White Dwarf Stars in Mass Transferring Binaries and their Outbursts

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Binary Evolution

- Wide: No interaction
- Common Envelope Ejection
- Increasing Orbital Period
- Secondary Mass
- Time

Post Common Envelope Binaries

- Merger to Supernova? or collapse?
- Stable mass transfer
- Recurrent surface H runaways
- Supernova?
- Stable hydrogen burning
- "Supersoft" X-ray sources
- Stable H mass transfer
- long interval surface H runaways
Binary Evolution

Merger to Supernova? or collapse?

Stable mass transfer

Supernova?

Stable hydrogen burning
"Supersoft" X−ray sources

Stable H mass transfer
long interval surface H runaways

WDMS
Stable mass transfer
Recurrent surface H runaways

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CV Angular Momentum Loss

\( \dot{J} \) determines evolution of compact binary

**Magnetic Braking**
- high \( \dot{J} \), \( P_{\text{orb}} \gtrsim 3 \text{ hours} \)
- Magnetically attached wind from companion star

\[
\dot{J}_{\text{mb}} = -9.4 \times 10^{38} \text{ erg} \left( \frac{M_2}{M_{\odot}} \right) \left( \frac{R_2}{R_{\odot}} \right)^3 \left( \frac{P_{\text{orb}}}{\text{hr}} \right)^{-3}
\]

**Gravitational Radiation**
- low \( \dot{J} \)

\[
\dot{J}_{\text{gr}} = -\frac{32GQ^2\omega^5}{5c^5} = -2.7 \times 10^{37} \text{ erg} \left( \frac{a}{R_{\odot}} \right)^4 \left( \frac{M_{\text{WD}}M_2}{M_tM_{\odot}} \right)^2 \left( \frac{P_{\text{orb}}}{\text{hr}} \right)^{-5}
\]
Interrupted Magnetic (Wind) Braking?

Evolved from prescriptions which reproduced the companion contraction necessary for the period gap.

Predicts a strong contrast in both $\langle M \rangle$ and evolution time – and therefore space density – of period bins.

Difficult to test due to CV variability and complexity of disks, but progress can be made by other means such as WD $T_{\text{eff}}$. (Townsley & Bildsten 2003, ApJ, 596, L227)

$M_{\text{WD}} = 0.7 M_{\odot}$, Howell, Nelson, & Rappaport 2001, ApJ 550, 897

Systems evolve from long to short orbital periods due to angular momentum losses causing the orbit to decay. Period gap caused by sudden drop in angular momentum loss rate.

$M_{\text{companion}} = 0.22 M_{\odot}$
Strong contrast in $M_{\text{ign}}$ at around few $\times 10^{-10} M_\odot$ yr$^{-1}$ created by change in ignition mode due to different $T_c$ as determined by $\langle \dot{M} \rangle$ (more on this later).

CVs generally are thought to have accretion rates that are low or high, but not much in between.

A system at a given mass can have a factor of 10 range in $M_{\text{ign}}$ depending on what evolutionary stage it is in.
Heat Sources

Temperature $T$ vs. log of pressure $P$ plot

- **Heat Sources**
  - **Accretion light**: only very near surface while actively accreting
  - **Compression**: throughout star, mostly in light-element layer (really gravitational potential energy)
  - **Nuclear “simmering”**: fusion near base of accreted layer (eventually becomes fast and triggers classical nova)
  - **Core heat capacity**

(very) leaky entropy advection

Heat liberated by compression is transferred out to surface and in to core. Often called “compressional heating”.
Quasi-static Profile

Local thermal time short compared to accretion

\[ t_{th} \equiv \frac{c_P T}{\left( \frac{4acT^4}{3\kappa y^2} \right)} < t_{acc} \equiv \frac{\Delta M}{\langle \dot{M} \rangle} \]

where \( y = \Delta M / 4\pi R^2 \) is the column depth.

Thermal state set by flux from deeper layers rather than from fluid element's history.

