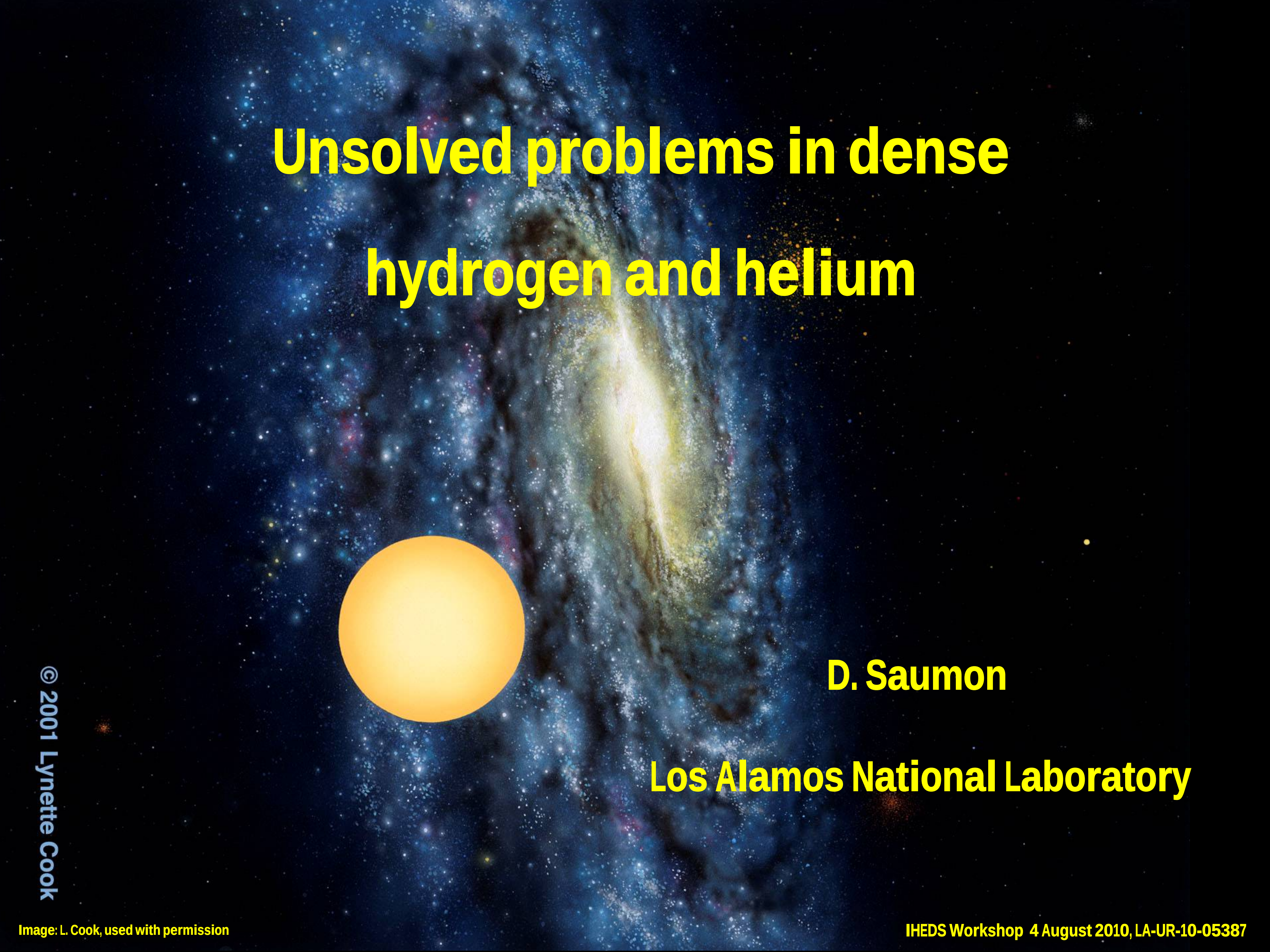
Unsolved problems in dense hydrogen and helium



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Very cool white dwarfs and their atmospheres

Three opacity problems:

- **Collision-induced absorption by H_2**
- **What is the opacity of cool, dense He?**
- **C_2 Swan bands in dense He**

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Very Cool White Dwarfs (T_{eff} < 6000K)

White dwarfs

The end stage of the evolution of ~95% of all stars: dead stars

Mass ~ 0.5 mass of Sun
Radius ~ radius of Earth!
Very high surface gravity ~ 10^8 cm/s^2 (= 10000g!)

