Problems with Line Broadening and Opacities in White Dwarf Stars

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What Are White Dwarf Stars?

• *Endpoint* of evolution for most stars, 98% of all stars, including our sun
• *Homogeneous* in mass and surface composition: essentially *monoelemental* photospheres
• *Uncomplicated* in structure and composition; evolution is just cooling

They Shed Their Complexity→ Cosmic Laboratories
Mono-elemental surface layers

Three White Dwarf Flavors
Why are they interesting?

• Representative (and personal)
  – Archeological history of star formation in our galaxy
    => White Dwarf *Cosmochronology*: from ages of coolest white dwarf stars

• A way to find Solar Systems dynamically like ours

• Exploration of Extreme physics in interiors possible through Asteroseismology
  – Matter at extreme densities and temperatures gives us a chance to study important and exotic physical processes:
    • plasmon neutrinos test electro-weak theory at low-energies
    • turbulent energy transport in high gravity environments
    • dark matter in the form of axions and/or WIMPS
    • study EoS for hot dense matter and the physics of crystallization of a dense Coulomb plasma ...
The observed space density of white dwarfs (points), with the theoretical white dwarf luminosity function (WDLF) as a function of intrinsic luminosity. The curves are theoretical models assuming a given age for star formation in our Galaxy.
Cosmochronology

• Constrain Age of Universe

• *Measure* Age and History of the Components of the Galaxy
  – Thin disk
  – Open clusters
  – Thick disk
  – Halo
  – Globular clusters
White Dwarfs "freeze" as they cool... and release latent heat.

These and other animations can be found at:
http://rocky.as.utexas.edu/~mikemon/FRI/ast2.html
Conclusions from NGC 6397 and M4

- Confirm that crystallization occurs in WDs
- Confirm that Debye cooling occurs in WDs
- We can measure the Gamma of crystallization
- Low metallicity clusters may not produce significant O in cores of some of the 0.5Msun stars (unlikely) … or the C/O mixture has
  \[ T_{\text{xtal}} = \frac{E_{\text{coul}}}{kT} = 230 - 260 \]
- We found the first empirical evidence that Van Horn’s 1968 prediction is correct:
  Crystallization is a first order phase transition!
Current techniques for studying white dwarf stars:

Precision Asteroseismology

Photometry

The Key: Spectroscopy

=> Mass and Temperature
Spectral Fits Give Unreliable Masses for SDSS sample of 3358 DAs and DBs

Mean DA Mass from Gravitational Redshift
=> this isn't physical
Mean DA Mass From GR

• For a sample of 449 non-binary thin disk normal DA WDs, Falcon et al. find

\[ \langle M \rangle = 0.647 \, M_\odot \]

  – Significantly higher than previous spectroscopic determinations except that of Tremblay & Bergeron (2009), which used improved Stark broadening calculations

• Unlike spectroscopic surveys, do not find significant change in mean mass across \( T_{\text{eff}} \) split at 12000 K:

\[ \Delta M = 0.046 \, M_\odot \]
- (from Falcon et al. 2010a) Distributions of spectroscopic masses (histograms) gives significantly different mean values (orange, black, green vertical lines; \(\sim 0.57M_\odot\)) than that derived from gravitational redshift (blue, vertical line; \(\sim 0.65M_\odot\)).

The situation is much worse, as we pointed out for line profiles in the DB (Helium) WDs and the DQ (C/O) WDs (Dufour et al. 2009; Kowalski 2010). Here there are no gravitational redshift results to-date to
From Tremblay & Bergeron 2009: Theoretical hydrogen line profiles as a function of distance from the line center, $\Delta \lambda$. The plasma conditions assumed are $T = 10,000 \text{ K}$ and $n_e = 10^{17} \text{ cm}^{-3}$. The recent calculations of Tremblay & Bergeron are shown as the solid (red) lines and the previous Vidal-Cooper-Smith (VCS) calculations are shown as the dashed (black) lines.
The H white dwarfs (Koester et al.)

He WDs have the same problem, just higher $T_{\text{eff}}$.
Carbon WDs are worse!
The 26 million Ampere current on Z provides access to new laboratory astrophysics regimes.

Z experiments use large magnetic fields or large x-ray flux to create extreme environments.
Experiments on Z access a large region of the energy density phase-space

High Energy Density Regime

\[ \varepsilon > 10^{11} \text{ J/m}^3 = 1 \text{ Mbar} \]
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ZAPP

**Z Astrophysical Plasma Properties (ZAPP):**

Experiment Purpose: Advance knowledge of four astrophysical plasmas: stellar interior opacities, spectral line broadening in White Dwarf photospheres, AGN warm absorbers, and plasmas surrounding accretion powered objects

