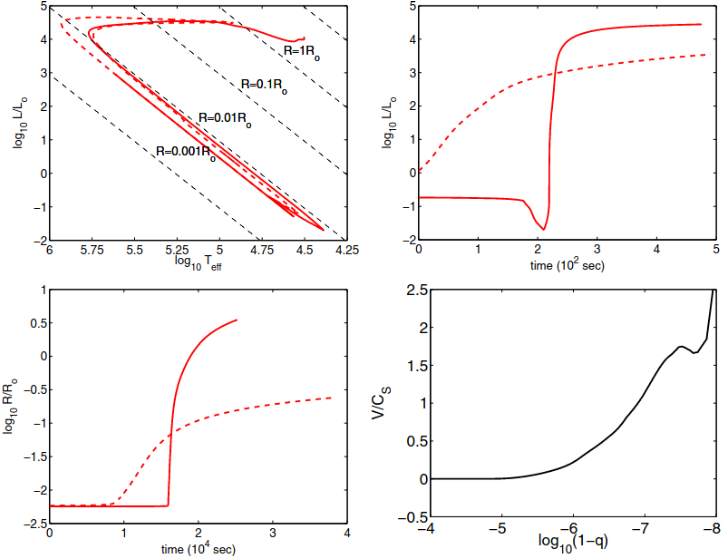
Thermally stable × unstable WD surface layer?



Credit: Shen, Bildsten 2007

- left panel: T and ρ for varying M and $\dot{M}$ of WDs with steady burning of H in cold CNO. $M = 0.5$ (squares) and $1.35\,M_\odot$ (circles).
- right panel: ranges of thermally stable accretion rates assuming no $L_{\rm core}$, with given metallicity. Burning is via the full CNO cycle.

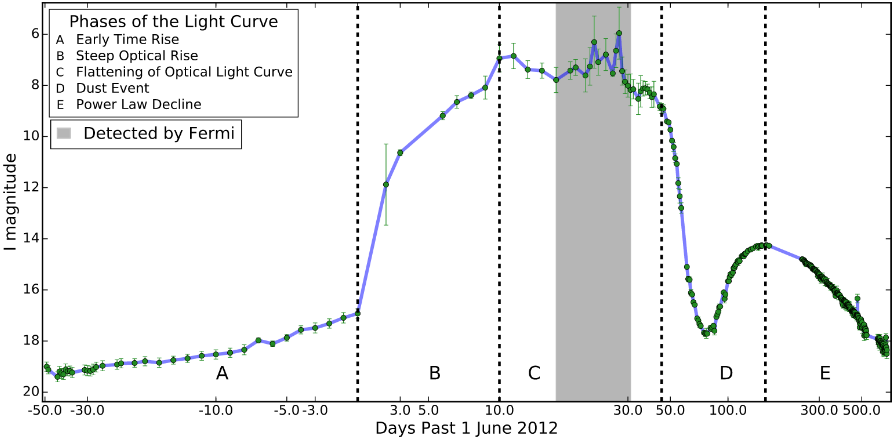
Thermally stable × unstable WD surface layer?



Credit: Denissenkov+ 2013

- 1.2 $M_\odot$ CO nova sims with MESA; dashed lines - without CBM

Thermally stable × unstable WD surface layer?

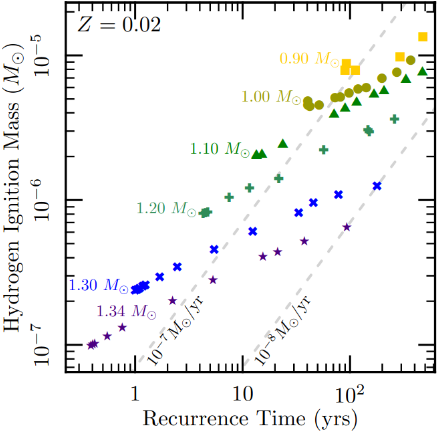


Credit: Finzell+ 2018

Thermally stable × unstable WD surface layer?