No internal source of energy. Evolution primarily a cooling problem as the star radiates its internal heat to space

- **A young WD starts with $T_{surf} \sim 10^5$ K**
- **The oldest WD known have T_{surf} ~ 4000K**

See presentation by Don Winget at 3:30PM

Very Cool White Dwarfs (T_{eff} < 6000K)

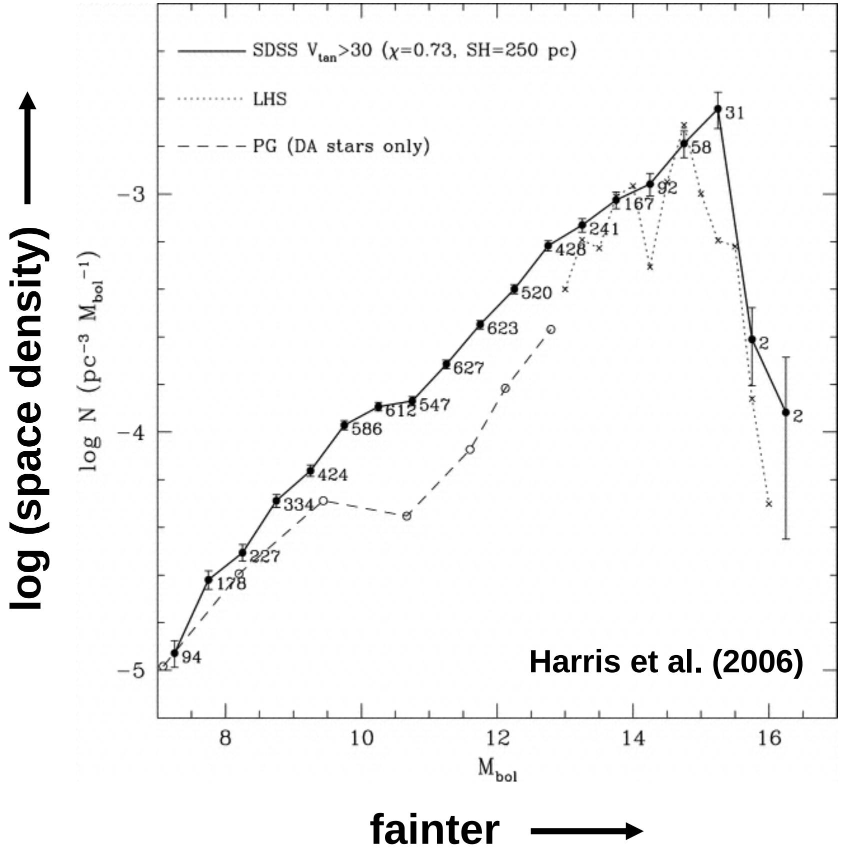
Well-defined drop in the space density of WDs at low luminosity
→ finite age of the population (~9Gyr)

A method for dating stellar populations: WD cosmochronology

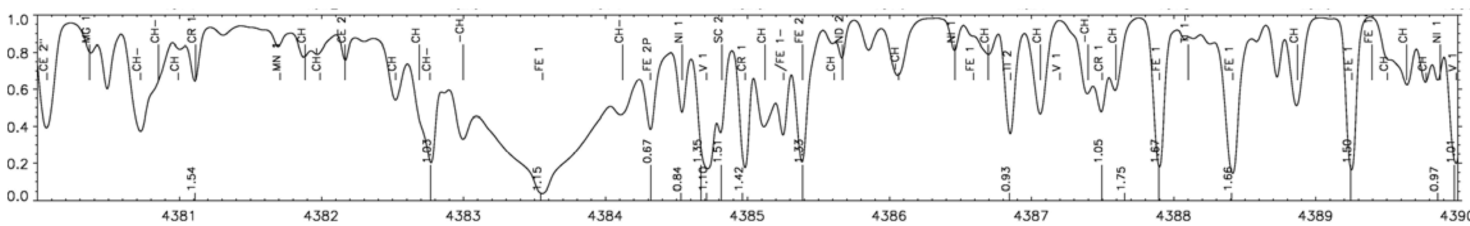
The age determination hinges on the properties of the coolest known WDs.

