The Thermal State of Accreting White Dwarfs
and What It Tells Us About the Evolution of Compact Binaries

Dean Townsley

JINA, The University of Chicago

(Ph.D. work performed with Lars Bildsten, U.C. Santa Barbara)
Outline

Accreting WD Thermal State essential for:
- Testing Interrupted Magnetic Braking – $\langle \dot{M} \rangle (t)$
- Fully consistent classical nova ignition – $M_{\text{ign}}$
- Interpretation of spectral measurements – $T_{\text{eff}}$
- Late-time population properties – $M_V$
- Accreting WD Seismology – $M$, $M_{\text{acc}}$

Context: Cataclysmic Variables
- Quasi-Static Model of Accreting WD
  - The equilibrium $T_c$
  - Comparisons with Observations – $T_{\text{eff}}$, $M_{\text{ign}}$, CN rate
  - Seismology
Cataclysmic Variables

WD with low mass star companion in Roche lobe contact. Exhibit outbursts:

**Classical Nova** – Thermonuclear explosion on WD
    recur $\sim 10^4 - 10^6$ yr

**Dwarf Nova** – Accretion disk “high” state
    recur $\sim 0.1 - 10$ yr
Angular Momentum Loss

Evolution of tight binaries determined by loss of angular momentum: $\dot{j}$

**Magnetic Braking**

magnetically attached wind from companion star

- **long** $P_{\text{orb}}$, high $\dot{j}$
- **short** $P_{\text{orb}}$, low $\dot{j}$

**Gravitational Radiation**
Interrupted Magnetic (Wind) Braking?

Open Questions:
- Is Mag. Braking prescription right?
- Does this fit observed population?

We can test this!

\[ M_{WD} = 0.7M_\odot, \text{ Howell, Nelson, & Rappaport 2001, ApJ 550, 897} \]
Measurements of WD \( T_{\text{eff}} \Rightarrow \langle \dot{M} \rangle \)

UV measurements (HST, IUE) During DN quiescence
(e.g. Howell, Gänsicke, Szkody, & Sion 2002, ApJ, 575, 419)

Thermal emission sensitive to \( \dot{M} \) averaged over the thermal time of the radiative envelope \((\sim 1000\,\text{yr})\)

- Dwarf Nova Systems
- Magnetics

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CV WD Environment

Observed timescales in Dwarf Nova (Disk outburst):

Disk Outburst: lasts days-weeks
Between Outbursts: month-years
Envelope Thermal time: $10^3$ yr

Timescales in Classical Nova (Thermonuclear outburst):

Outburst: lasts $< 10$ years
Between Outbursts: $10^5 - 10^7$ years

Using $\langle \dot{M} \rangle$: The time averaged accretion rate
We have calculated

$$M, \langle \dot{M} \rangle \rightarrow T_{\text{eff}}, M_{\text{ign}}$$

which connects the WD evolution to that of the binary.
Gravitational Energy Release

Heat liberated by compression

transferred out to surface
in to core
“compressional heating”
Quasi-static Model

Heat Equation:

\[ T \frac{Ds}{Dt} = T \frac{\partial s}{\partial t} + T v_r \frac{\partial s}{\partial r} = - \frac{dL}{dM_r} + \epsilon_N \]

\[ v_r = -\langle \dot{M} \rangle / 4\pi r^2 \rho \]
Envelope Dominates

\[ \frac{\dot{M}}{4\pi r^2 \rho} T \frac{\partial s}{\partial r} = \frac{dL}{dM_r} + \epsilon_N \]

Without \( \epsilon_N \), \( dr = g\rho dP \)

\[ L = -\langle \dot{M} \rangle \int_0^P T \frac{\partial s}{\partial P} dP \]

Simple integration to \( M_{\text{acc}} \sim 10^{-3} M_\odot \)

\[ L_{\text{H/He}} \approx 2.5 \frac{kT_c}{\mu m_p} \langle \dot{M} \rangle \quad L_{\text{C/O}} \approx 16 \frac{kT_c}{\mu_i m_p} \langle \dot{M} \rangle \]

\( \mu = \) mean molecular weight

with \( \mu \approx 0.6 \) and \( \mu_i \approx 14 \)

\[ \frac{L_{\text{H/He}}}{L_{\text{C/O}}} \approx 4 \]
dependence on $T_c$

Increasing $M_{\text{acc}}$

$M=0.6 \, M_\odot$

Cooling WD

Increasing $M_{\text{acc}}$

$M_{\text{acc}} = 10^{-10}$

$M_{\text{acc}} = 10^{-10.4}$

$M_{\text{acc}}/\text{yr}$

$L/L_\odot$

$T_c (K)$

$10^{-4}$

$10^{-3}$

$10^{-2}$

$10^{-1}$

$4 \times 10^6$

$10^7$

$4 \times 10^7$
Core will be **Reheated** until equilibrium is reached.