After a big ejection:
Supersoft phase

- Always an amount of H left to burn stably over a prolonged time, typically once the WD radius shrinks inside it's RL
- These post-nova WDs are then seen in what's called a **supersoft phase**; can be seen also in MW, likely responsible for keeping the expanded ejecta hot for so long that a radio source is detected



Credit: Wolf+ 2013

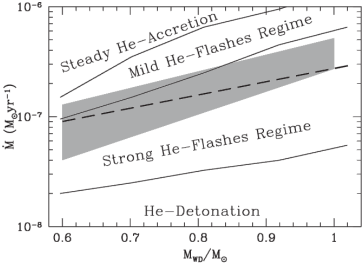
- Physics best studied in M31, which is well monitored for Novae and can be observed by soft X-ray instruments to measure how long the supersoft source is on

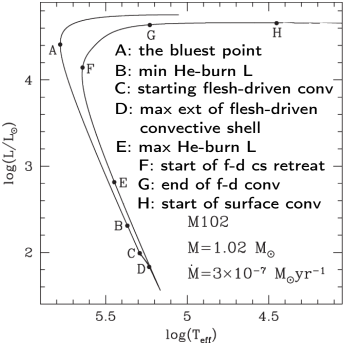
He-accreting WDs (shortly)

He accretion scenarios:

- Low mass **He WD donors**, accretion rates are in the unstable regime, but flashes are likely weak
- Burning **He WDs cores** (sdB stars) accrete for a long time at low rates and allow for accumulation of very thick unstable He shells
- More massive He burning cores can find their way into stable regime, avoiding flashes

Credit: Piersanti+ 2018

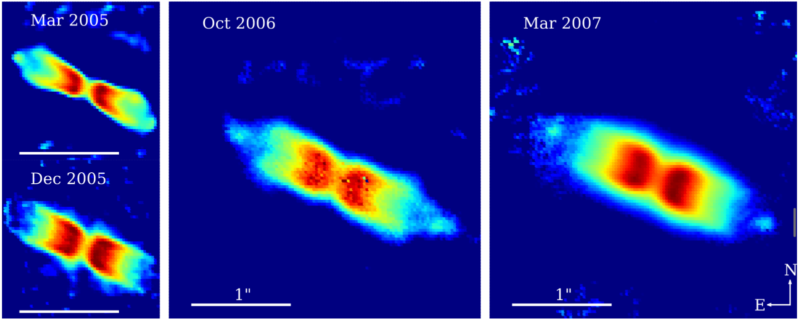




He-accreting WDs (shortly)

The expanding bipolar shell of He Nova V445 Puppis

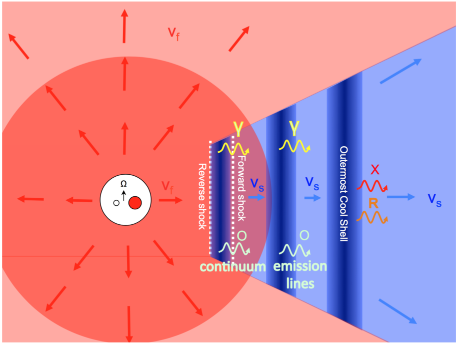
He nova V445 Puppis:



Credit: Woudt+ 2009

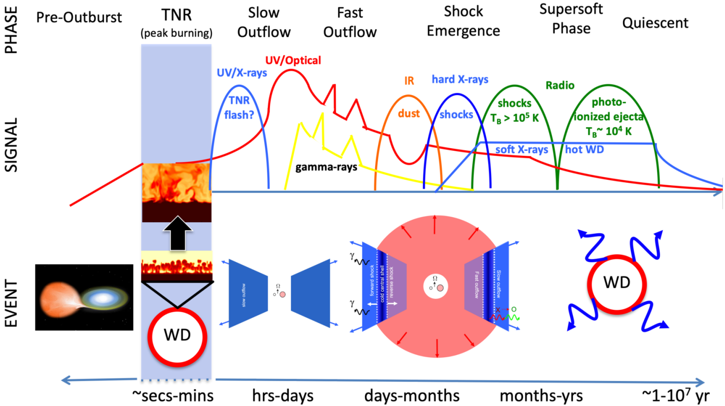
CSM interactions

- Early UV/X-ray Flash from the TNR + short-lived phases soon after
- Many CNe are gamma-ray sources, most likely due to internal shocks in the ejected material



- Collisions generate internal shocks → sweep up gas into a cool thin shell (Steinberg& Metzger 2020)
- These radiative shocks generate a correlated gamma-ray and optical flare via ejecta reprocessing of accelerated relativistic particles and thermal UV/X-ray emission

CSM interactions



- Schematic timeline of the physical processes and electromagnetic signals from novae. The figure includes modified images of convection/mixing during the thermonuclear runaway (Metzger+ 2020)