White Dwarfs
Their evolution and structure

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Astronomický ústav AV CR

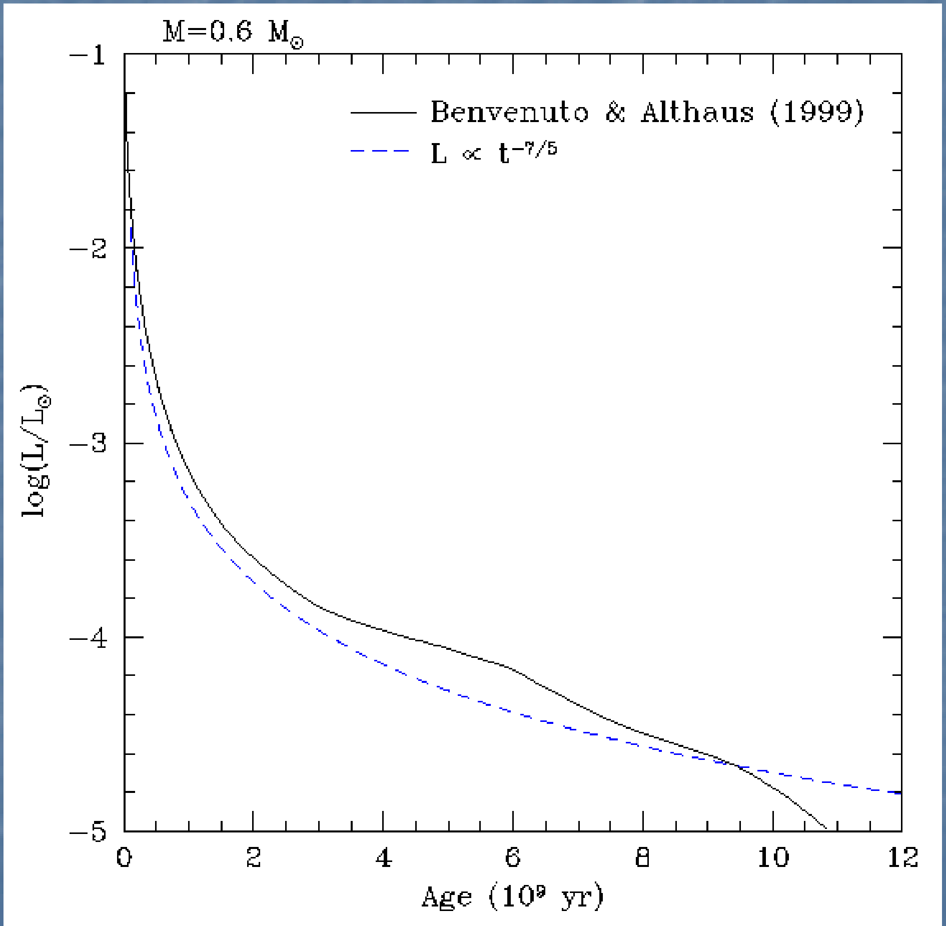
Outline

- Evolution toward a white dwarf.
- White dwarf properties.
- Brief history of the discovery and observations of white dwarf stars.
- White dwarf structure.
- Evolution – cooling.
- Atmosphere.
- Variable white dwarfs.
- White dwarfs in binary systems.
- Their distribution and importance in the Galaxy.
- White dwarfs in globular clusters.

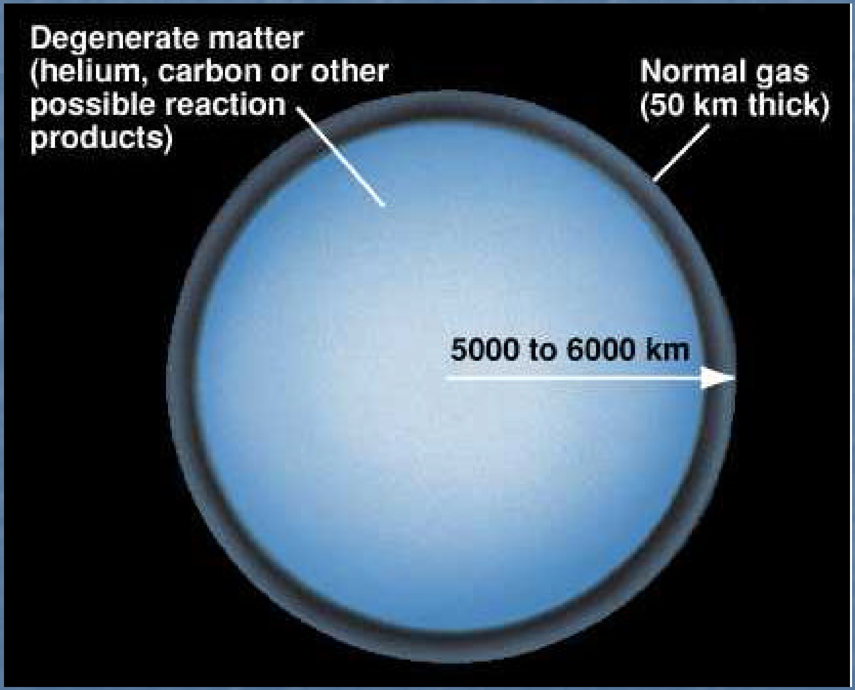
http://sunstel.asu.cas.cz/~kawka/notes.html

Revision - Cooling

- The evolution of a white dwarf is determined by its rate of thermal energy loss, i.e., cooling.
- Other energy sources that determine how a white dwarf evolves are:
  - Gravitational energy,
  - Nuclear energy,
  - Crystallization,
  - Neutrino loss.

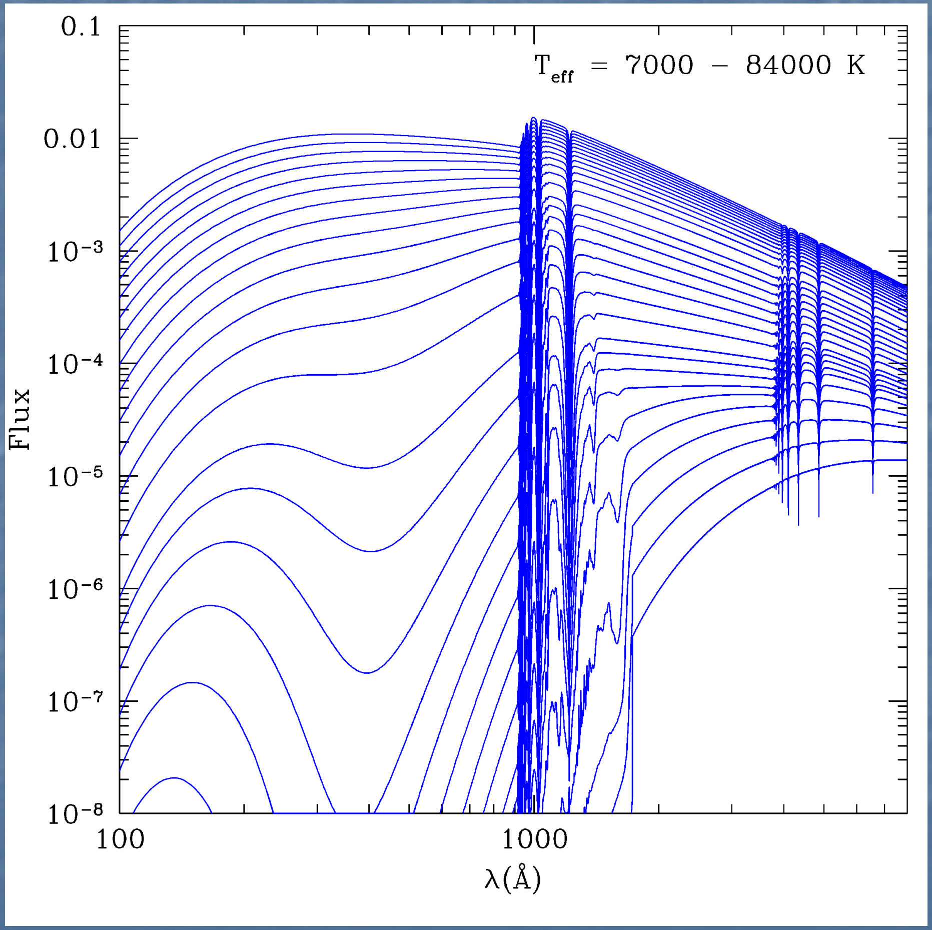


Revision - Cooling



- Transfer of energy within the core of the white dwarf is essentially electron conduction.
- Energy transport in the non-degenerate envelope is radiative diffusion.
- It is the thin envelope (atmosphere) that is responsible for the cooling rate.

Revision - Atmosphere

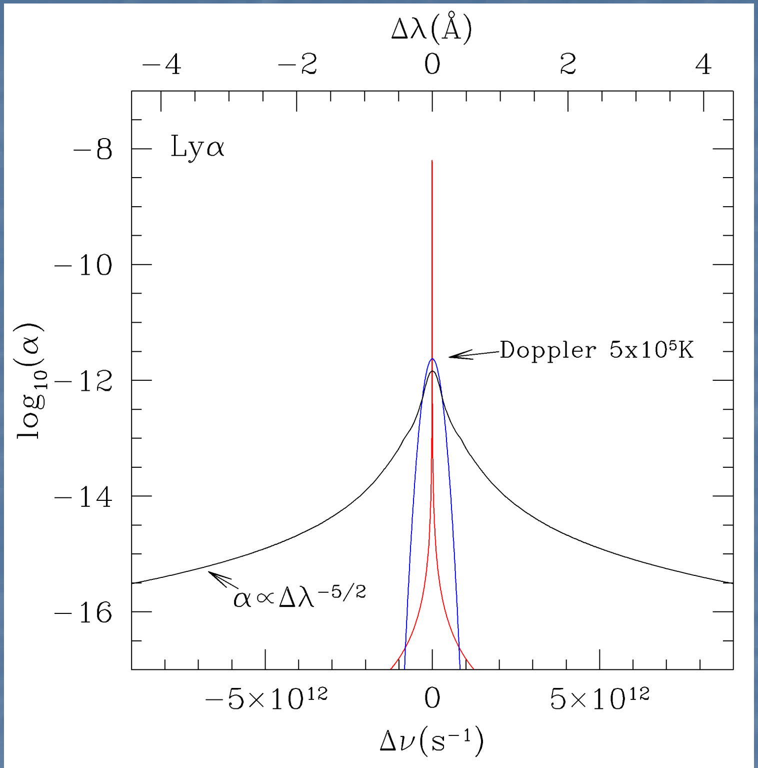


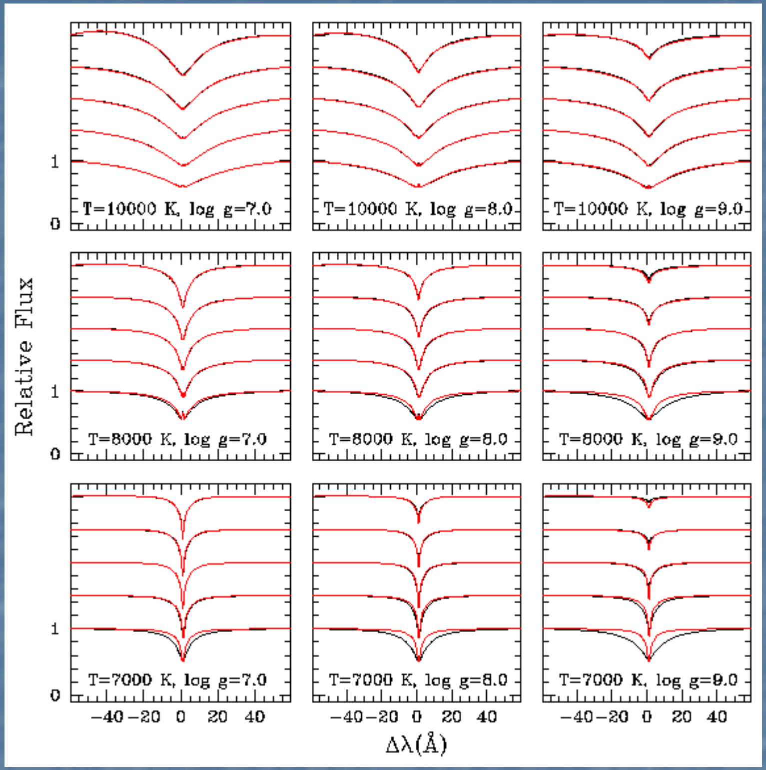
- Total radiated flux emitted at the surface.

$$\mathcal{F}_{\rm total} = 4\pi H_{\rm total} = 4\pi \int_0^\infty H_\nu d\nu = \sigma_R\, T_{\rm eff}^4$$

- To provide a physical description of the atmosphere, we require:
  - Radiative/convective transfer,
  - Flux conservation,
  - Hydrostatic equilibrium,
  - Equation of state – population of levels,
  - Charge and particle conservation.

