Class Y - The Coolest Brown Dwarfs

CFBDS J005910.90 - T9/Y0 - first class Y, 30 light-years distance, Temp 620K, Mass 15-30 M_Jup

WISE 0855−0714 – Y2 - coolest at Temp ~ 250K, 7.3 light-years distance, Mass 3-10 M_Jup
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Why are all brown dwarf stars about the same size, even if the mass ranges from 10-500 M_Jup?
Stellar evolution so far

Different energy sources during different stages in the star's evolution

Protostar phase (KH contraction)

MS phase H->He

RGB phase (shell H->He)

And remember: more massive stars evolve faster during all stages
What is this Plot Showing?
M5 (NGC 5904) globular cluster
Announcements

• Today – More low mass stellar evolution
• Thursday – High mass stellar evolution and HW#4 is due
• Tuesday Feb 25 – Review
• Thursday Feb 27 – Exam#1
Intrinsic variability

- Those that vary in brightness as a result of conditions within the star itself.
- Found in the *instability strip*. Any star within these portions of the H-R diagram will become unstable to pulsations.
- The different regions produce different kinds of observed phenomena.
- Stars may go through these stages several times during their lives.
Cause of pulsations

• Stars are variable because they are unstable in one way or another: they lack hydrostatic equilibrium beneath surface.

• Miras are not well understood, but other, more periodically varying stars are better understood, like the Cepheids:

• The ionization zone of He lies at a distance from the center of the star, close to the surface.

• When He gas is ionized, it is opaque to radiation, thus effectively absorbing photons, trapping the heat.

• Radiation will push the surface layer outward, and cooling will begin.

• As the gas cools, it will recombine. Neutral He is transparent, ceasing the outward push and layers fall back as a result of gravity.

• Heating of those layers causes the process to repeat.
How to study variable stars

We use lightcurves, which show the brightness versus time for the star.

We can also look at the periodic change of other properties, such as the radial velocity, surface temperature, and size.
At max brightness, the star expands most rapidly. As it cools, the outer layers will start falling back onto the stars. The surface temperature will vary with the brightness. The star reaches its minimum size before maximum brightness, since it will take a little time to transport the radiation to the surface. A time lag.
Distance indicators

- Variable stars like Cepheids, and RR Lyrae stars can be used as distance indicators. How?
- They exhibit a relation between their period and their luminosity.
  => if we can measure the period of the star, then we know its luminosity (or absolute magnitude).

The period-luminosity (P/L) relationship for Cepheids

Type I and II Cepheids behave differently because they have different abundances of heavy elements in their atmospheres, affecting the opacity.
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The period-luminosity (P/L) relationship for Cepheids

Type I and II Cepheids behave differently because they have different abundances of heavy elements in their atmospheres, affecting the opacity.
• The P/L relationship for RR Lyrae stars is trivial: all have $M=+0.5$.

• For Cepheids, the relation is fitted by:

$$M_{<V>} = -2.81 \log_{10} P_d - 1.43$$

![Graph showing the period-luminosity relation for Cepheids.](image)

**Fig. 1.**—The composite period-luminosity relation at mean intensity in $B$ and $V$ wavelengths derived from the sources indicated at the lower right. The absolute calibration was made by using the nine Cepheids of the galactic system shown as open and filled circles. The photographic data from the SMC are plotted with smaller crosses than the Gascoigne and Kron photoelectric data.
• Knowing \( L \) or \( M \), we can calculate the distance. Apparent magnitude \( (m) \) is always easy.

\[
m - M = 5 \log(d) - 5
\]

• Important relation: Cepheids and RR Lyrae stars are giant and thus very luminous. We can see them as individual stars in other galaxies.

Cepheids in the Small Magellanic Cloud
Mass transfer can affect stellar evolution

- Close binary systems - some binary systems are so close they are in contact.

![Diagram showing different types of binary systems]

- Detached binary
- Semi-detached binary
- Contact binary
- Overcontact binary
Gas may flow from one star to another in close systems. This can alter the standard evolutionary pattern.
Last time: post-main sequence evolution

- Core hydrogen exhaustion => inert He core, contracting and heating.

- Pushes outer layers outwards => expansion, and cooling (to the right in H-R diagram)

- Shell H fusion starts => luminosity increase (upwards in H-R diagram)

- Helium fusion starts (the triple alpha process, producing C and O) => the core expands and cools
Binding Energy per nucleon

Average binding energy per nucleon (MeV)

Stellar Nucleosynthesis

Fission releases energy

s-, r-, rp-process
Death of a Low Mass Star

Planetary Nebula NGC 6751

PRC00-12 • Space Telescope Science Institute • NASA and The Hubble Heritage Team (STScI/AURA)
Low mass stars

- How stars live and die depends entirely on their masses
- Today: low mass stars (< 4M_☉), when they evolve off the main sequence
- These stars have two, distinct red giant phases
On the red giant branch

- Shell H burning continues after core H burning stops (core now filled with He).
- Outer layers expand and cool.
- As core contracts and heats, He burning starts with a flash (triple alpha process).
- The triple alpha process less efficient, can only last for about \(10^8\) yr.
• Core expands and cools when core He burning starts.

• H burning slower => lower luminosity. This means downwards in the H-R diagram.

• With less internal pressure, the outer layers shrink and heat up => to the left in the H-R diagram.