What are their T_{eff}, gravity and surface composition?

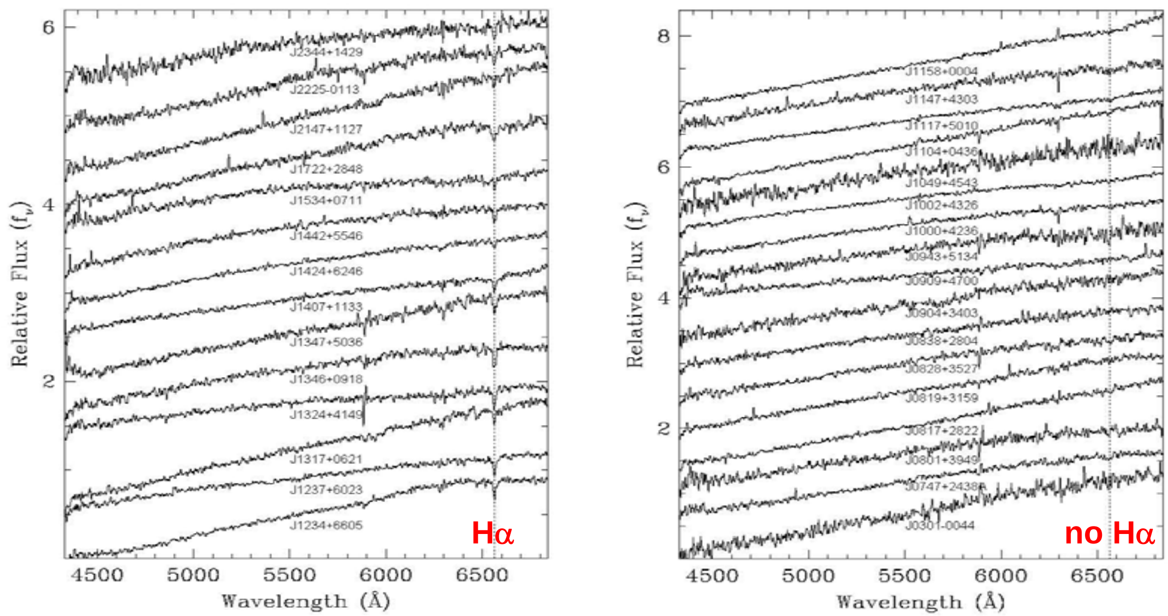
Based on fitting spectra with models



Analysis of stellar spectra



The Sun's spectrum is very rich in information



Very cool WD spectra are featureless:
For T_{eff} < 12000K (He atmospheres) or 5000K (H)
Analysis relies on continuum opacities only

Figure from Kilic et al. (2010)

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Physical conditions in very cool WD atmospheres

"Atmosphere" of a star:

The observable "surface" layer where the spectrum is formed and light escapes to space

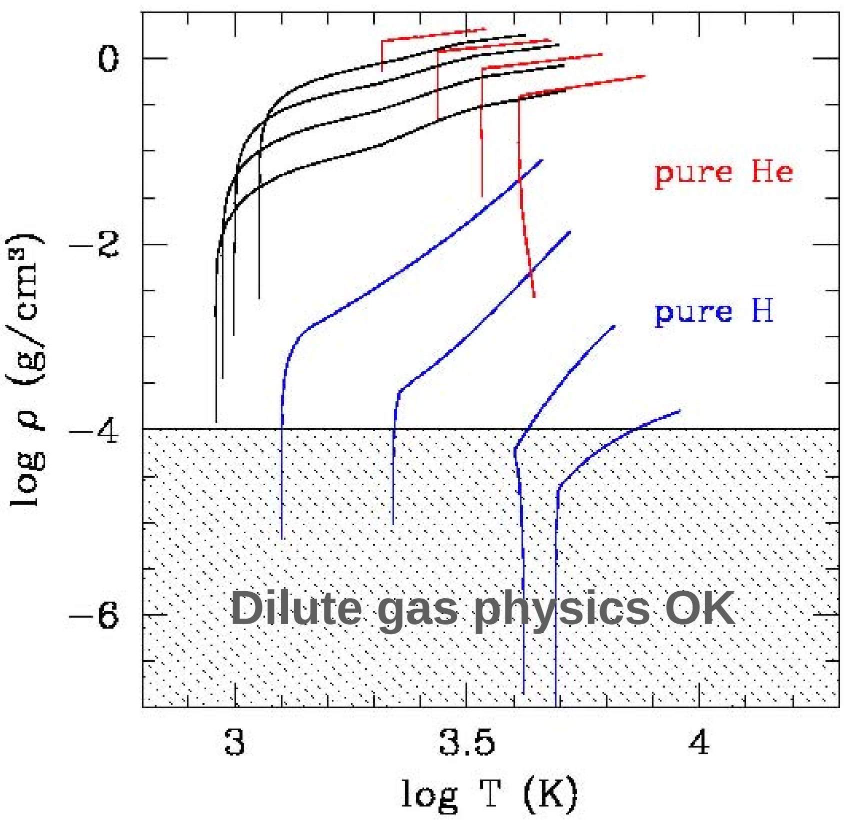
Main physical parameters:

Effective Temperature, T_{eff}
Surface gravity, log g (cm/s^2)
Composition: H, He, traces of C, Ca, Mg…

Physical conditions (high gravity!):

Pure H: $T \sim 10^3 - 10^4$ K
$\rho < 0.01\ g/cm^3$
Pure He: $T \sim 1000 - 5000$K
$\rho < 1 g/cm^3$ (~Mbar!)

T_{eff}= 3000 (1000) 6000K log g=8



EOS well understood but opacities are not!

Very cool white dwarfs and their atmospheres

Three opacity problems:

- **Collision-induced absorption by H_2**
- **Collision broadening of Lyman α of H**
- **What is the opacity of cool, dense He?**

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Collision-induced absorption (CIA) by H_2

H_2 molecule

no permanent dipole moment → radiative dipole transitions are forbidden

However

during a collision (with H_2, H, He, etc), a temporary dipole is induced.
dipole transition is possible→ Collision-induced absorption

$$\alpha(\nu,\rho,T) = \underbrace{a_1(\nu,T)}_{=0\text{ (dipole)}} + \underbrace{a_2(\nu,T)\rho}_{\text{2-body collisions}} + \underbrace{a_3(\nu,T)\rho^2}_{\text{3-body collisions}} + \dots$$

H_2 CIA present in WD atmospheres for T_{eff} <~ 5500K

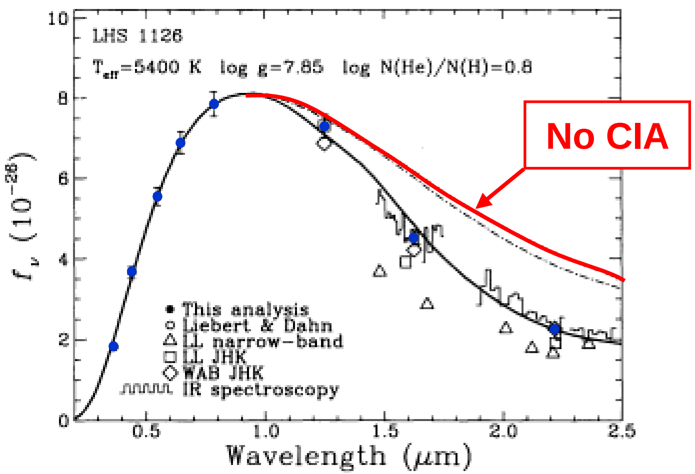

Figure from Bergeron et al (1994)