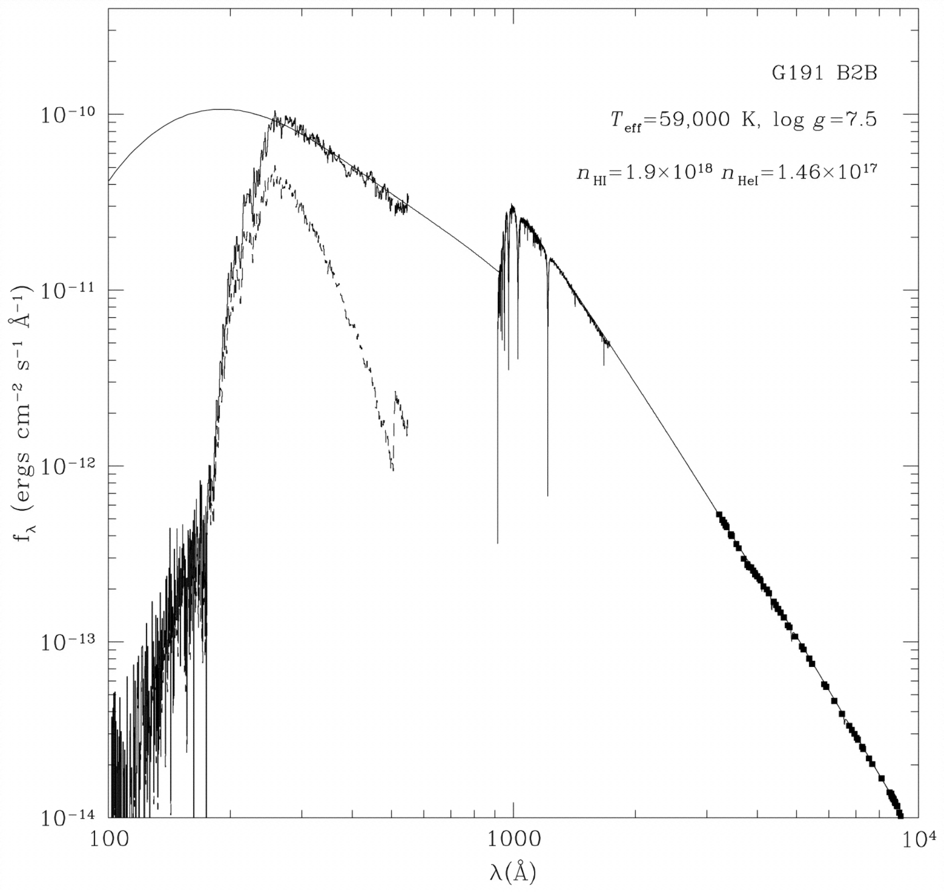
Revision – Line Profiles





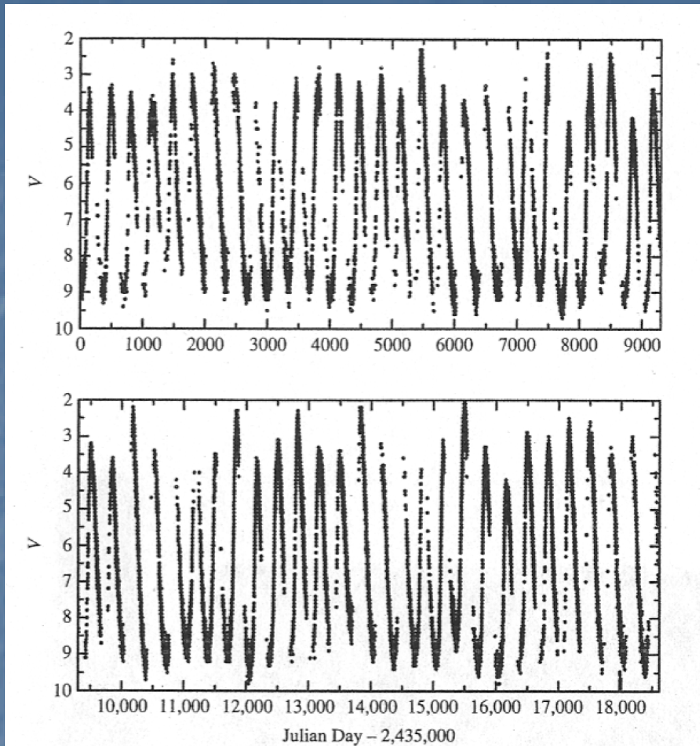
- Pressure broadening dominates over thermal broadening.
- In hot white dwarfs, Stark effect dominates:
  - interaction between H atoms perturbed by protons and electrons.
- In cooler white dwarfs, resonance begins to dominate:
  - interaction between neutral H atoms.

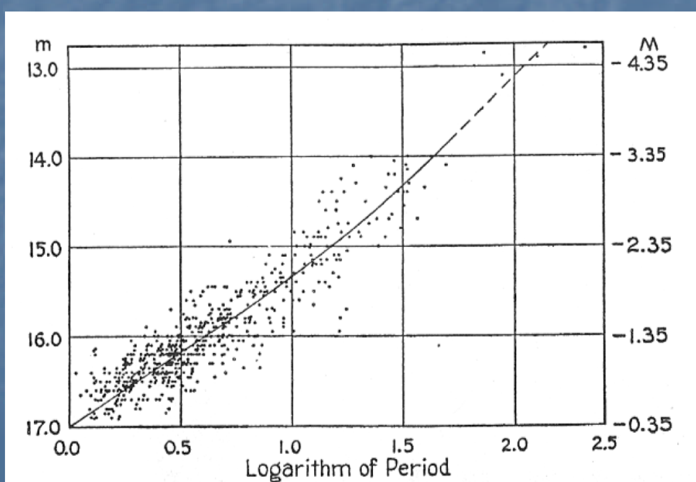
Revision – Observing WDs



(Vennes & Lanz 2001)

- White dwarfs are observed mostly in the optical and ultraviolet.
- We can determine their atmospheric parameters by fitting the observed spectra to model spectra.
- The ultraviolet is sensitive to any heavy elements present in the atmosphere.

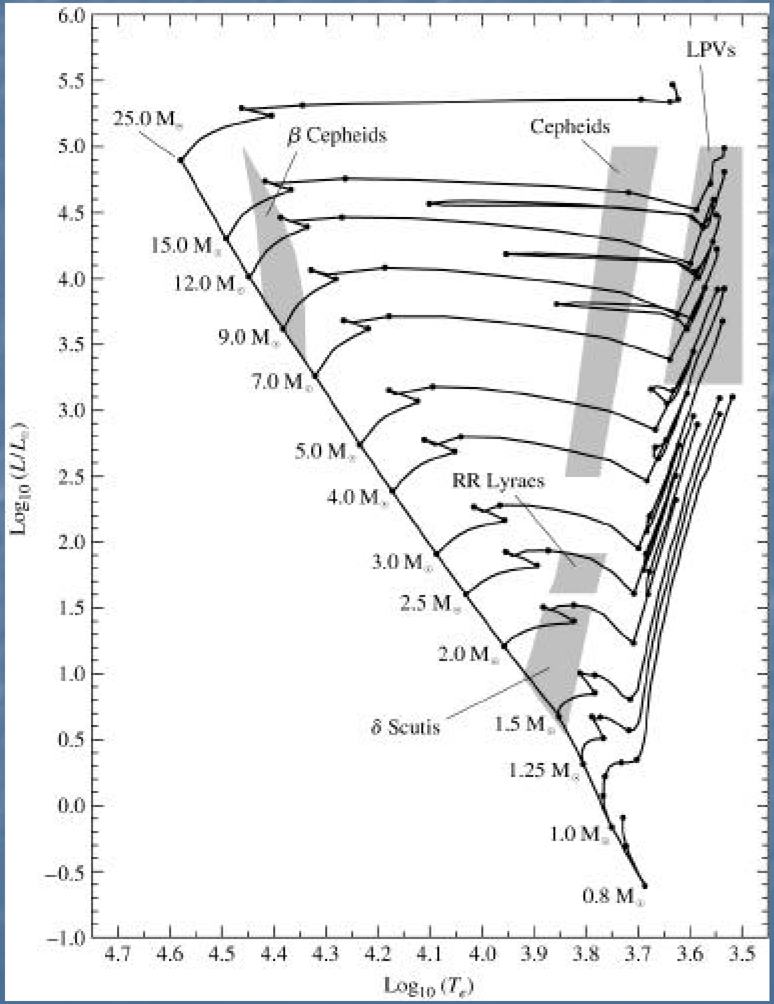




Pulsating Stars

- Mira (ο Ceti) was found to be variable in 1595 by David Fabricius.
  - P = 11 months,
  - ΔV ~ 6 mag (3-9 mag).
- In 1784, δ Cephei was found to vary by John Doosricke.
  - P = 5 d 8 hr 48 min,
  - ΔV < 1 mag (2.1 – 2.9 mag).
  - Prototype for the “classical” Cepheid stars.
- Henrietta Swan Leavitt noticed that the pulsation periods of brighter stars are longer than those of fainter stars.
  - Used as distance indicators.

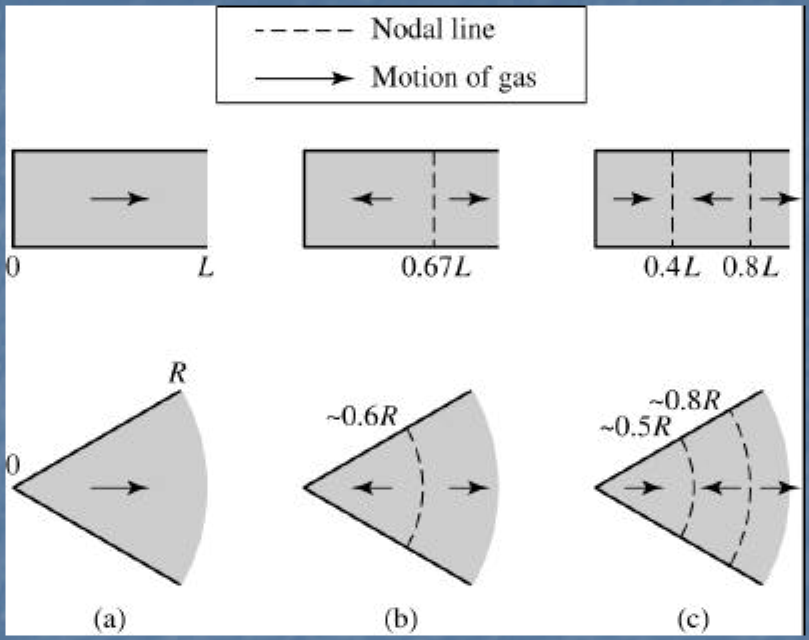
Pulsating Stars



- In 1914, Harlow Shapley proposed that the variations in brightness and temperature of Cepheid stars were caused by radial pulsation of single stars.

Type	Period	Radial/Non-radial
Long-period Variables	100-700 d	R
Classical Cepheids	1-50 d	R
W Virginis stars	2-45 d	R
RR Lyrae stars	1.5-24 hrs	R
δ Scuti stars	1-3 hrs	R/NR
β Cephei stars	3-7 hrs	R/NR
ZZ Ceti stars	100-1000 s	NR

Pulsating Stars

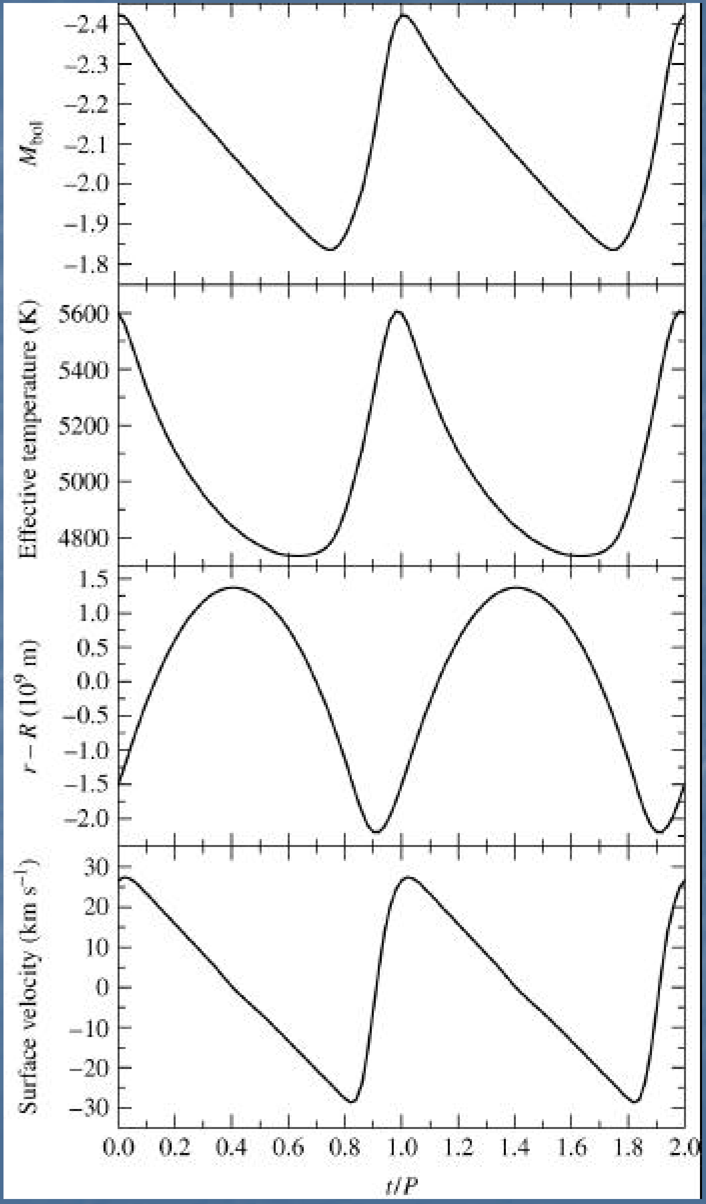


- Most Cepheids and W Virginis pulsate in the fundamental mode.
- RR Lyrae can pulsate in either the fundamental or 1st overtone mode.
- Radial oscillations of a pulsating star are the result of sound waves resonating in the star's interior.
  - That is they are standing waves, with the node at the center of the star, and anti-node at the surface.
- The pulsating period depends on the radius and density of the stellar interior.

Pulsating Stars

- In 1918, Arthur Eddington suggested that pulsating stars are thermodynamic heat engines.
  - Gas in the star do P dV work as they expand and contract throughout the pulsation cycle.
  - If the total work done is positive over the whole cycle then the oscillations will grow in magnitude.
  - If the total work done is negative over the whole cycle then the oscillations will decay.
  - The layers will pulsate until an equilibrium is value is reached, i.e., when the total work done is zero.
- The net work done by each layer of the star during one cycle is the difference between the heat flowing into the gas and the heat leaving the gas.
- For driving oscillations, the heat must enter the layer during the high-T part of the cycle and leave during the low-T part.

Pulsating Stars



- Eddington suggested a *valve mechanism* that can drive the oscillations.
  - The layer of the star needs to become more opaque upon compression so that the photons are trapped and hence heating the gas and increasing the pressure.
  - The high-pressure gas then expands, and as it becomes more transparent the photons can escape, and the gas cools and pressure drops, and the layer can fall back down due to gravity.