Core thermal time $\sim 10^8$ yr
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\[
\langle L_{\text{core}} \rangle = \frac{1}{t_{\text{CN}}} \int_{0}^{t_{\text{CN}}} L_{\text{core}} \, dt
\]
\[ \langle L_{\text{core}} \rangle \text{ and the equilibrium } T_c \]

\[ \langle L_{\text{core}} \rangle = \frac{1}{t_{CN}} \int_0^{t_{CN}} L_{\text{core}} \, dt \]

When \( M_{ej} = M_{\text{ign}} \),
\[ \langle L_{\text{core}} \rangle = 0 \] defines an

Equilibrium \( T_c \)

which is set by \( M \) and \( \langle M \rangle \)
Equilibrium $T_c \rightarrow M_{\text{ign}}, T_{\text{eff}}$

$X_3 = \text{mass fraction of } ^3\text{He in accreted material}$
$T_{\text{eff}}$ vs. $P_{\text{orb}}$

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?!


○ Dwarf Nova Systems
○ Magnetics

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$T_{\text{eff}}$ vs. $P_{\text{orb}}$ Below Gap

Graph showing $T_{\text{eff}}$ vs. $P_{\text{orb}}$

\[ \dot{\mathcal{J}} \text{ from GW,} \]

Filled points,

\[ M = \begin{cases} 
0.9 \pm 0.15 M_{\odot} \\
0.82 \pm 0.05 M_{\odot}
\end{cases} \]

\[ M \text{ average of 0.76} \]
expected from selection,
Dünhuber & Ritter 1993

$M$ is surprisingly consistent
Likely $\langle \dot{M} \rangle > \langle \dot{M} \rangle_{GW}$, but only by small amount
Magnetics appear to have slightly lower $\langle \dot{M} \rangle$
Theoretical $P_{\text{min}}$ well-known outstanding problem
Self Consistent $M_{\text{ign}}$

Data points are $M_e$ for systems with $P_{\text{orb}}$ also measured, various sources.

Lines are our $M_{\text{ign}}$ with $\langle \dot{M} \rangle$ from magnetic braking (3-6 hours) and grav. rad. (< 2 hours)

Consistent with $M_e = M_{\text{ign}}$, but not conclusive
Classical Nova $P_{\text{orb}}$ Distribution

**Theory curve** uses Interrupted Magnetic Braking for

$$P_{\text{orb}} \rightarrow \langle \dot{M} \rangle$$

and population $n_P$


Our $M_{\text{ign}}$ is used to calculate classical nova rate assuming average $\dot{M} = 1.0 M_\odot$

- Again 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
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.
\[ M = 0.6 M_\odot, \]

\[ \dot{J}_{\text{binary}} \text{ from grav. waves} \]

\[ \Rightarrow \langle \dot{M} \rangle(t) \]


Transition from main sequence broadband fluxes to those of a WD.

Companion Mag. from

(Brocato, Cassisi, & Castellani 1998, MNRAS, 295, 711);

WD Mag. from

Proper-motion selected members of M4 at 4 core radii

Color selection criteria for old CVs

CVs Mixed with WD population used to date cluster
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

Townsley - MSU 2004 – p.22/30
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!
Distance broadly constrains $M$, $T_{\text{eff}}$ relates $\langle \dot{M} \rangle$ and $M_{\text{acc}}$

Only three modes observed, not well characterized

Fitting three modes finds weakly favored solution at $M = 1.02M_\odot$, $M_{\text{acc}} = 0.31 \times 10^{-4}M_\odot = 0.23M_{\text{ign}}$

Need more, better characterized modes to constrain rotation
Summary

- Accreting WDs are reheated by “compressional heating” and Hydrogen “simmering”
- Equilibrium $T_c$ allows relation of observables to $M, \langle \dot{M} \rangle$
- Find good agreement between Interrupted Magnetic Braking and observations
  - Quiescent Dwarf Nova $T_{\text{eff}}$
  - Reproduces classical nova period distribution
  - Both support a factor of 10 or more drop in $\langle \dot{M} \rangle$ across gap
  - Comparison implies $M_{\text{ej}} \approx M_{\text{ign}}$
- Predict evolution of broadband colors in quiescence, important for surveys such as SDSS
- Predict late time magnitudes for both CVs and AM CVns
- Seismology can determine $M, M_{\text{acc}}$, need better data
Accreting WD Envelope

Envelope thermal time

\[ \sim 10^3 \text{ yr} \]

Infall energy deposited near surface and quickly radiated away

Interested in energy deposited deep in the envelope
Accreting WD Envelope

\[ L_{\text{env}} \sim g h \langle \dot{M} \rangle \]
\[ \sim \langle \dot{M} \rangle \frac{k T_c}{\mu m_p} \]

So actually:

\[ T_{\text{eff}}(M, \langle \dot{M} \rangle, M_{\text{acc}}, T_c) \]

\[ M_{\text{ign}}(M, \langle \dot{M} \rangle, T_c) \]
NGC 6397

NGC 6397 Predicted CV Color Evolution

0.6 $M_\odot$ WD  No accretion disk included

Proper-motion selected members of NGC 6397
and Non-Flickerers
$T_c$ and Classical Nova Ignition

Conditions at base of H/He:

Evaluating envelope stability:

\[
\frac{\partial \varepsilon_N}{\partial T} = \frac{\partial \varepsilon_{\text{cool}}}{\partial T}
\]

What thermal state ($T_c$) corresponds a given $\langle \dot{M} \rangle$?