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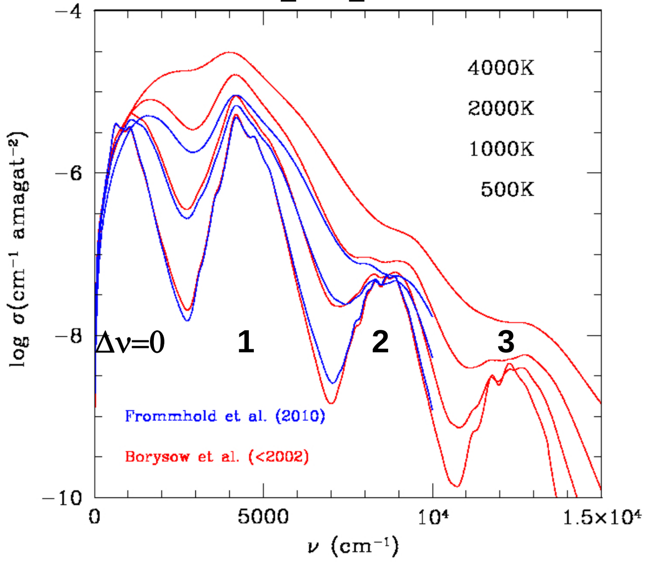
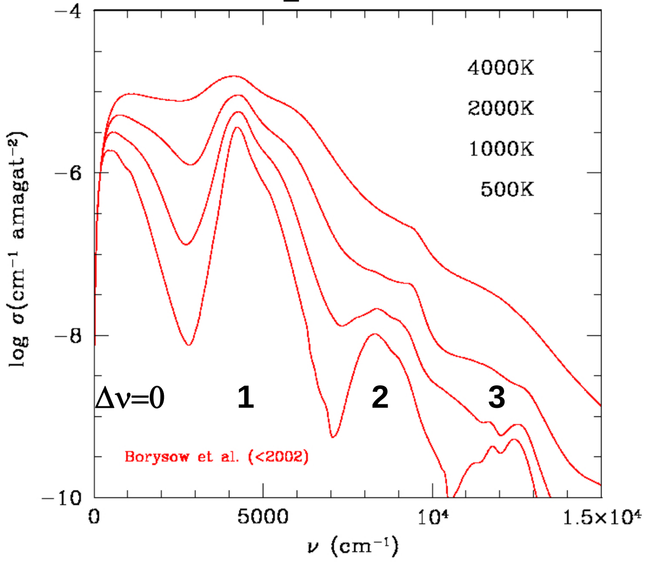
Collision-induced absorption (CIA) by H_2

H_2-H_2 CIA



H_2-He CIA



Available data

H_2-H_2: T=12 - 300K, up to 5 kbar, Δν=0, 1, 2

H_2-He: T= 77 - 300K, up to 6.7 kbar, Δν=0, 1

3- and 4-body virial spectral coefficients (Δν=0 only): T=300K up to 6.7kbar

Diamond Anvil Cell: H_2 5-9 GPa 300-400K Δν=1 only (liquid & solid)

Shock tube: H_2-Ar, H_2-Ne, H_2-Xe, ~150 bar T<3500K Δν=1 only

Collision-induced absorption (CIA) by H_2

First principles calculations of H_2-H_2 and H_2-He CIA

Up to 7000K, Δv=0, 1, 2, 3 (2-body collisions only), to various degrees of approximation/accuracy

Very elaborate (and more uncertain) at high T and high ν

Spectral *moments*: good agreement with 3-body virial coefficient for H_2-H_2 and H_2-He (T<300K)

No spectrum calculation for 3-body interaction

Agreement with data is excellent (T<300K)

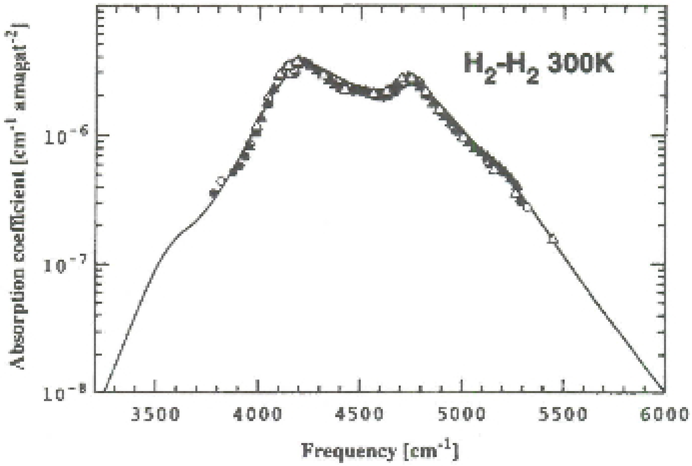


Figure from Borysow (1991)

A major puzzle: What are these?