Pulsating Stars

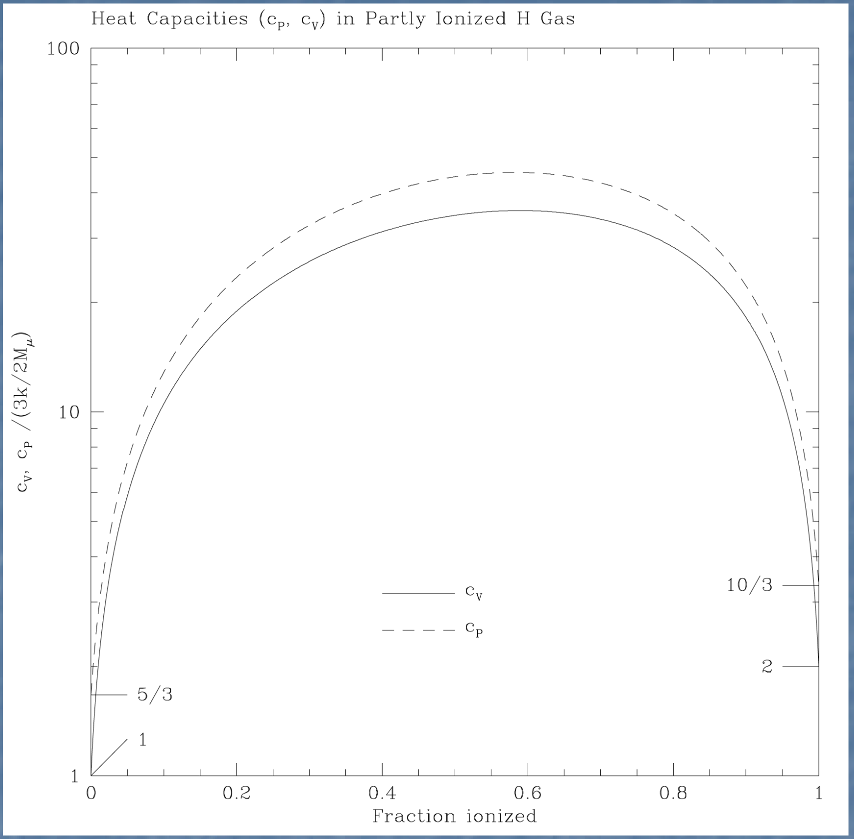
- In most stars, the opacity decreases with greater density.

$$\kappa = \kappa_0 \rho T^{-3.5}$$

- As a star is compressed, the density and temperature both increase.
- Since opacity is more sensitive to the temperature than to the density, the opacity increases upon compression.
  - This would dampen any oscillations, and therefore that is why most stars do not pulsate.
- The regions of a star where the valve mechanism can operate are the partial ionization zones.

Partial Ionization Zones

- In the layers where the gases are partially ionized, part of the work done on the gases as they are compressed produces further ionization rather than raising the temperature of the gas.
  - With a smaller temperature rise, the increase in density produces an increase in the Kramer's opacity law.
- Similarly, when the gas expands, the temperature does not decrease as much as expected since the ions recombine with electrons and release energy.
  - Again the density term dominates, and the opacity will decrease during expansion.



- This mechanism is referred to as the κ-mechanism.

Discovery of Variable WDs

- White dwarfs were used as standard stars because their luminosities were observed to be constant with time.
- However, in 1968 Arlo Landolt found that HL Tau 76 was varying with a period of 12.5 minutes.
- 2nd white dwarf to be found variable was ZZ Ceti (hence the name for DAV) with a period of 212.864 seconds (0.1 mag variation).

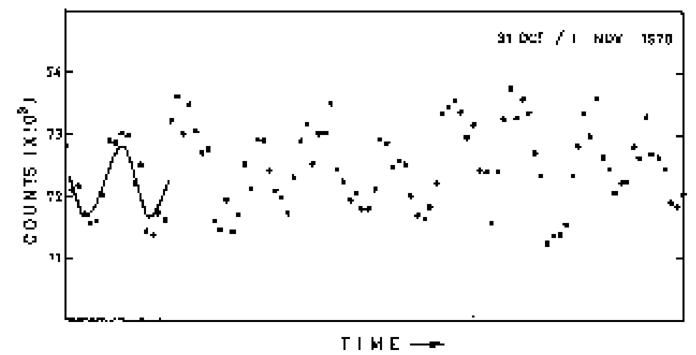
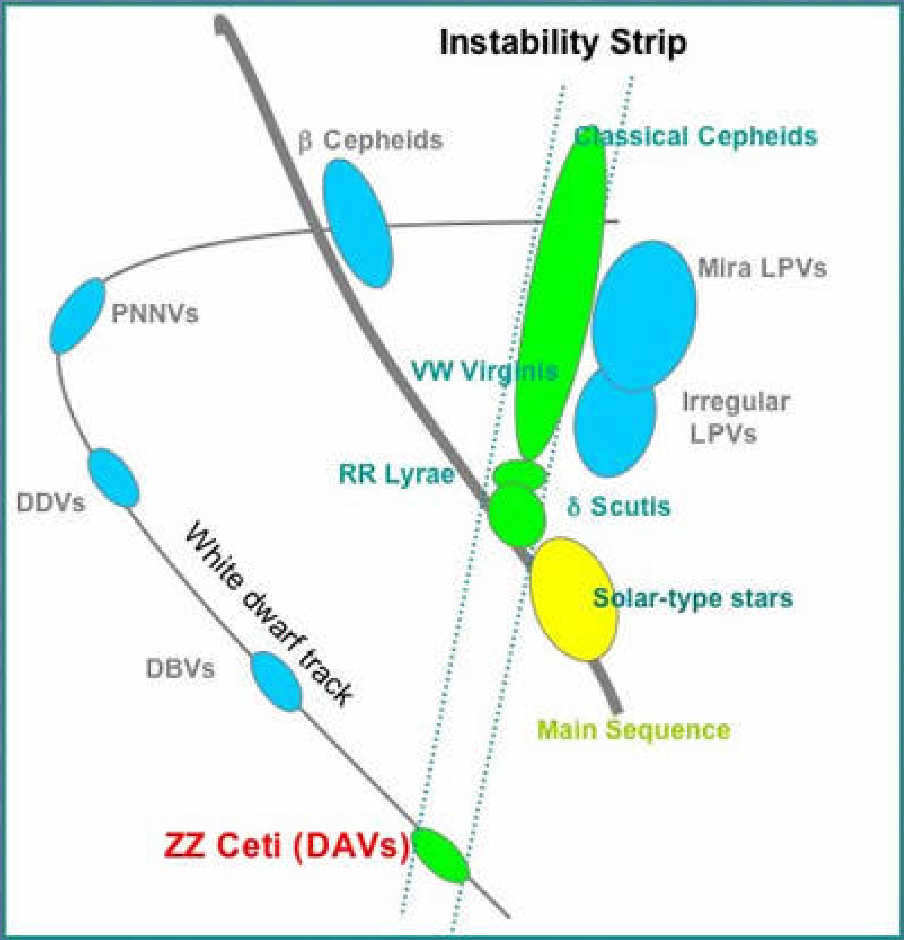


FIG. 1.—A data sample of consecutive 20-sec integrations in white light from the night of 1970 October 31/November 1, which shows the 213 sec variation clearly. For the first 1.5 cycles, an approximate light curve for $P = 213$ sec is sketched. The sky level, which has not been subtracted, was at about 10^4 counts per integration.

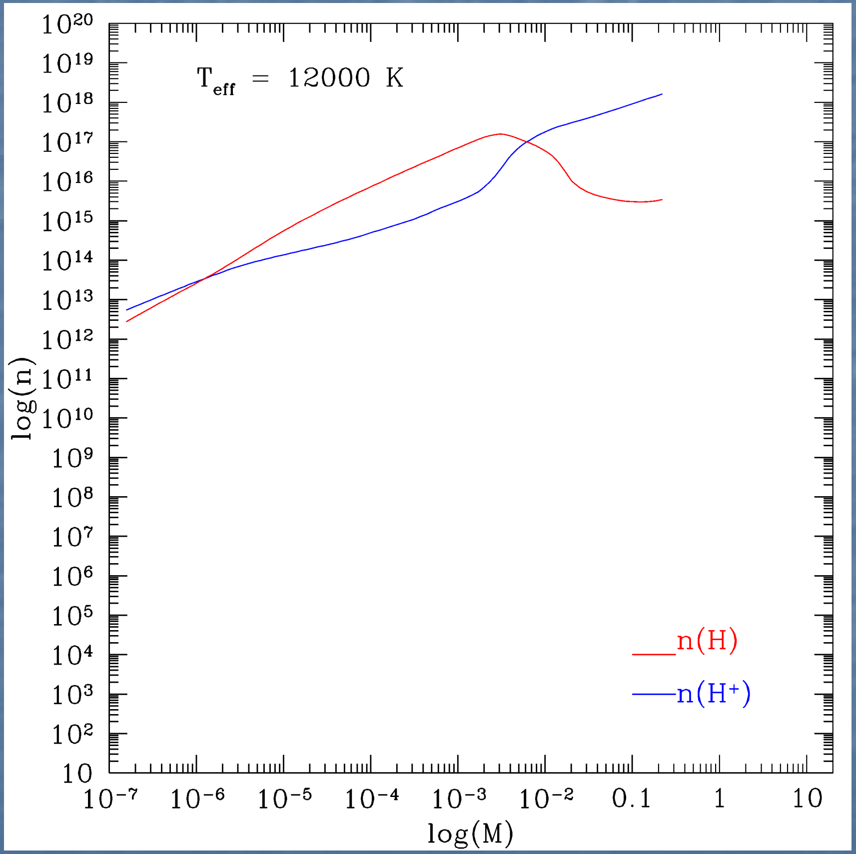
- Winget et al. (1982) successfully demonstrated that the H- partial ionization zone is responsible for driving the oscillations in ZZ Cetis.
- Predicted that hotter DBs should also pulsate – driven by the He-partial ionization zone.

Variable White Dwarfs



- ZZ Ceti (DAV):
  - Extension of the Cepheid instability strip.
  - Hydrogen partial ionization zone.
  - T_{eff} = 10 500 to 13 000 K.
  - Amplitudes = 0.01 to 0.3 mag.
  - Periods = 3 – 20 minutes.
- DBV:
  - He partial ionization zone.
  - Teff = 22 000 to 25 000 K.
- PG1159 (DOV):
  - Excitation is less understood.
  - Variations are complex.

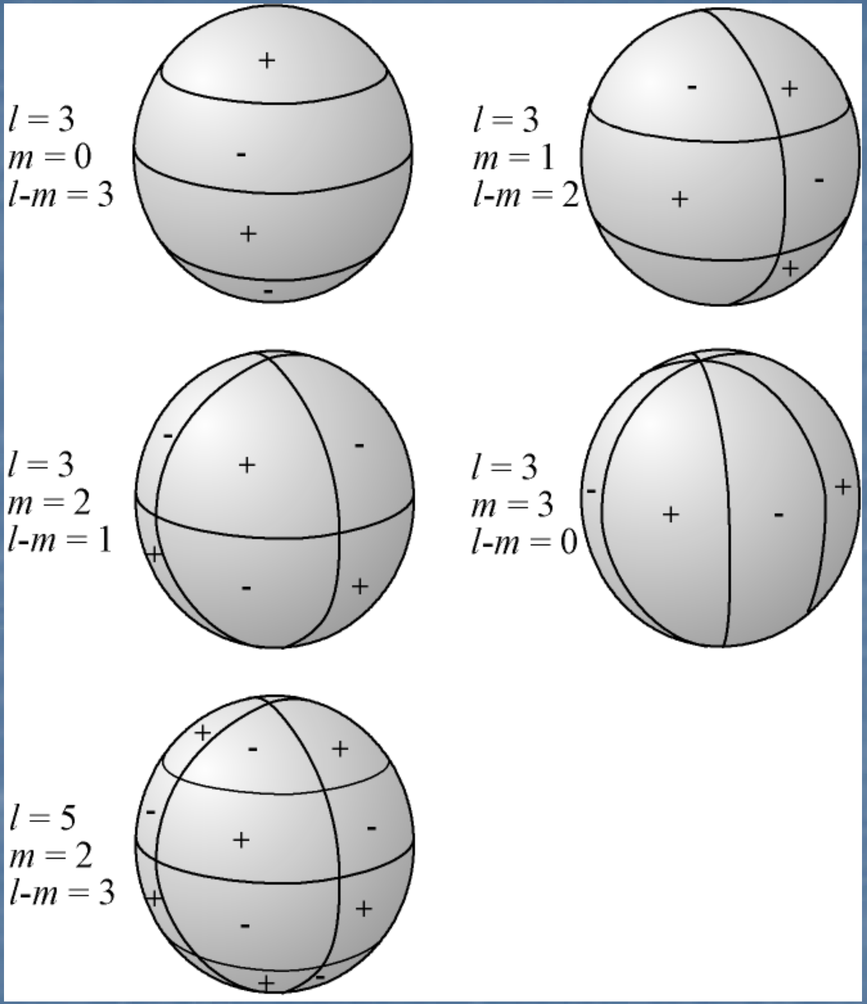
Variable White Dwarfs



- Excitation for pulsations is the partial ionization zone.
- Non-radial oscillations are observed in white dwarfs.
- Non-radial oscillations can be split up into 3 groups:
  - g-modes – gravity,
  - p-modes – pressure,
  - f-modes – intermediate between g and p modes.

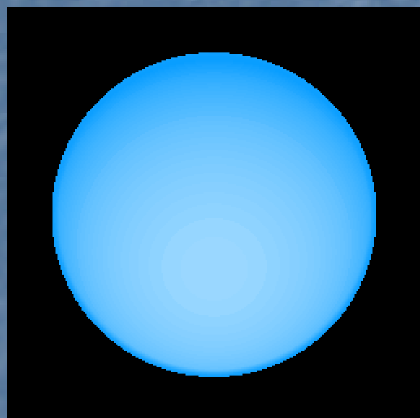
Variable White Dwarfs

- The spherical symmetry of white dwarfs allow the stellar pulsations to be described with spherical harmonic functions.
- Each pulsation mode can be described by 3 integer numbers.
  - k: determines the number of times the surface oscillates between the center of the star and the surface.
  - l: determines the number of borders between hot and cool zones on the surface of the star.

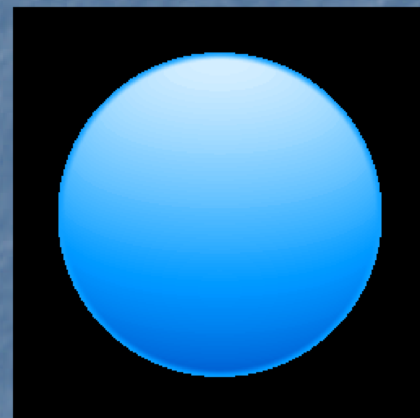


- m: represents the number of borders between hot and cool zones on the surface that pass through the pole of the star’s rotation axis (-l = m = l).