Heat equation near surface:

\[-\frac{dL}{dM_r} + \epsilon_N = T \left( \frac{\partial}{\partial t} + v_r \frac{\partial}{\partial r} \right) s = T \frac{\partial s}{\partial t} + T v_r \frac{\partial s}{\partial r} \]

where \( v_r = -\langle \dot{M} \rangle / 4\pi r^2 \rho \). Solve with structure equations. Gives excellent representation of envelope structure.

\[ L \simeq \frac{kTc}{\mu m_p} \langle \dot{M} \rangle \]

Energy release related to heat content of compressed material.
\( T_c \) and Classical Nova Ignition

Physical Conditions at base of H/He Envelope determine runaway

Evaluating envelope stability:

\[
\frac{\partial \epsilon_N}{\partial T} = \frac{\partial \epsilon_{\text{cool}}}{\partial T}
\]

- One-zone approximation, 
  \( \epsilon_{\text{cool}} \propto 4acT^4 / \kappa y^2 \), only works in upper portion.

- Lower part of curved better modeled by
  \( \epsilon_{\text{cool}} = L(T_c) / M_{\text{acc}} \), were \( L(T_c) \) is given by that of a cooling WD: radiative envelope overlying a conductive region.

- Thermal state \( (T_c) \) has an important influence on when the instability line is crossed.

- Composition has significant influence on position of upper portion.
Two Kinds of Ignition

\[ \langle \dot{M} \rangle = 3 \times 10^{-9} M_\odot \text{ yr}^{-1} \]

\[ T_c = 10^7 \]

Direct to \( p + C \) or \(^3\text{He} + ^3\text{He}\)

Most novae by number

\[ \langle \dot{M} \rangle = 5 \times 10^{-11} M_\odot \text{ yr}^{-1} \]

\[ T_c = 5 \times 10^7 \]

\( p + p \) (partial chain) envelope heating eventually leads to \( p + C \)

Large accumulated mass
Core will be **Reheated** until equilibrium is reached.
Core thermal time $\sim 10^8$ yr
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$$\langle L_{\text{core}} \rangle = \frac{1}{t_{\text{CN}}} \int_0^{t_{\text{CN}}} L_{\text{core}} \, dt$$
\[ \langle L_{\text{core}} \rangle \quad \text{and the equilibrium } T_{\text{core}} \]

\[
\langle L_{\text{core}} \rangle = \frac{1}{t_{\text{CN}}} \int_{0}^{t_{\text{CN}}} L_{\text{core}} \, dt
\]

When \( M_{\text{ej}} = M_{\text{ign}} \), \( \langle L_{\text{core}} \rangle = 0 \) defines an Equilibrium \( T_{\text{core}} \) which is set by \( M \) and \( \langle \dot{M} \rangle \).

Can approximate evolution:

\[
\langle L_{\text{core}} \rangle(T_{c}, \dot{M}) = C_{WD} \frac{dT_{c}}{dt}
\]

where \( C_{WD} \) is the total heat capacity of the WD – proportional to mass (have to be careful with latent heat at crystallization)
Phases of accretion

1. Magnetic Braking $\langle \dot{M} \rangle \sim 5 \times 10^{-9} M_\odot \text{ yr}^{-1}$
2. Period gap $\langle \dot{M} \rangle = 0$
3. Gravitational radiation $\langle \dot{M} \rangle \simeq 5 \times 10^{-11} M_\odot \text{ yr}^{-1}$
4. Post-period minimum $\langle \dot{M} \rangle < 10^{-11} M_\odot \text{ yr}^{-1}$

Phases of WD evolution

1. Reheating – $T_{\text{eff}}$ set by $\langle \dot{M} \rangle$
2. Equilibrium – $T_{\text{eff}}$ set by $\langle \dot{M} \rangle$
3. Cooling – $T_{\text{eff}}$ set by core cooling

Accretion resets the clock for WD cooling
**$T_c$ Evolution**


Full, multi-cycle nova simulations

$$M = 1.0 M_{\odot}, \langle \dot{M} \rangle = 10^{-11} M_{\odot}/yr$$

$$M = 0.65 M_{\odot}, \langle \dot{M} \rangle = 10^{-9} M_{\odot}/yr$$

Demonstrates equilibrium and evolution times. Unlikely to come fully into equilibrium above gap, but plenty of time below gap, especially with the “boost” from above-gap evolution.