~15 stars like LHS 3250 ("ultracool white dwarfs")

- **Apparently among the coolest WDs known**
- **Cannot be fit by any model so far!**
- **Strong suspicion of mixed H/He composition**
- **T_{eff}, g, composition, significance?**

Inadequate H_2-He CIA strongly suspected

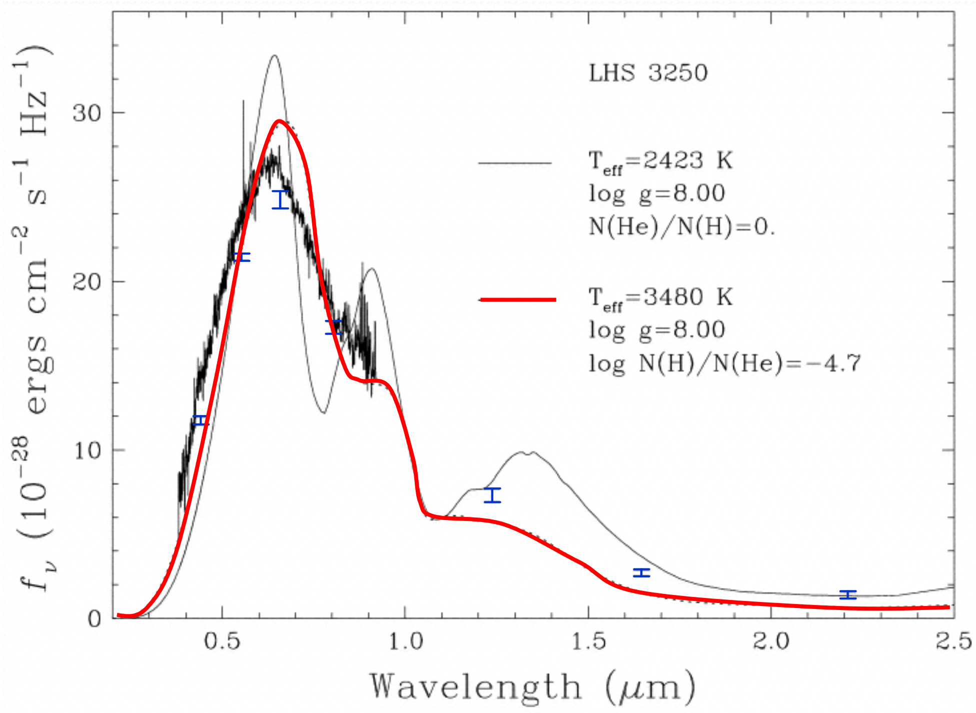


Figure from Bergeron & Leggett (2002)

Testing CIA calculations in the lab?

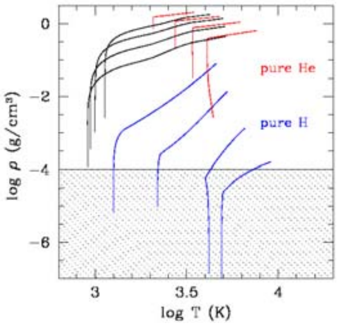
Calculations are untested above 300K and of limited reliability for $\Delta\nu \geq 2$

A recent, state-of-the-art calculation of H_2-H_2 CIA (Frommhold et al.):

- **Excellent agreement with previous calculation for T<1000K**
- **Factors of 2 change for T=2000K**

CIA measurements under cool WD conditions sorely needed!

Observe emission in shock experiments (gas gun?)



H_2-H_2	1000-5000K	0.1-5kbar	0.5-10μm
H_2-He	1000-5000K	0.1-30GPa	0.5-10μm
He-He-He?	2000-5000K	10-100GPa	0.5-10μm?

Challenges:

- **Making accurate measurements and diagnostics**
- **Separating other sources of opacity (H_2-H CIA, H^- bf+ff, H_3^+ bf), H_2 dissociation**
- **Absorption length**

$$L = \frac{10^{-5} \text{ to } 10^{-2}}{\rho^2 \ (\text{g/cm}^3)} \ \text{mm}$$

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Pure He WD atmospheres at T_{eff} < 6000K

The X-games of stellar atmospheres:

$T < 7000K$ ρ up to $1 g/cm^3$ P up to ~100GPa An ocean of helium!

No other element detected (log Ca/He < –12 log H/He < –5)

The high pressure is a consequence of the low opacity of He

No molecules, no optical/IR lines, ~ no free electrons I_p=24.6eV

Absorption mechanisms: Rayleigh scattering

He^- ff (inverse bremsstrahlung)

He-He-He CIA? He_2^+? HeH^+?

What is the opacity of cool, dense He?

Very few measurements. Calculations are very hard.