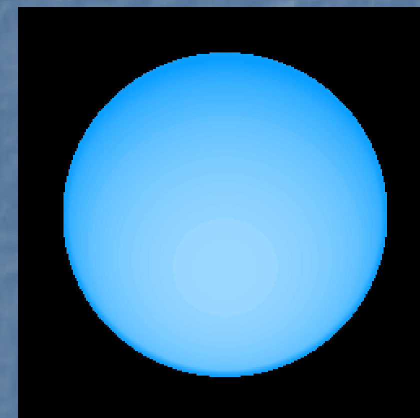
Variable White Dwarfs



l = 1, m = +1



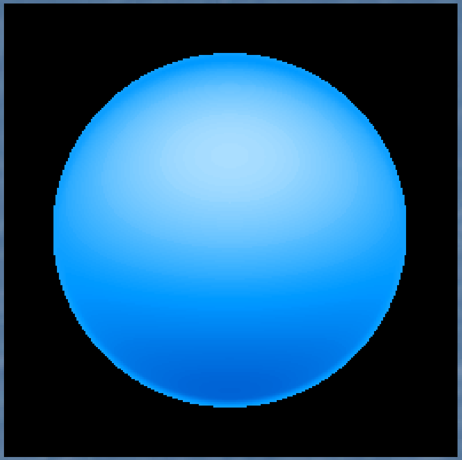
l = 1, m = 0



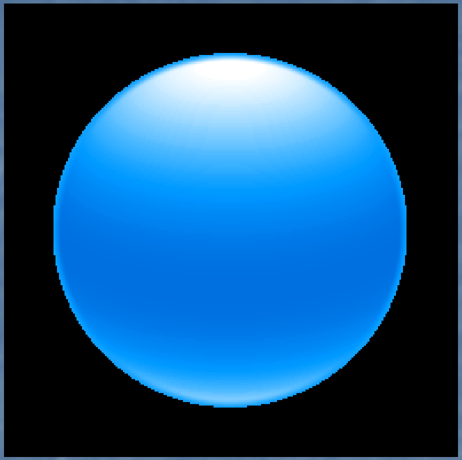
l = 1, m = -1

- Non-zero values for m, represent traveling waves that move across the star parallel to its equator.
- The time required for the waves around the star is |m| times the star’s pulsation period.

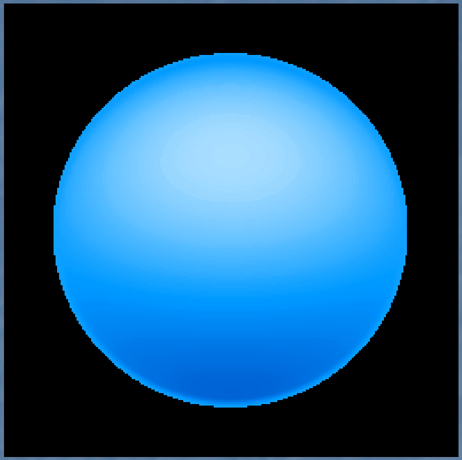
Variable White Dwarfs



l = 2, m = +1



l = 2, m = 0

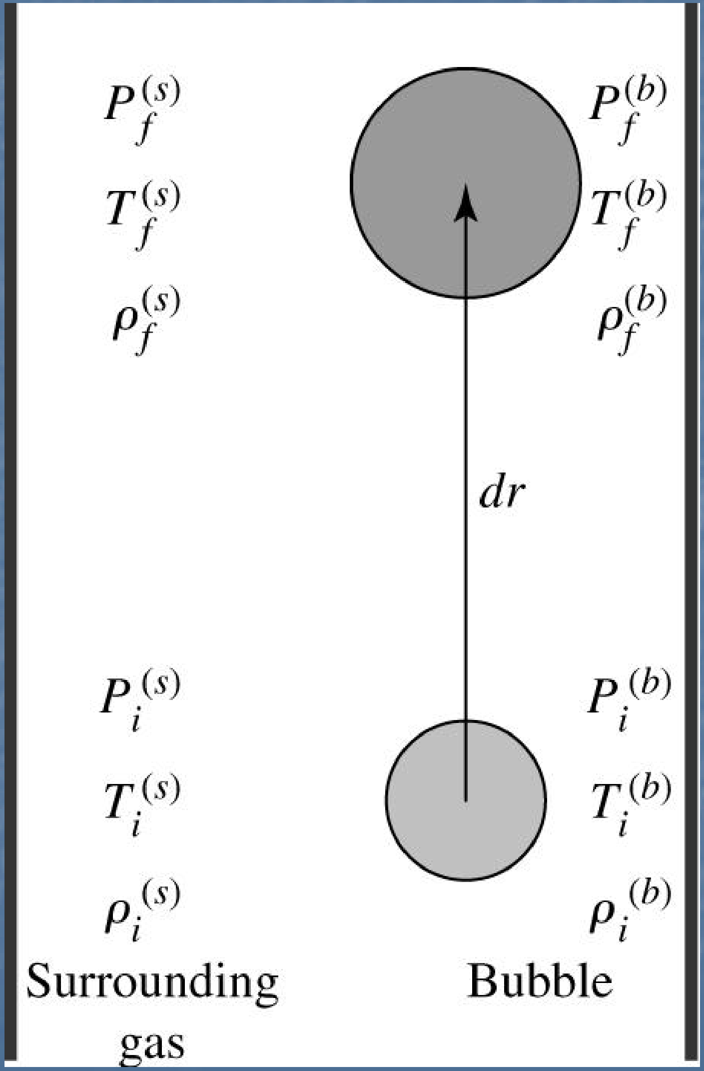


l = 2, m = -1

l = 2, m = +2

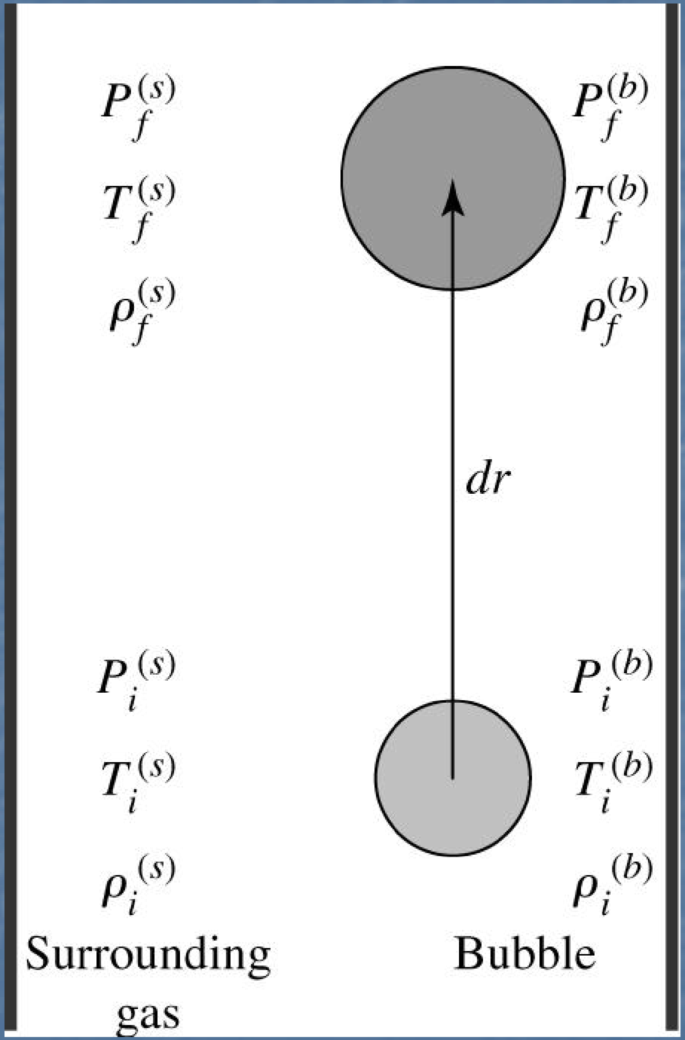
l = 2, m = -2

Variable White Dwarfs



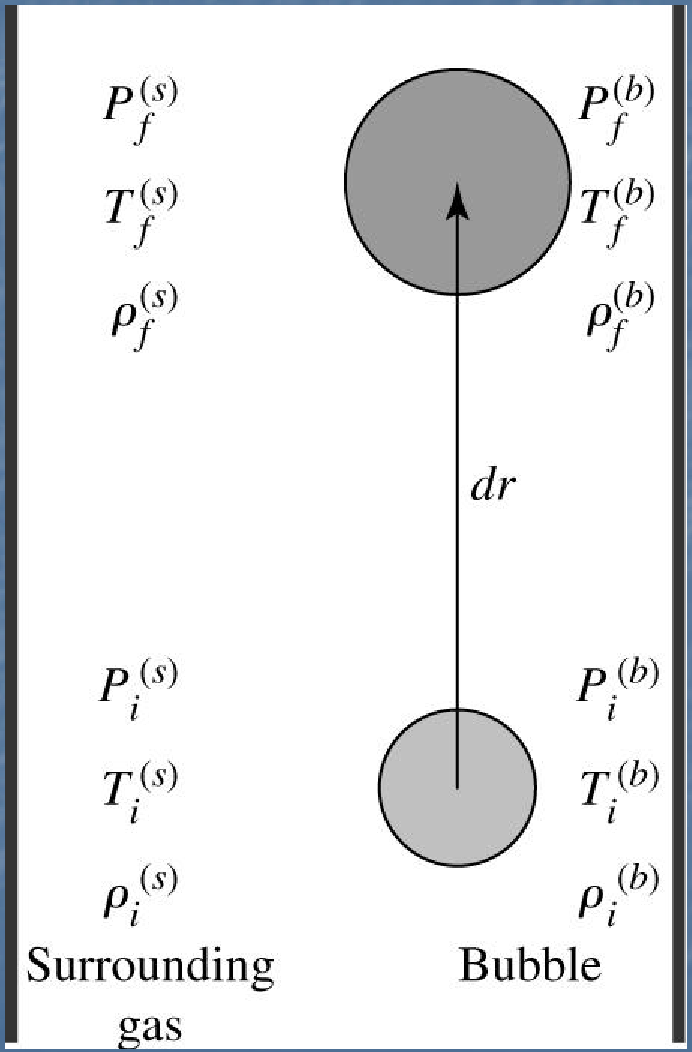
- In white dwarfs, the pulsation periods correspond to g-modes that resonate within the surface layers of hydrogen and helium.
- In g-modes, gravity is the restoring force.
- There are no radial analogs for g-modes.
- To find the periods of g-mode oscillations we can consider a small bubble of stellar material that is displaced upward from its equilibrium position in the star by an amount dr.

Variable White Dwarfs



- We will assume that the motion of this bubble:
  - Is slow enough such that the pressure within the bubble is always equal to the surrounding pressure.
  - But rapidly enough that there is no heat exchange between the bubble and its surroundings.
- 2nd assumption means that the expansion and compression of the gas bubble (cell) are adiabatic.
- The net restoring force on the cell is the difference between the upward buoyant force (Archimedes' law) and the downward gravitational force:

Variable White Dwarfs



- The net restoring force on the cell is the difference between the upward buoyant force (Archimedes' law) and the downward gravitational force:

$$f_{\text{net}} = (\rho_{f,s} - \rho_{f,c})\ g$$

$$f_{\text{net}} = \left(\left(\rho_{i,s} + \frac{d\rho_s}{dr}dr\right) - \left(\rho_{i,c} + \frac{d\rho_c}{dr}dr\right)\right)\ g$$

- Where $g = GM/r^2$ is the local gravitational acceleration.
- Initial densities of the cell and the surroundings are the same.

$$f_{\text{net}} = \left(\frac{d\rho_s}{dr} - \frac{d\rho_c}{dr}\right)\ g dr$$

Variable White Dwarfs

- Since the cell is adiabatic then:

$$\frac{dP}{P} = \Gamma_1 \frac{d\rho}{\rho} \longrightarrow \frac{d\rho}{dP} = \frac{\rho}{\Gamma_1 P}$$

$$f_{\rm net} = \left(\frac{d\rho_s}{dr} - \frac{d\rho_c}{dP_c}\,\frac{dP_c}{dr}\right) gdr$$

$$f_{\rm net} = \left(\frac{d\rho_s}{dr} - \frac{\rho_{i,c}}{\Gamma_1 P_{i,c}}\,\frac{dP_c}{dr}\right) gdr$$

- The initial densities are equal (i.e., $\rho_{i,c} = \rho_{i,s}$) and pressures inside and outside the cell are always the same ($P = P_c = P_s$).

$$f_{\rm net} = \left(\frac{1}{\rho}\,\frac{d\rho}{dr} - \frac{1}{\Gamma_1 P}\,\frac{dP}{dr}\right) \rho g dr$$

Variable White Dwarfs

$$f_{\rm net} = \rho A g dr$$

$$A = \left(\frac{1}{\rho}\frac{d\rho}{dr} - \frac{1}{\Gamma_1 P}\frac{dP}{dr}\right)$$

- If A > 0, then the cell will rise, this is also the condition necessary for convection to occur.
- If A < 0, then the net force will be in the opposite direction to the displacement and the cell will be pushed toward its equilibrium position, i.e., Hooke's law (F = -k x) where the restoring force is proportional to the displacement.
- Therefore, if A < 0 then the cell will oscillate about its equilibrium position with simple harmonic motion.