Also demonstrates that nova WDs in CVs generally will not stay very hot ($\gtrsim 2 \times 10^7$) for more than a few 100 Myr. (Note being "caught" in this state would be exceedingly rare in any case due to post-CE cooling.)
Theory range shown: $0.6-1.0 M_\odot$

Factor of $\sim 10 \langle \dot{M} \rangle$ contrast across period gap confirmed

Current Mag. Braking prescription matches well with DN at 4-5 hours

Separate population of high $\langle \dot{M} \rangle$ at 3 hours?

Magnetic CVs above gap near Grav. Radiation prediction
– WD magnetic field preventing magnetic braking?!

Classical Nova $P_{\text{orb}}$ Distribution

Theory curve uses Interrupted Magnetic Braking for $P_{\text{orb}}\langle \dot{M} \rangle$ and population $n_P$


$$\nu_{\text{CNP}} = n_P \frac{\langle \dot{M} \rangle}{M_{\text{ign}}}$$

But since $n_P \propto M_2/\langle \dot{M} \rangle$ this gives

$$\nu_{\text{CNP}} \propto \frac{1}{M_{\text{ign}}}$$

Thus the dominant contribution is from the variation in the ignition mass across the period gap (2-3 hours)


- Supports a factor of $> 10$ drop in $\langle \dot{M} \rangle$ across gap
- Consistent with idea that CVs evolve across the gap
- Possible population of magnetic systems filling in gap
- Ignores selection effects – hard to quantify
Classical Nova $\langle \dot{M} \rangle$ Distribution

$\Phi(\langle \dot{M} \rangle)$

- Most observed Novae have “high” $\langle \dot{M} \rangle \sim 10^{-9} M_\odot \text{ yr}^{-1}$
- Similar amount of matter is ejected from Novae with $\langle \dot{M} \rangle \sim 10^{-9} M_\odot \text{ yr}^{-1}$ and $\sim 10^{-10} M_\odot \text{ yr}^{-1}$.
- Character of ignition very different for these two
  - direct Carbon or $^3$He trigger
  - $p$-$p$ heated deep envelope trigger
- Features of Novae which depend on $\langle \dot{M} \rangle$ are expected to have a bimodal character.
- The $P_{\text{orb}}$ distribution below 6 hours shows initial indications of this.
Luminosity Function of Old CVs

Low $\langle \dot{M} \rangle$ leads to infrequent disk outbursts
CV $V$ magnitude dominated by WD

Most old CVs appear as cooling WDs until inspected carefully

Color selection criteria for old CVs

CVs Mixed with WD population used to date cluster
Evolution of He Accretors (AM CVns)


WDs which accrete helium from a companion lower mass helium WD
\( \langle \dot{M} \rangle \) monotonically decreases with time as \( P_{\text{orb}} \) increases

Curves show 2 WD masses and 2 possible donor thermal states

Similar evolution: reheating, equilibrium (short!), WD cooling

Accretion disk phenomenology not well understood, two-state (DN) accretion expected with increasing time spent in quiescence

Both measured \( M_V \) agree well with theory!
Accreting WD Seismology

- Can greatly change character of mode spectrum
- Naturally gives sets of many closely spaced modes
- Surface eigenfunctions have distinctive shape (squeezed to equator) that can be confirmed by multi-band observations
- Can give modes at frequencies much higher and much lower than the driving frequency in the rest rest frame

Shown are the first ~ 20 modes from the same physical model of GW Lib. The horizontal line represents a moderate spin hypothesis, in which $\Omega \sim \omega$ for the low radial order modes. **Heavy blue** indicates a single mode triplet ($m = -1, 0, +1$). Plotted are frequencies in the observer’s frame $|\omega - m\Omega|$. Modes that "bounce" off of zero are modes travelling opposite to the rotational sense.
Summary

- Gaining understanding about the accreting WD binary population constrains the properties of outbursts

- Accreting WDs are reheated by “compressional heating” and Hydrogen “simmering”

- Equilibrium $T_{\text{core}}$ allows relation of observables to $M, \langle \dot{M} \rangle$

- Consistent with quiescent $T_{\text{eff}}$, indicating variation in $\langle \dot{M} \rangle$ across period gap

- Reproduces classical nova $P_{\text{orb}}$ distribution

- Evolution of broadband colors in quiescence

- Late time magnitudes and $T_{\text{eff}}$ for both CVs and Helium accretors

- Seismology can determine spin, $M, M_{\text{acc}}$