A theoretical look at He^- ff opacity

Basic difficulty

I_p=24.6 eV T~ 0.5 eV → $e^{-Ip/kT}$ ~ 10^{-22} VERY low ionization with high T-sensitivity

Dilute gas physics (ionization equilibrium, opacities): No longer valid

Approach as a problem of condensed (liquid) matter: ab initio methods

Calculate the direct band gap $E_{gap}(\rho,T)$ with QMD-DFT (GGA)

Calculate the electronic conductivity (Kubo-Greenwood approximation)

Derive the opacity from conductivity (Kramers-Kronig relations)

Difficulty

We're trying to estimate the conductivity of a very good insulator

QMD-DFT methods notorious for underestimating band gap

Conductivity ~ $e^{-Egap/2kT}$ is very sensitive to E_{gap}!

Band gap corrections: GW method, hybrid functional 3-6 eV!

Resulting uncertainty on σ_{DC} ~ factor of 30 at T=0.5eV!

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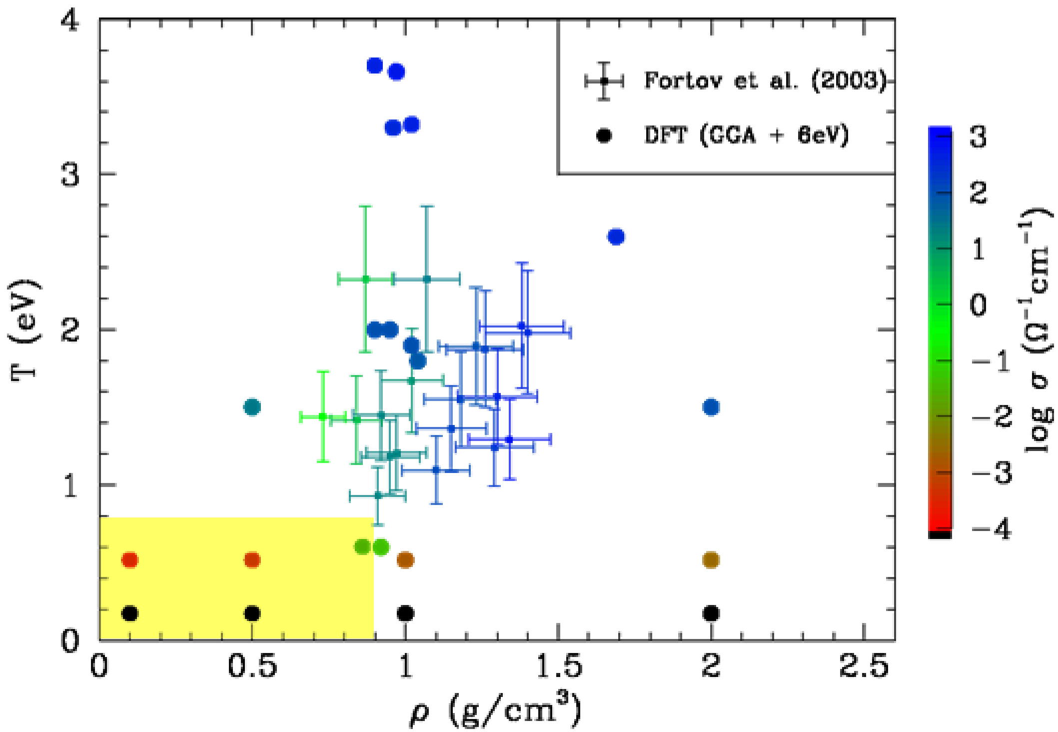
Ab initio conductivity meets experiments



Strong disagreement!

Calculation: little ρ dependence, rapid increase with T. Gap closes at ~13g/cm^3

Data: strong density dependence, gap closes at < 2g/cm^3.

No data in regime of interest to cool He atmospheres

Figure from Kowalski et al. (2006)

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Measuring the opacity of cool, dense He

The best calculation of the opacity of cool, dense He remain very uncertain.

The only data near the relevant regime (σ_{DC}) do not look right.

Good measurements will be very helpful

- Optical and near infrared absorption of He in the 0.1 -1 Mbar range, T~0.5 eV
- Sampling a range of (T,P) points will help identify the absorption mechanisms as well as effectively test models
- Impurities (H, Ca, Mg, Si) in homeopathic dilutions would mimic a more realistic composition

Challenge

- The absorption coefficient is very low
- May be difficult to isolate the various absorption mechanisms

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Very cool white dwarfs and their atmospheres

Three opacity problems:

Collision-induced absorption by H_2

What is the opacity of cool, dense He?