Variable White Dwarfs

$$f_{\rm net} = \rho A g dr$$

$$A = \left(\frac{1}{\rho}\frac{d\rho}{dr} - \frac{1}{\Gamma_1 P}\frac{dP}{dr}\right)$$

- The acceleration is the force (per unit volume) divided by ρ (mass per unit volume), a = f_{net}/ρ.
- Since the acceleration is related to the displacement for simple harmonic motion:
  - F = ma = -kx for a spring,
  - where a = $-\omega^2 x$ (ω = v (k/m) is the angular frequency)

$$a = -N^2 dr = Ag\ dr$$

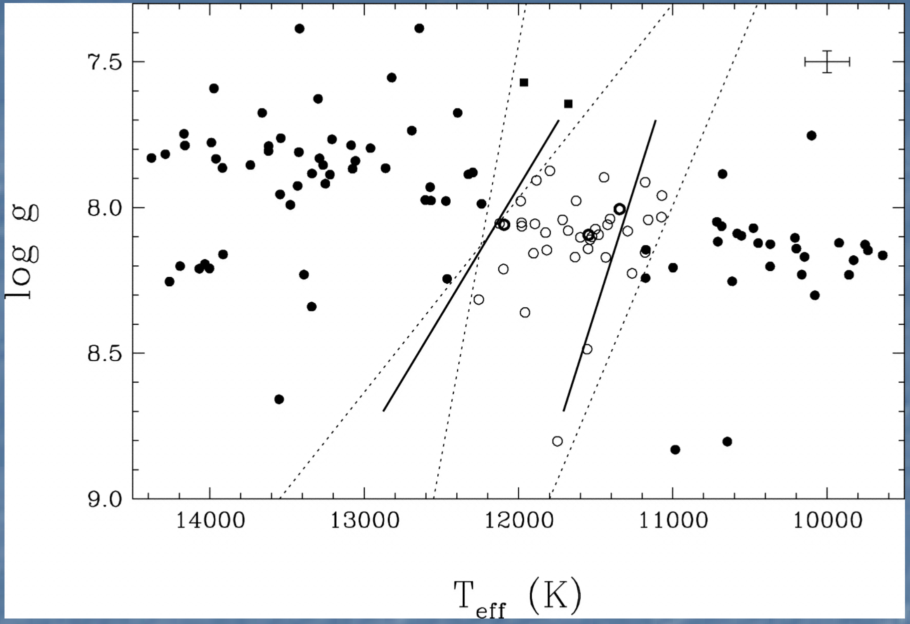
$$N = \sqrt{-Ag} = \sqrt{\left(\frac{1}{\Gamma_1 P}\frac{dP}{dr} - \frac{1}{\rho}\frac{d\rho}{dr}\right)g}$$

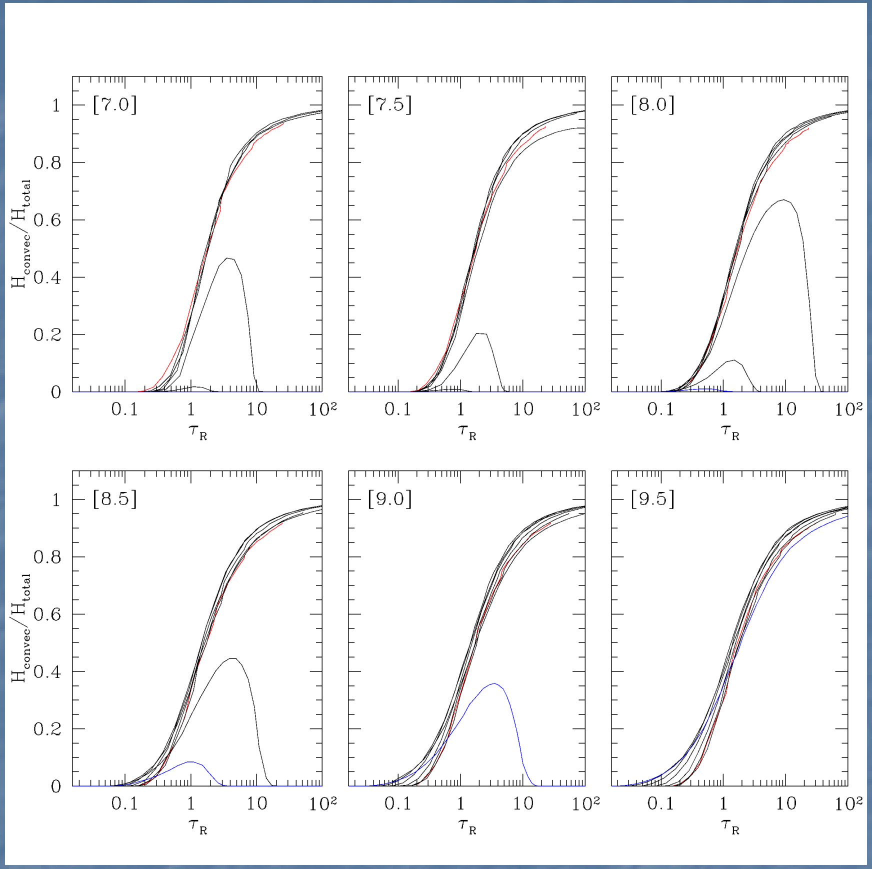
Variable White Dwarfs

$$N = \sqrt{-Ag} = \sqrt{\left(\frac{1}{\Gamma_1 P}\frac{dP}{dr} - \frac{1}{\rho}\frac{d\rho}{dr}\right)g}$$

- N is the angular frequency of the bubble about its equilibrium position and is call the Brunt-Väisälä frequency (buoyancy frequency).
- N=0 at the center of the star (where g=0).
- N=0 at the edges of convection zones (i.e., A=0).
- A < 0: there is no convection, so N is larger in regions that are more stable against convection.
- A > 0: inside a convection zone, N is undefined.

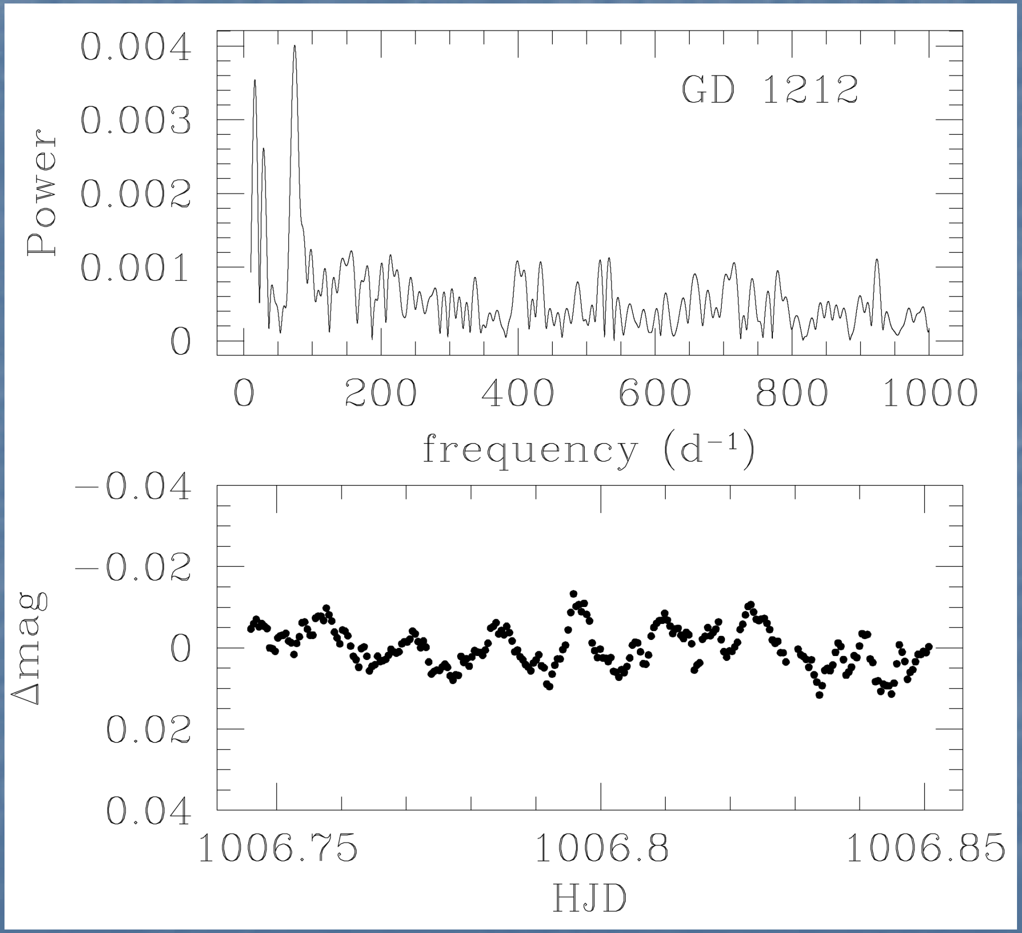
Variable White Dwarfs





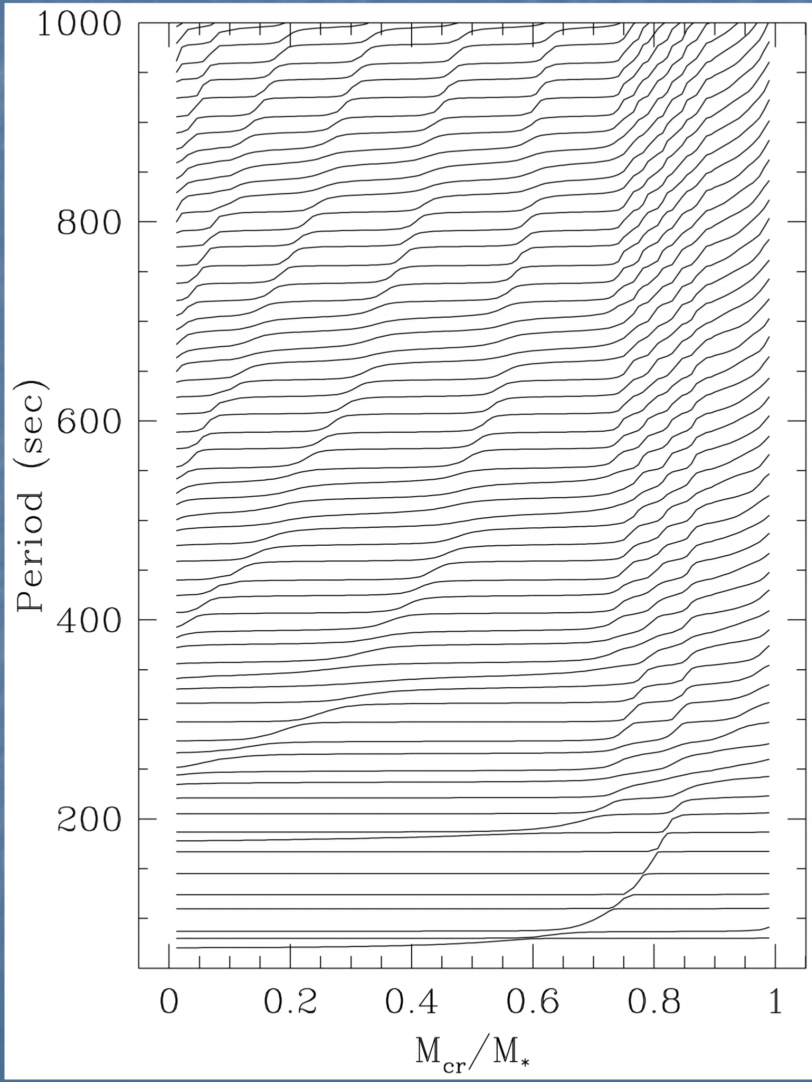
- The ZZ Ceti instability strip is correlated to the temperature and gravity of the white dwarf.
- As the star cools, the convection zone moves inward and gets bigger allowing more modes to be excited.
- As the WD evolves from the blue (hot) edge to the (cool) red edge, the periods get longer and amplitudes larger.

GD1212 – A Variable WD



- T_{eff} = 11010 ± 210 K,
- log g = 8.05 ± 0.15,
- M = 0.63 ± 0.09 $M_{\odot}$.
- Red edge of the instability strip.
- Period = 1150 seconds (~20 minutes).
- Amplitude ~ 0.02 mag.

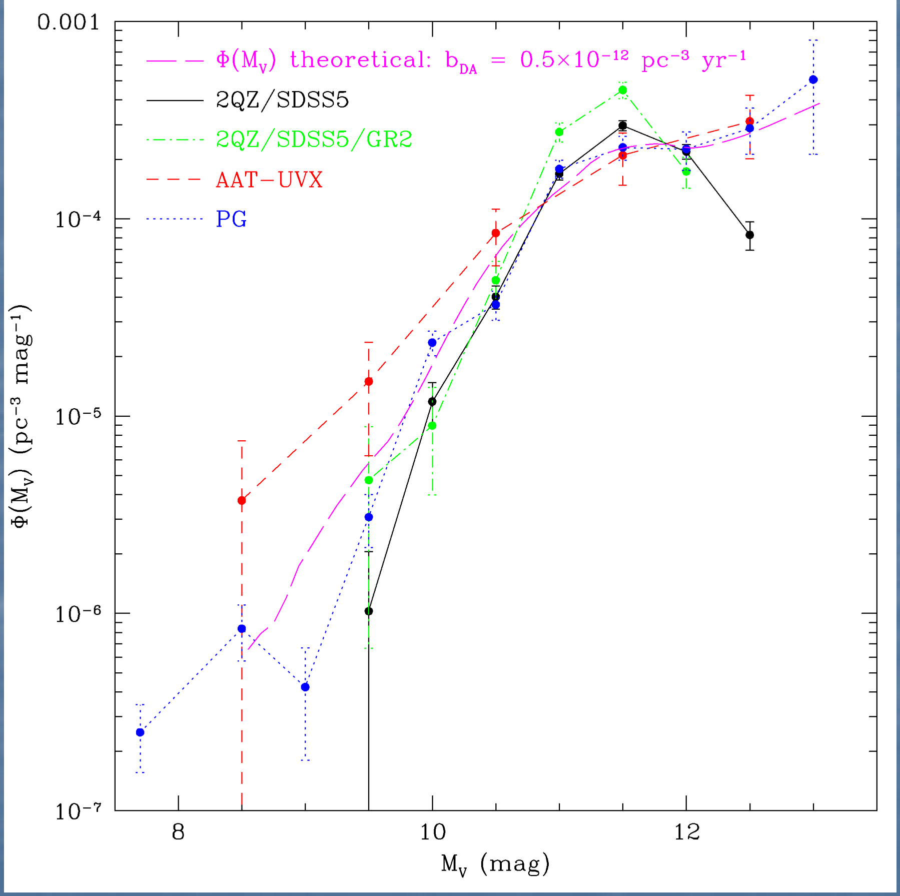
White Dwarf Interior



- g-modes allow the interior of a star to be studied.
- The g-mode period can be altered if a crystallized core is introduced.
- The white dwarf core begins to crystallize around 12 000 K (more massive WDs begin to crystallize at hotter temperatures.
- BPM 37093 is a massive white dwarf ($M=1.1\ M_{\odot}$) which has a partially crystallized core (32% – 82%: Brassard & Fontaine 2005).