**Four Experiments carried out simultaneously on each shot:**

1) Develop stellar interior opacity measurements (w/ Ohio State, LLNL, CEA, LANL)
2) Measure photo-ionized plasma kinetics (w/ U. Nevada, LLNL, and Swarthmore)
3) Measure spectral line profiles for White Dwarf atmospheres (w/ U. Texas, Weizmann Institute, & UCLA)
4) Measure self emission to examine Resonant Auger Destruction in black hole accretion disk plasmas (w/ LLNL, U. Nevada, Swarthmore)
Primary Near Term Science Goal of White Dwarf Photosphere Project:

• Measure relative line shapes for Hβ, Hγ, and Hδ at white dwarf photospheric/atmospheric conditions

Approach:

• Radiatively heat gas cells to conditions of
  \( T_e = 11,400 \text{ K} \sim 1\text{eV} \)
  \( n = 10^{16}-10^{19} \text{ atoms/cc} \)
Measuring Hydrogen line-shapes

Relevant Diagnostics

• Streaked Visible Spectrometer
  • 2.3 – 3.0 eV

Fielded by UT students Ross Falcon, Thomas Gomez and Jennifer Ellis.

H Gas Cell

<table>
<thead>
<tr>
<th>Time</th>
<th>Wavelength</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>H$\gamma$</td>
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<tr>
<td></td>
<td>H$\beta$</td>
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H Gas Cell

Hβ Line Shape
Shot z2084 H-beta line profile averaged over 10 ns centered about a time 80 ns after the peak of the z-pinch

- Shot z2084
- Wiese et al., 1972 ($n_e = 8.3\times10^{16}$ cm$^{-3}$, $T_e = 1.15$ eV)
$\lambda_0 = 4860.966 \, \text{Å}$
$n_e = 5.76e+16$
$n_H = 1.55e+17$
$T = 13526.2 \, \text{K}$
$\text{cont} = 0.00518$
Measuring Line Profiles at White Dwarf Photospheric Conditions => Accurate Masses
May 2010

- Acquired data in emission and absorption
- Great signal in absorption; MCP gain at 125 V less
Measuring plasma conditions using the 50 Angstroms around the line center
of a 200 ns integration from streaked data that clearly shows H\(\beta\)
August 2011: A Spectrum from a White Dwarf Plasma in the Lab
Lab WD plasma vs Observed WD
3.5 cm plasma path length
6.5 cm plasma path length
Cool DQ White dwarfs
This Dynamic Field

- White Dwarf photospheric plasmas in the lab in absorption and emission
- Multiple new competing theories for line shapes—significant disagreements for H!
- Within 2-3 years test to see which, if any, is most accurate or best with dual purposes:
  - Improve astrophysics--small changes have large effects!
  - Improve line-broadening theory
- Use new discoveries to advance the field…
Mono-elemental surface layers

Three White Dwarf Flavors
The Opportunity of Newly Discovered Extremely Low Mass (ELM) White Dwarf Stars

- New binaries
- Eclipsing binaries
- Gravities more than 10 times lower than normal mass white dwarf stars: gives a significant dynamic range in masses
- Boundary conditions for comparing with stellar evolution codes
- Accurate comparison points for lab measurements at low electron densities
- A chance to study core He EoS, role of residual time-dependent nuclear burning
JJ Hermes’ new ELM Pulsator: ELMV1
The Pulsational H-R Diagram

$\log g \approx 8$

$\log T_{\text{eff}}$

$\log g \approx 4.2-4.4$

$\log g \approx 5-6$

$\log g \approx 5.0 - 4.0$

$\log (L/L_\odot)$

$20M_\odot$

$\beta$ Cep

Cepheid

GW Vir

SPB

$4M_\odot$

$\delta$ Scuti

$\gamma$ Dor

Solar-like

$1M_\odot$

DQV

DBV

DAV
The White Dwarfs are orbiting around each other at a very rapid speed - 1,315 km/s

The orbit should be shrinking rapidly so the WDs should come in contact due to loss of energy through gravitational wave radiation.

We expect this to happen in less than 1 million years.

In 1-2 years we can measure this change at the McDonald Observatory.

The change in orbital period, coupled with direct gravity wave measurements will provide a fundamental test of Einstein’s General Relativity. This object should have a high signal to noise and be easily detected with LISA or ELISA.

From: A 12 Minute Orbital Period Detached Eclipsing Binary (Brown, Mukremin, Hermes, Winget et al., 2011)
Q: How do we improve our understanding of white dwarf photospheres?
A: By going from telescope to laboratory and back again...

- Spectra give unphysical masses
- Measurements of lines at White Dwarf photospheric conditions
- Accurate Observed Masses

**Cosmochronology**
- Age of universe
- Age and history of the galaxy

**Asteroseismology**
- Dark Matter & Dark Energy
- SniA Progenitors: DE
- EoS of C/O/He
- Crystallization of Dense Coulomb Plasmas
Video from Aug 19 shot on Z
Z
A painting by Leah Flippen
Dedicated to the memory of two mentors and friends:
Carl J. Hansen and Francois Wesemael

Thanks!