C_2 Swan bands in dense He

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Carbon in very cool WDs

Some WDs with He-rich atmospheres show carbon in their spectra: Swan bands of C_2 ("DQ" white dwarfs).

log C/He= -7 to -3

Carbon is dredged up from the core by convection/diffusion

25 year old puzzle:

Below T_{eff}~6000K, the bands are shifted to the blue by ~700cm^{-1} ("DQ peculiar" white dwarfs, <10 known)

Most likely explanation(s):

- **Pressure-shifted C_2 bands? But P may not be higher than in normal DQ.**
- **Magnetic field? But only 1 DQp is known to be magnetic (B~100 MGauss)**
- **Both?**

Swan bands
$a^3\Pi_u \rightarrow d^3\Pi_u$

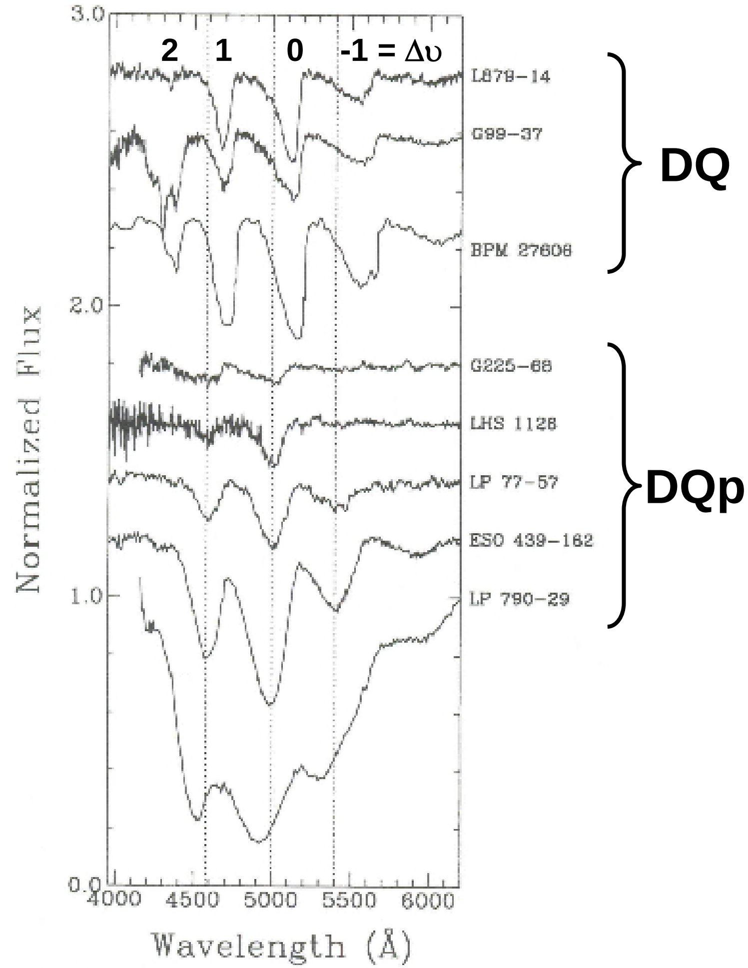

Figure from Schmidt, Bergeron & Fegley (1995)

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Spectroscopy of C_2 Swan system at high-P

There is no lab measurement of pressure-shifts of the C_2 Swan bands

How much pressure is needed to shift the bands by 700cm^{-1}?

Desired measurement

Optical spectroscopy of C+He mixture

430-600nm   T = 4000-7000K   P ~ 0.1-10 GPa

With a magnetic field (B > 0.1MG)?

Challenge:

Can a C+He mixture be done?

C+H can be done fairly easily but could introduce absorption by various CH compounds

Summary

Very cool WDs present many interesting problems in dense fluid physics

Opacities are particularly challenging (theory and experiments)

Limited knowledge casts significant uncertainty on the inferred properties of several types of very cool white dwarfs

Three pressing problems in need of data

- Collision-induced absorption of H_2 and H_2+He mixtures at high T and P
- Pure (or nearly pure) opacity of cool, dense He
- Effect of pressure (and magnetic fields) on the Swan band system of C_2