Age of the Galactic Disk

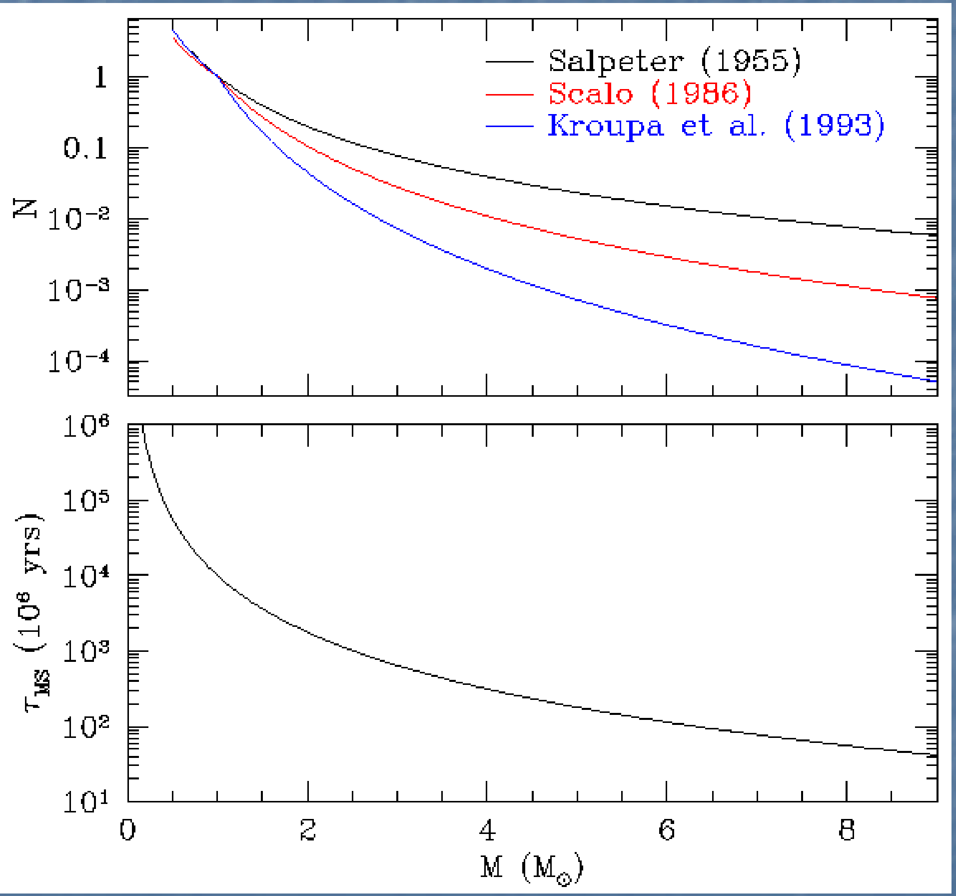
- The luminosity function and mass function can be used to constrain the Galactic evolutionary models.
- The observed luminosity function is simply the number of stars per luminosity bin.
- Need to take into account the area of sky observed and the volume sampled.



Age of the Galactic Disk

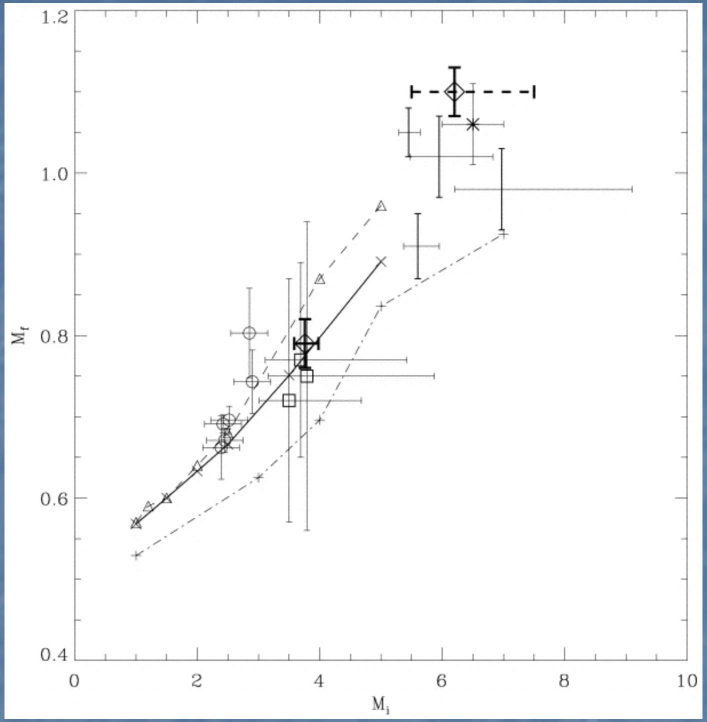
- Schmidt (1959) proposed that white dwarfs can be used to determine the age of the Galactic disk.
- Only recently that the very old, cool and hence faint white dwarfs (T_{eff} ~ 4000 K: cooling age > 10 Gyrs) been detected in greater numbers.
- To build a theoretical white dwarf luminosity function.
  - Initial mass function.
  - Star formation rate.
  - Pre-white dwarf lifetime.
  - Initial-to-final mass relationship.
  - White dwarf cooling rate.

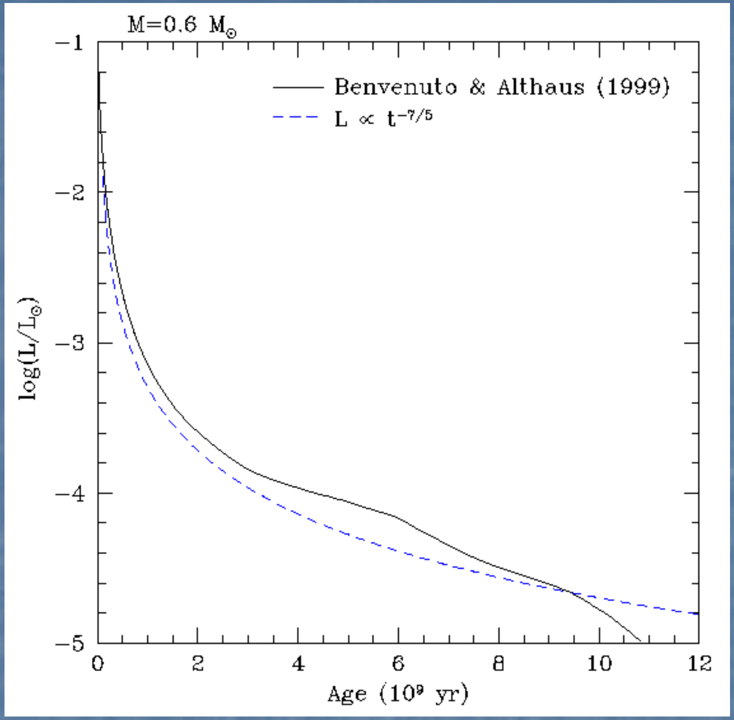
WD Luminosity Function



- Initial mass function:
  - We can use the Salpeter (1955) IMF: $\phi(M) = (M/M_\odot)^{-2.35}$.
  - Scalo (1986) and Kroupa et al. (1993) predict a steeper IMF at the high-mass end.
- The lifetime of star before it becomes a white dwarf:
  - $\tau_{MS} = 10(M/M_\odot)^{-2.5}$ Gyrs.

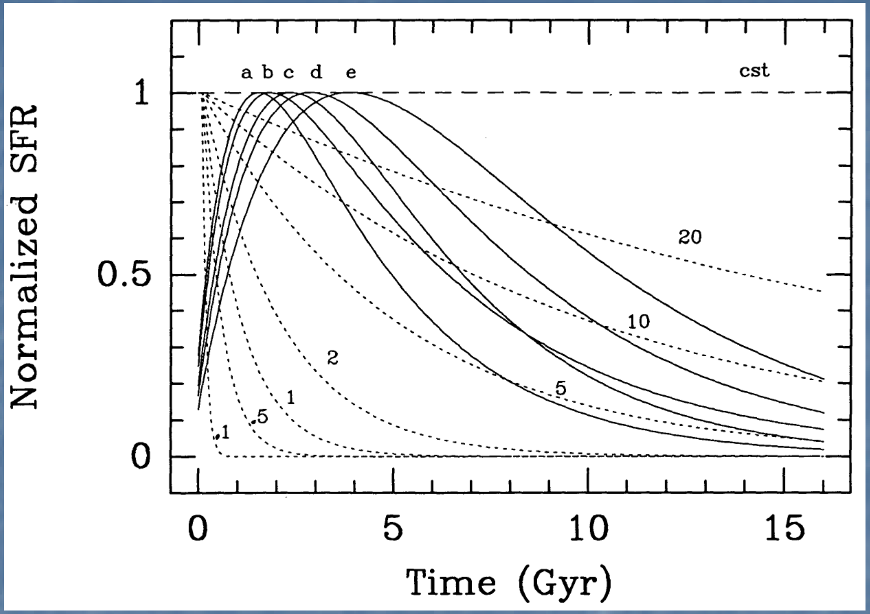
WD Luminosity Function

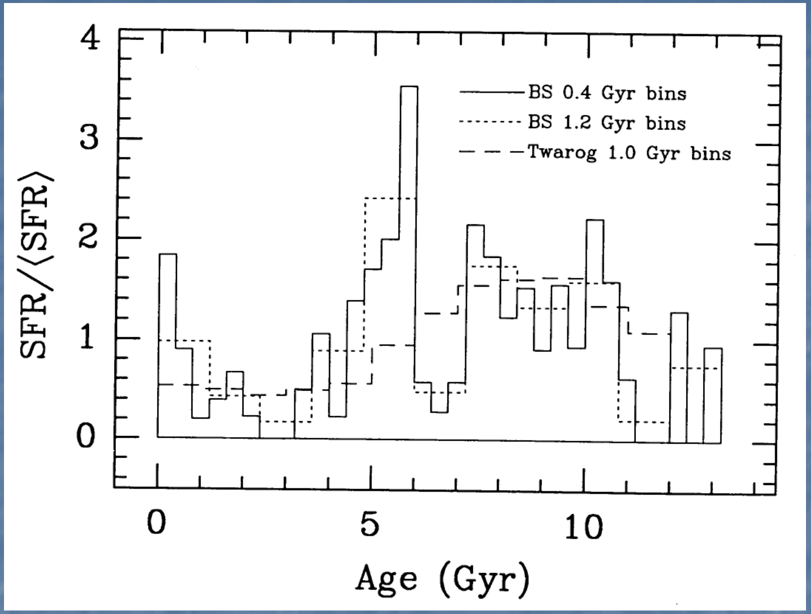




- Initial-to-final mass relationship.
- Mass limits:
  - Upper limit, that is the maximum mass of a star that will become a white dwarf: $M_U = 8M_\odot$.
  - Lower limit which is the turn off mass for the disk.
- Cooling age of the white dwarf.

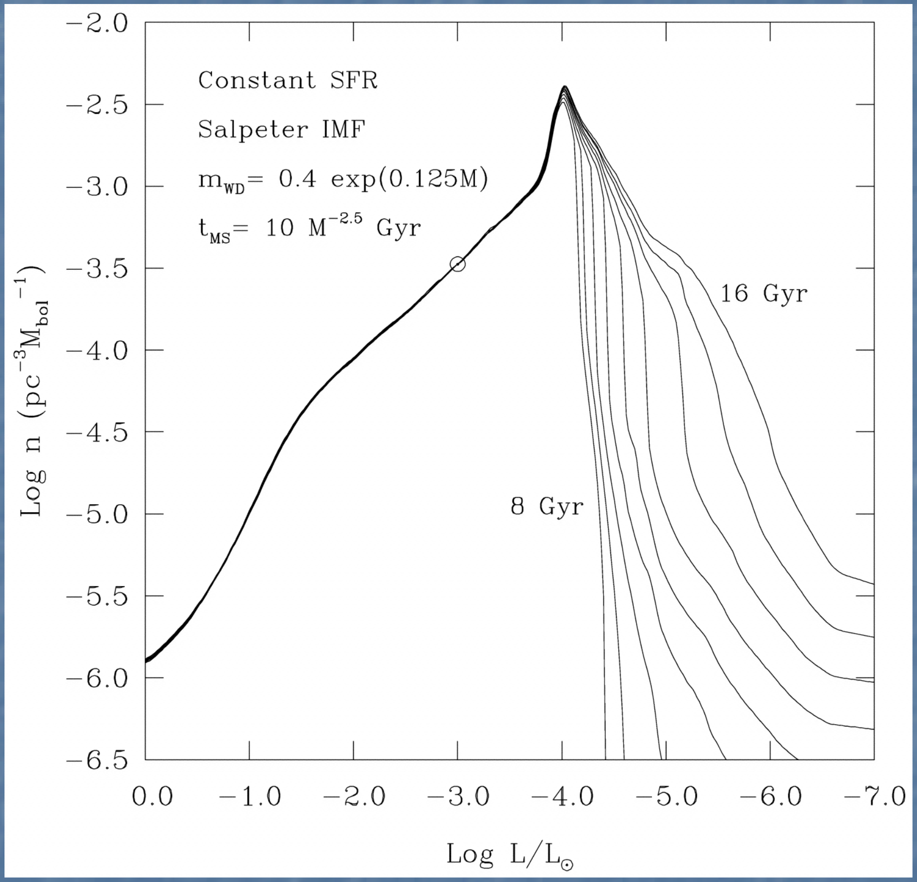
WD Luminosity Function





- There is a large uncertainty in the star formation rate (SFR) in the Galactic disk.:
  - Constant SFR,
  - Exponential decay with time: $\psi(t) = e^{-t/\tau_{SFR}}$,
  - If there was substantial infall of gas then the exponential decay SFR is a poor approximation.
  - Empirical determination of the SFR – from either metallicity/ chromospheric activity studies of low-mass main-sequence stars.