• Now the star is on the horizontal branch.
On the asymptotic giant branch

- After some time, the core will fill with C and O.
- Core He burning stops, core contracts => shell He burning
- Produces a lot of energy => outer layers expand and cool. Red giant again!
- This is an AGB (asymptotic giant branch) star.
An old, low-mass AGB star—the action is within a volume about the size of the Earth.
Mass loss

- Sun loses $4 \times 10^9$ kg/s (4 million tons/s) on MS
- Up to AGB, stars lose mass very slowly (e.g. via the solar wind).
- After AGB, mass loss is more extreme and stars are shedding their outer layers. Could reach $10^{-4}$ $M_{\text{sun}}$/year
- Produces *Planetary Nebulae* (PN), and PN central stars that cool to become *White Dwarfs*.

**What is going on? Instabilities!**

- He burning very temperature sensitive, triple-alpha fusion rate $\sim T^{40}$
- Small changes in $T$ $\Rightarrow$ large changes in fusion output
- Star experiences thermal pulses, destabilizing the outer envelope
When He burning shell is depleted, the triple-alpha process stops and He shell starts contracting.

H shell also contracts, heats up => H fusion starts again

The p-p produced He replenishes the He shell, which will cause another He flash => pushes material outwards

Cools off H shell, which then becomes dormant again => cycle
Dredge-up

- Convection zone may extend down to core: convection brings enriched core material to surface.

- Produces objects like carbon stars.

- These stars are important sources for replenishing the ISM.

Molecular CO emission from shell surrounding the carbon star TT Cygni.
Core-envelope separation

- Rapid process ($\sim 10^5$ yr), outer envelope gets ejected

- C-O core still contracts, but less weight of envelope results in a core that never gets hot enough for C to ignite (600M K)

- Core and envelope separate physically, expanding envelope forms a nebula around the C-O core (*planetary nebula*)

M57, the Ring Nebula. Located in Lyra.
The ring is really a shell - illustration of how one sees more and more with increased exposure times.
Why do planetary nebulae shine so brightly?

- Dying star ejects outer layers and exposes the hot core.
- The hot core emits UV radiation => excites and ionizes the surrounding low density gas

...what kind of spectrum would a planetary nebula show?

The Spirograph Nebula
Not all are spherical: bipolar shapes are common
Planetary Nebula Gallery

IC 3568  NGC 6826  NGC 3918
Hubble 5  NGC 7009  NGC 5307

HST • WFPC2

PRC97-38b • ST Sci OPO • December 17, 1997
H. Bond (ST Sci), B. Balick (University of Washington) and NASA
Planetary Nebulae

PRC98-11b • ST Sci OPO • March 12, 1998
S. Kwok (University of Calgary),
R. Rubin (NASA Ames Research Center),
H. Bond (ST Sci) and NASA
What happens to the core?

- For stars with original mass < 4M☉, the central temperature never becomes hot enough for C or O to fuse.
- The central star of the PN is a *White Dwarf*. No more nuclear fusion processes occur.
- Shines because it is hot, and doesn't collapse because of pressure of degenerate matter.
- Core contracts until degenerate ($P$ independent of $T$)

- Then $P$ grows fast, halting contraction (when $R \sim R_{\text{earth}}$)

- $\Rightarrow$ Bare core = white dwarf

<table>
<thead>
<tr>
<th>Evolutionary track</th>
<th>Giant star</th>
<th>Ejected nebula</th>
<th>White dwarf</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>3.0</td>
<td>1.8</td>
<td>1.2</td>
</tr>
<tr>
<td>B</td>
<td>1.5</td>
<td>0.7</td>
<td>0.8</td>
</tr>
<tr>
<td>C</td>
<td>0.8</td>
<td>0.2</td>
<td>0.6</td>
</tr>
</tbody>
</table>
White dwarfs are of the size of the Earth, with the mass of the Sun. Much denser than anything ever made on Earth.

Density ~ 1.9 billion times the density of water

Made of C and O with possibly a thin atmosphere of H.
Where are white dwarf stars on the H-R diagram as they cool? Follow “Cooling Curves”:

As a white dwarf ages, its radius stays the same but its luminosity and surface temperature decrease: Its evolutionary track moves down and to the right on the H-R diagram.
We can see some white dwarfs directly (with telescopes). For example, Sirius has a WD companion Sirius B. You can easily see this from the campus observatory.
Discovery of Sirius B aka “the pup”
Spectrum of Sirius B and A
X-ray image of Sirius B aka “the pup”
Discovery of Sirius B aka “the pup”
M4, a globular cluster. A stellar graveyard!

WD represents endpoint of stellar evolution for solar-mass stars.
Mass-radius relation

- Totally different from that for main sequence stars.
- The greater the mass, the smaller the white dwarf.
- This is why more massive WDs are fainter at a given $T$. 
Types of White Dwarf Stars

Core:
• Carbon/Oxygen
• Helium
• Oxygen/Neon/Magnesium

Atmosphere
• Hydrogen rich
• Helium rich
• Metal lines

Temperatures 3000 – 50,000 K
Note the catastrophe at $M=1.4$ solar masses!

What happens to density as $R \to 0$?
Chandrasekhar limit

- WD starts with C and O ions floating in sea of degenerate electrons
- As the WD cools, C and O form a lattice structure (solid, like a diamond), held up by degeneracy pressure
- Larger masses put more strain on structure. Beyond 1.4 $M_\odot$ (*Chandrasekhar limit*), structure collapses.

What does the star become?
Type Ia supernovae

If enough mass dumped onto WD by binary companion to push it over Chandrasekhar limit, starts collapsing until hot enough for C,O fusion. Proceeds rapidly through WD, explosion, no remnant.

Problem, not enough of these systems
New idea: white-dwarf white dwarf merger (the double degenerate)