Unstable He Shell Burning in AM CVn Systems: SNe Ia

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SNe .Ia: A Brief Overview
(Bildsten, KS, Weinberg, & Nelemans ‘07)

- AM CVn evolution naturally yields unstable He-burning shells of ~0.1 M$_{\odot}$
- Hydrostatic calculation shows these shells burn hydrodynamically, potentially yielding He detonations; the majority of the talk will go into detail
- Small ejecta mass $\rightarrow$ short lifetimes (~5-10 days), 10% as bright as SNe Ia

- .Ia rate is few percent of Ia rate in an old population
- SDSS SN ($r = 22.5$; 280 deg$^2$; 2 day cadence) gets 0.5 – 7 .Ia/yr
- PS-1 medium-deep survey ($V = 24$; 50 deg$^2$; 4 day cadence) gets 1 – 10 .Ia/yr
AM CVn accretion outcome: He-burning

- Initially, very low $P_{\text{orb}} < 4 \text{ min}$ & high $\dot{M} > 10^{-6} \text{ Msol/yr}$: stable He-burning (Tutukov & Yungelson ‘96; KS & Bildsten ‘07; SSSs)

- Binary evolves to lower $\dot{M}$: $\sim 10$ unstable helium novae (Iben & Tutukov ‘89)

- Eventually, $M_{\text{donor}} < M_{\text{ign}}$:
  - No novae $< 10^{-8} \text{ Msol/yr}$ and above 10 min, just He accretion
  - Last flash has largest $M_{\text{ign}} \approx 0.1 \text{ Msol}$
Progress of the convective phase

- He-burning injects entropy into the convective (isentropic) shell, raising $T$:

$$T \, ds = du + P \, dV$$

- Need to be consistent with hydrostatic equilibrium because $M_{\text{env}}$ can be large
- Initially no expansion work done b/c $P_b \sim GM_c M_{\text{env}} / 4\pi R^4$, but then $T_b \sim T_{\text{virial}}$
Small $M_{\text{ign}}$: He nova

- For smaller envelopes $< 10^{-2}$ Msol, entropy increase eventually leads to expansion. Like a hydrogen classical nova in a regular CV: helium nova (e.g., V445 Pup)

- What about bigger envelopes?
Large $M_{\text{ign}}$: He shell detonation!

- For larger envelopes, the heating timescale can become shorter than the dynamical timescale:

$$ t_{\text{heat}} = \frac{c_PT}{\epsilon_{\text{nuc}}} $$

$$ t_{\text{dyn}} = \frac{H}{c_s} = \sqrt{\frac{P}{\gamma \rho g^2}} $$

- Heat is injected faster than shell can respond and maintain hydrostatic equilibrium: large overpressure, dynamical explosion: likely outcome is a detonation!

- There is a minimum $M_{\text{env}}$ that can detonate
Many AM CVn’s should undergo He detonations

- Last flash for each system is the biggest
- For $M_{\text{acc}} > 0.8$ Msol, last flash should be dynamical / detonation
Initial abundances for detonation

- Determines:
  - neutron-to-proton ratio / $Y_e \rightarrow$ isotopic yield
  - likelihood that detonation will propagate (ZND length)

- The smaller ZND length is compared to scale height, the more likely a detonation will propagate
- Pure He ZND length $10^2 - 10^3$ times smaller than scale height
\( \alpha \)-chain elements (\(^{12}\text{C}, ^{16}\text{O}, ^{20}\text{Ne}, ^{24}\text{Mg}, \text{etc.}) \)

- Lower limit set by triple-\( \alpha \) burning \( \rightarrow X_{^{12}\text{C}} \sim 0.01-0.05 \)
- But dredge-up may yield \( X_{^{12}\text{C}/^{16}\text{O}/^{20}\text{Ne}} \sim 0.1 \) (depending on WD core)

\[ P_b = \frac{1}{3} a T_b^4 \]

\[ t_i < t_{\text{heat}} \]

\[ t_i > t_{\text{heat}} \]

\[ t_{\text{dyn}} = t'_{\text{heat}} \]

\[ M_c = 0.6 \, M_{\odot} \]

\[ 0.1 \, M_{\odot} \]

\[ 0.2 \, M_{\odot} \]

- To see if given isotope hangs around, want to compare \( t_{\text{heat}} \) to \( t_i \)
  \[ t_i \equiv \left| \frac{d \ln X_i}{dt} \right|^{-1} \]
- \( \alpha \)-chain elements unburned when detonation begins
- At post-shock \( T > 10^9 \, \text{K} \), \( \alpha \)-chain elements burn as fast as or faster than triple-\( \alpha \)
- So ZND length is shorter than for pure He
$^{14}\text{N}(\alpha, \gamma)^{18}\text{F}(\alpha, p)^{21}\text{Ne}$

- Majority of accreted metals are $^{14}\text{N}$ due to donor’s CNO-processing $\rightarrow X_{^{14}\text{N}} \sim 0.01$
- Timescales too short for $^{18}\text{F}$ to $\beta$-decay ($\tau_{1/2} = 110$ min) $\rightarrow Y_e$ unchanged

- Post-shock $\alpha$-capture on $^{18}\text{F}$ yields proton
- Proton catalyzes slow step of $\alpha$-chain via $^{12}\text{C}(p, \gamma)^{13}\text{N}(\alpha, p)^{16}\text{O}$ (Weinberg et al. ‘06)
- Further reduces ZND length!
- Self-propagating detonation more likely
- Hydrodynamic studies must include these elements
Conclusions

- AM CVn evolution leads to dynamical He shell explosions: \textit{Ia} supernovae
  - Quick rise of a few days, 10\% as long as SNe Ia, allowing short-lived radioactivity to be seen
  - Peak of $M_V = -17$ to $-15$, 10\% as bright as SNe Ia
  - AM CVn birth rate gives upper limit of a few percent of the Ia rate
  - Upcoming (and maybe current) optical surveys should see a few every year!
    (And SN2008ha [Foley et al. ‘09] is close…)

- Trace elements ($^{12}\text{C}/^{16}\text{O}/^{20}\text{Ne} \& ^{14}\text{N}$) important for detonation
  - Won’t change $Y_e$ and isotopic yield
  - BUT can significantly affect ZND length and likelihood of propagation
  - Future hydro simulations must take these into account

- Calculation also applicable to He core flash; see paper for more details

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.Ia Light Curves (courtesy of D. Kasen [UCSC])

- Radiative transfer of expanding $^{56}\text{Ni}$ and $^{56}\text{Ni}/^{28}\text{Si}$ balls
- $M_{\text{peak,B}} = -18$ to $-15$, $\Delta m_{15} = 3 – 4$

- Compare to SNe Ia, including subluminous ones, from Phillips et al. (2007):

Bright .Ia, 0.1 Msol of $^{56}\text{Ni}$

$M_{\text{peak,B}} = -17.5$, $\Delta m_{15} = 3$