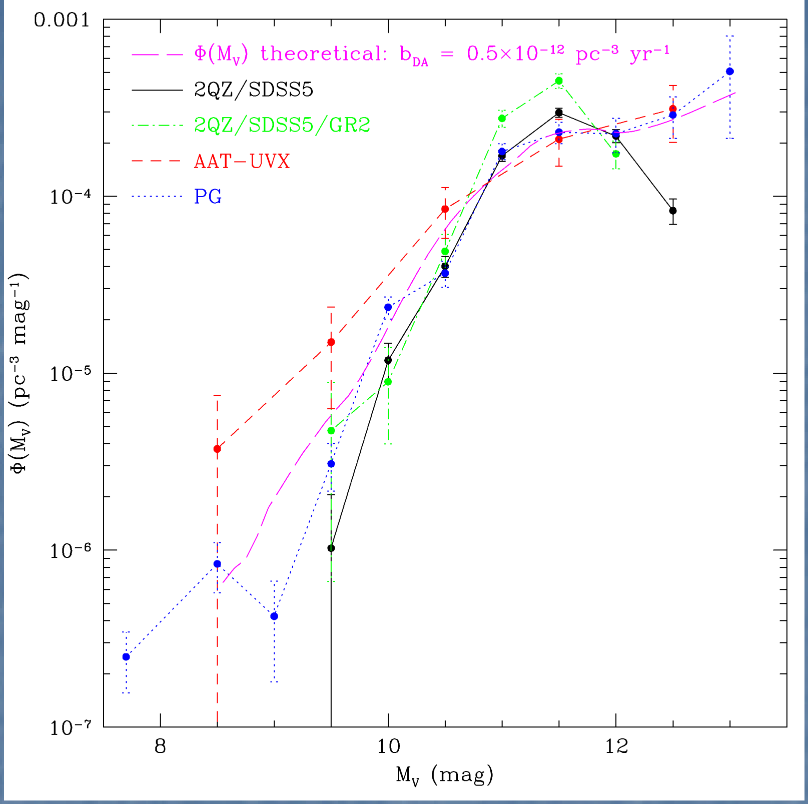
WD Luminosity Function



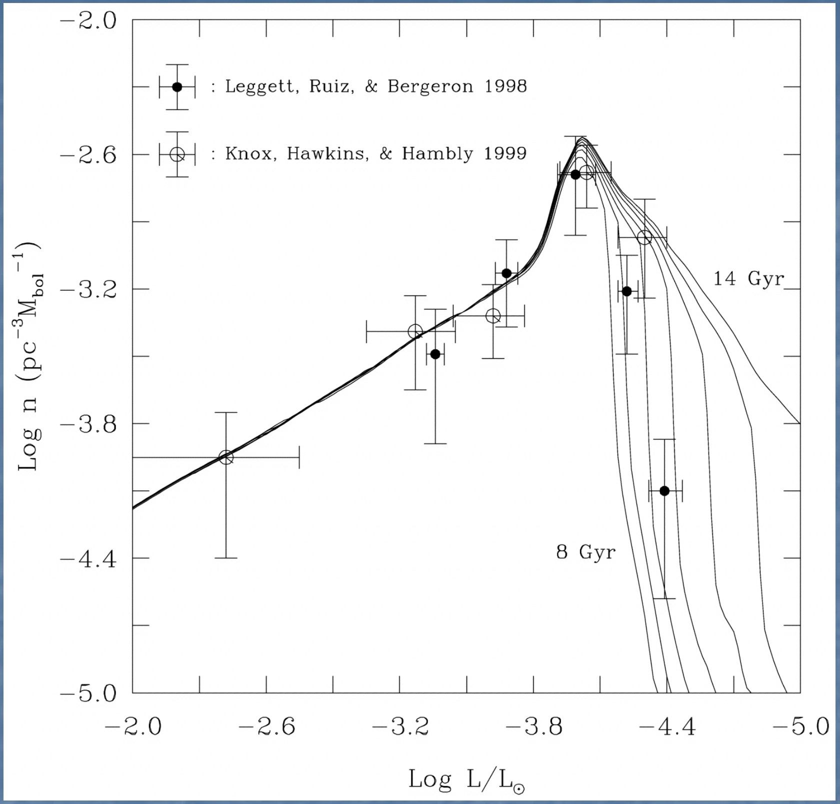
(Fontaine, Brassard & Bergeron 2001)

- To calculate the luminosity function, we need to *evolve* the stars in the disk:
  - Start with the IMF,
  - Over time additional stars are formed (SFR),
  - And the more massive eventually become white dwarfs (IMR).
  - And the white dwarfs cool.
- We can determine the luminosity of the white dwarfs as they would be observed after a given period of time.

WD Luminosity Function



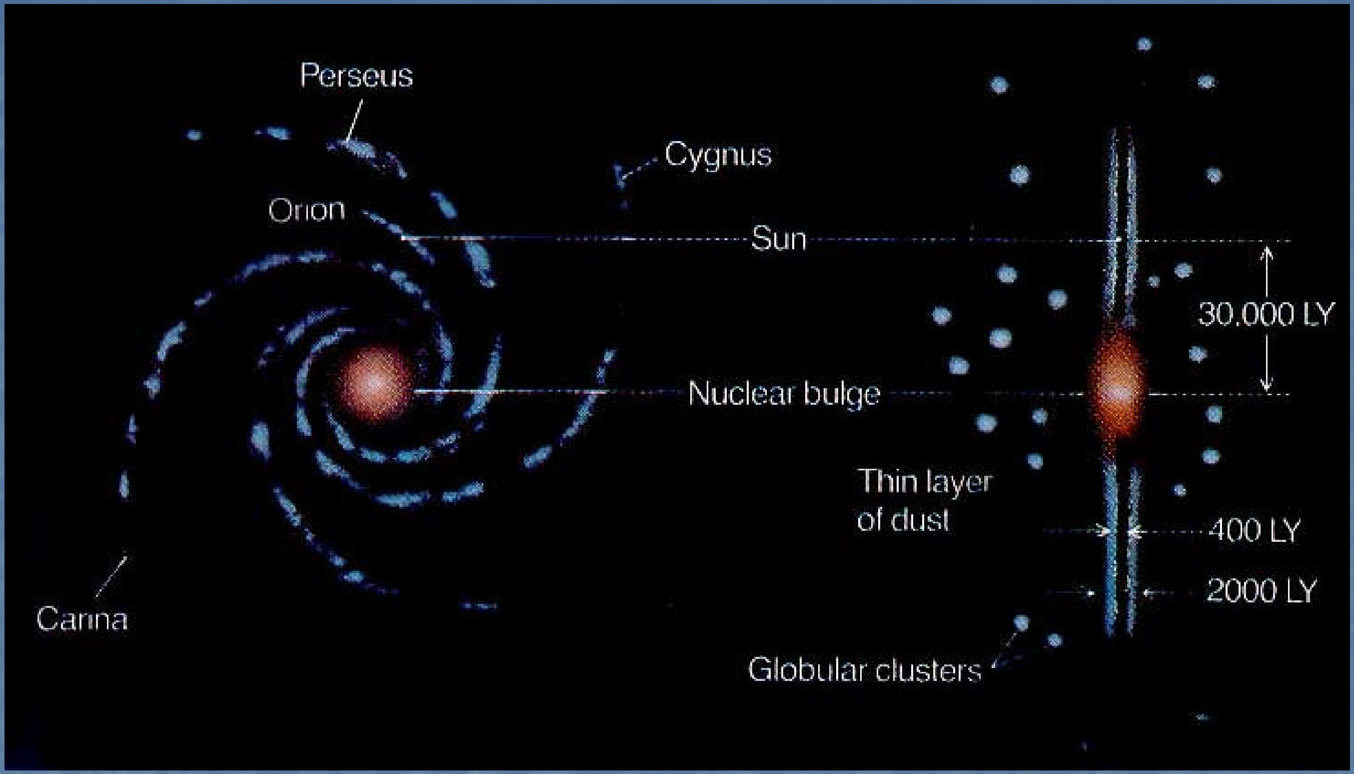
(Kawka & Vennes 2006)



(Fontaine, Brassard & Bergeron 2001)

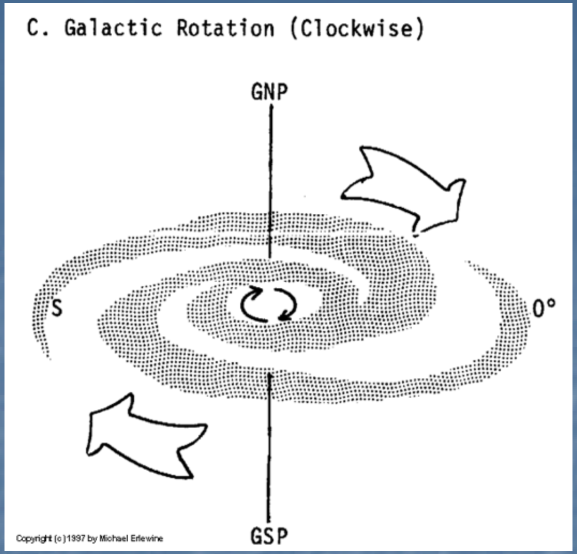
- The large bump near $L/L_\odot = 10^{-4}$ is due to crystallization of the core and convective coupling of the white dwarf.
- The age of the Galactic disk is sensitive to the number of very cool white dwarfs.

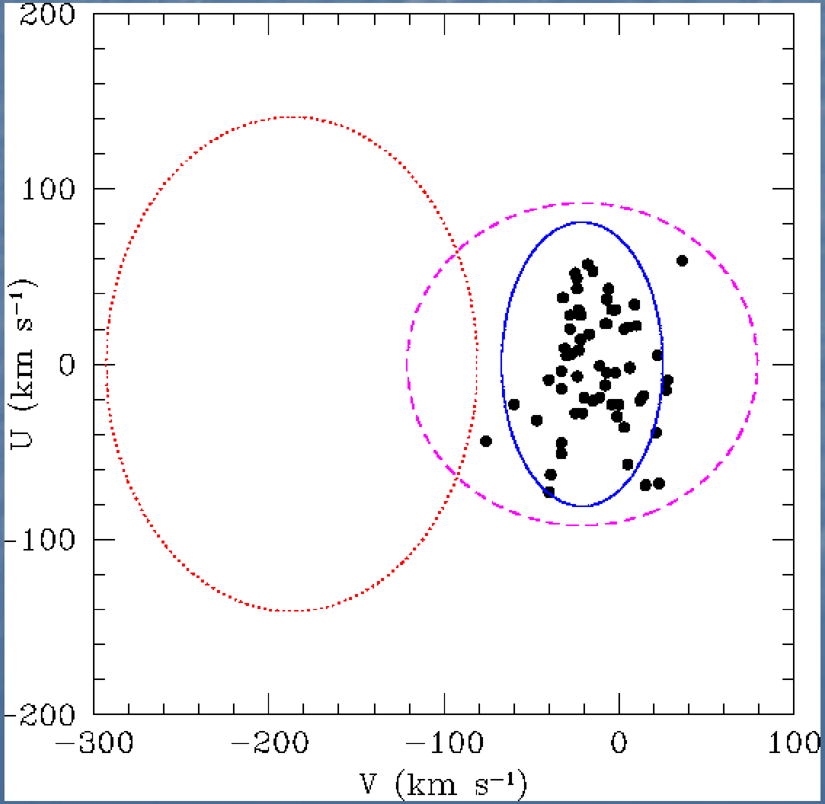
Galactic Structure



- Our Galaxy is believed to have formed ~10 Gyrs ago following the gravitational collapse of a gas nebula leading to the oldest population of white dwarfs.
- Approximately 1Gyr following its formation, it may have collided with a smaller galaxy triggering star formation and disrupting the Galaxy leading to the formation of the thick-disk.

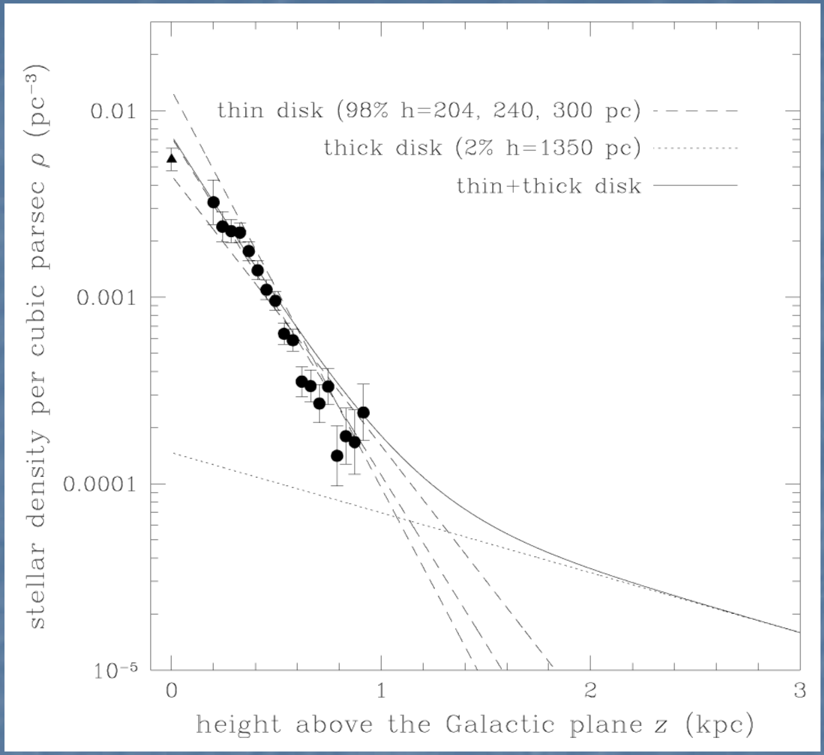
Galactic Structure

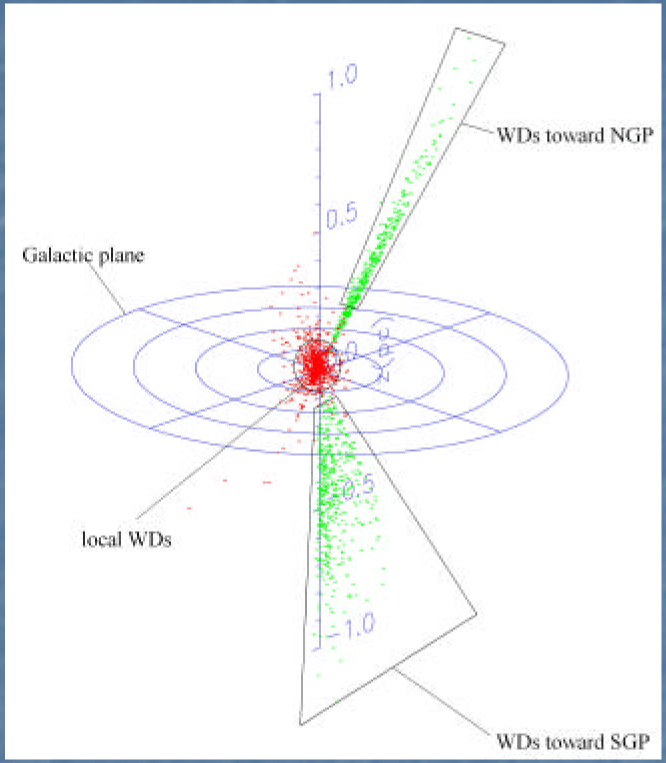




- The motion of stars within a galaxy can be described using:
  - U – toward the Galactic center,
  - V – in the direction of Galactic rotation,
  - W – toward the north Galactic pole.
- Kinematics of a sample of stars can be used to determine which group it belongs to:
  - Thin-disk
  - Thick-disk
  - Halo
- Oldest white dwarfs would be found in the Halo.

Galactic Structure





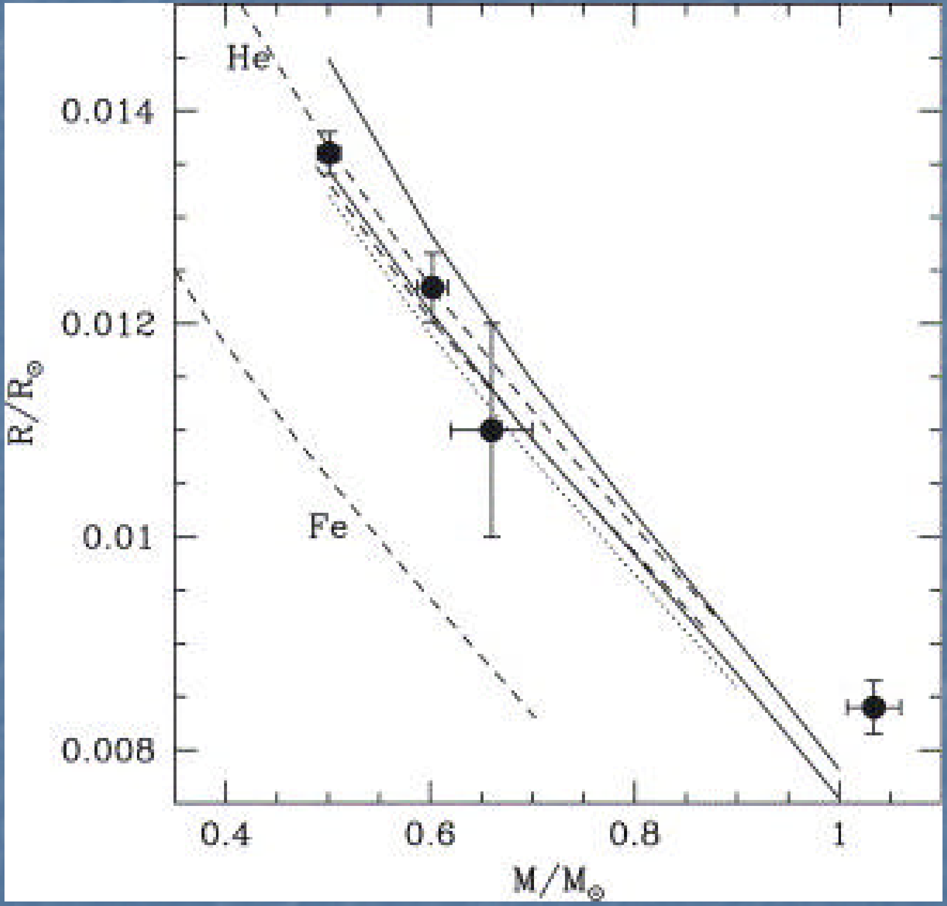
- The density distribution of the Galactic disk can be modeled as a double exponential.
  - Perpendicular distance from the Galactic plane.
- The thick-disk might be contributing to between 2 and 25% of the local population of white dwarfs.

White Dwarfs in Binaries

40 Eridani

- About 1/3 of white dwarfs are in binary systems.
- They can be found in:
  - Wide binary systems, e.g. Sirius A & B, Procyon A & B, common proper motion binaries.
  - Close binary systems – post-common envelope binaries, pre-CV.
  - Cataclysmic variables – novae, dwarf novae, magnetic CVs, Type Ia supernovae.

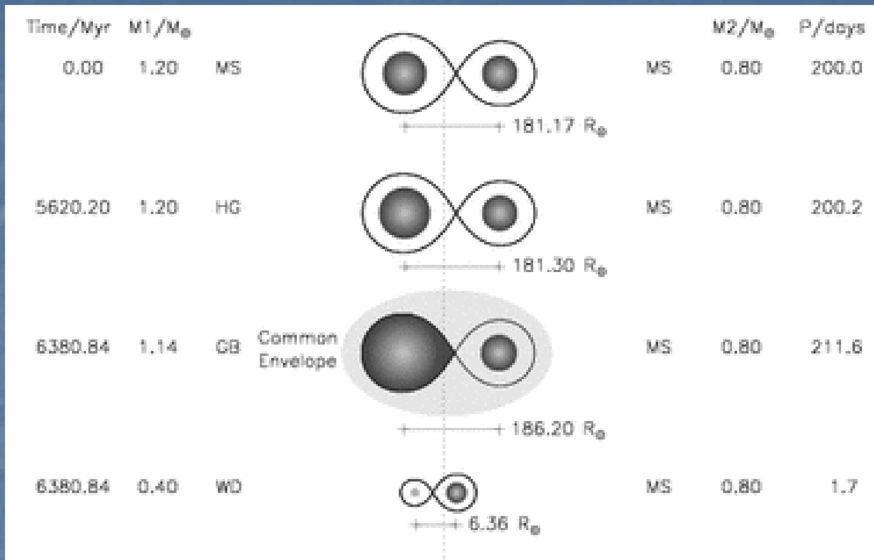
Wide Binaries

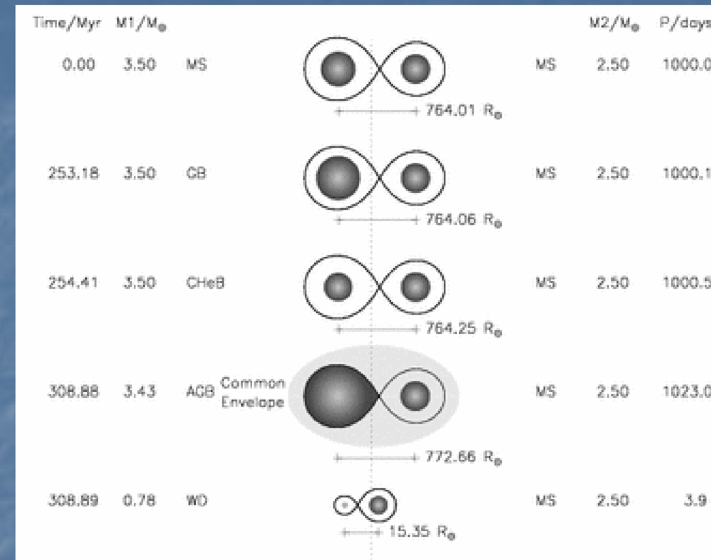


Hansen (2004) – 40 Eri B, LHS 27, Procyon B And Sirius B.

- Can be used to constrain the initial-to-final mass relation.
- Can help determine the mass and radius of the white dwarf, if the distance to the brighter main-sequence is known.
  - Mass can be determined from Kepler's law,
  - Effective temperature from spectral models,
  - Radius from combining the spectral model with an accurate distance.

Close Binary Systems

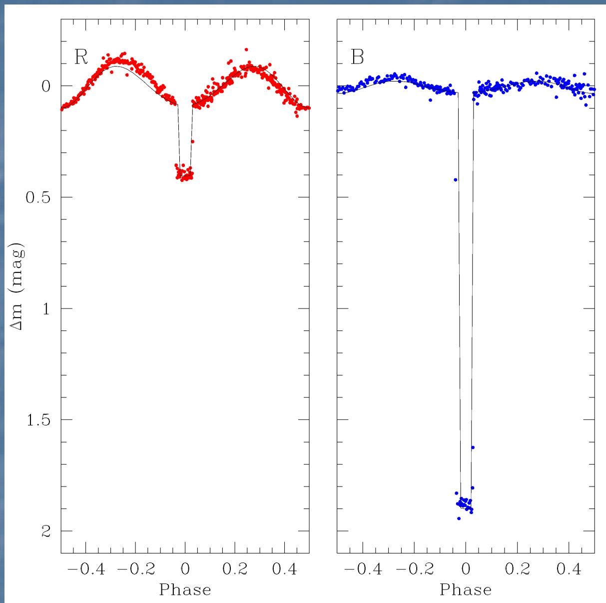


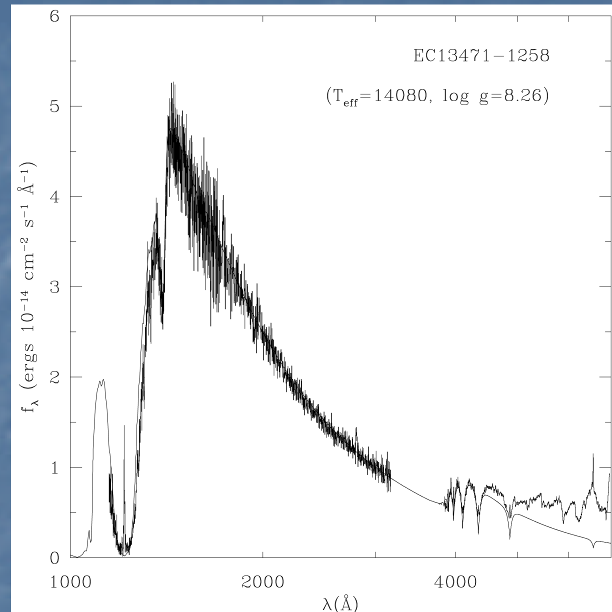


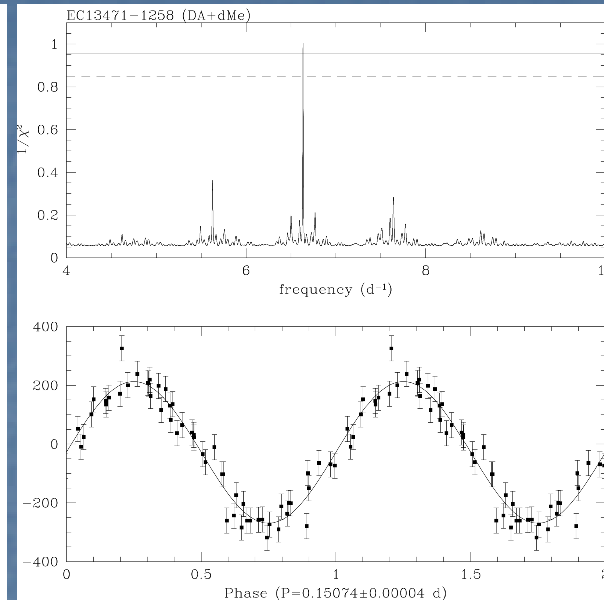
(Willems & Kolb 2004)

- The common envelope scenario was first developed by Paczynski (1976).
  - In system containing two MS stars, the more massive will evolve off the MS first and fill its Roche lobe, initiating mass transfer.
  - Mass transfer may be dynamically unstable forming a common envelope.
  - Friction will cause the two stars to lose angular momentum to the envelope.
  - This energy transfer will allow the envelope to be expelled.

Close Binary Systems

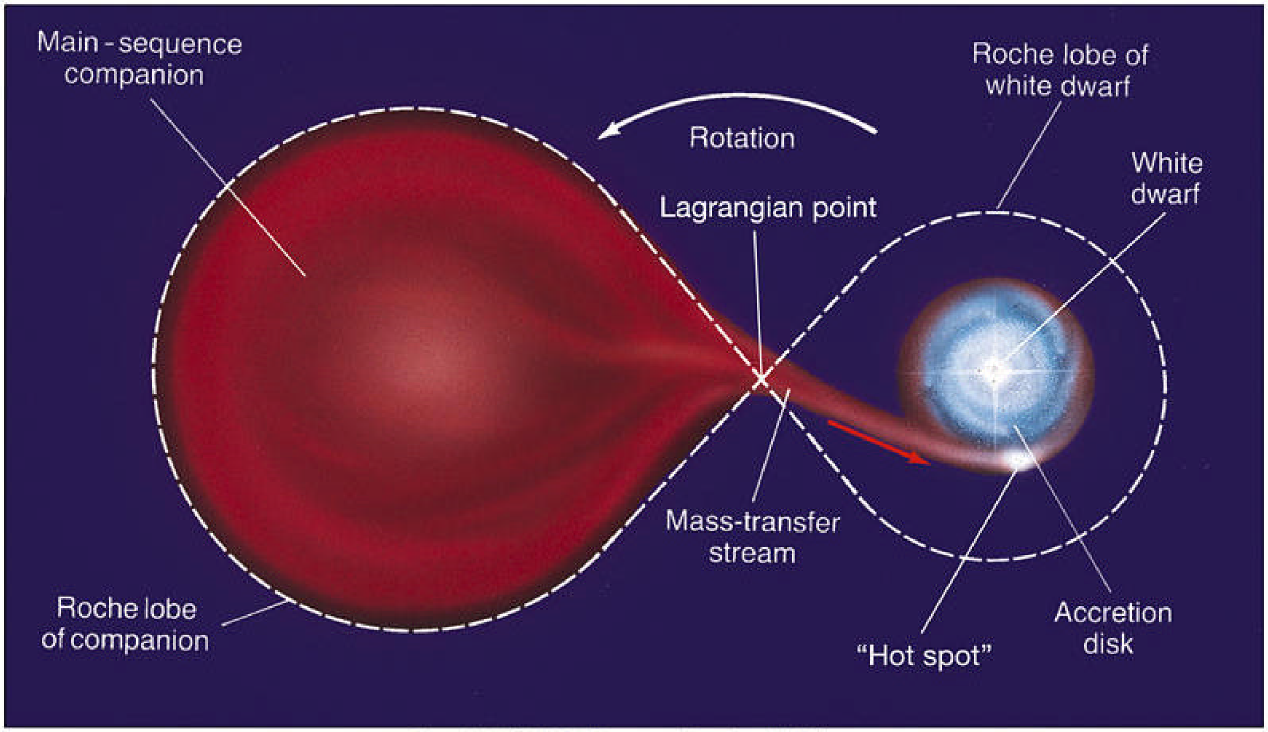






- Close binary stars can help determine the evolution of binary stars toward contact.
- In some cases to constrain the properties of the two components.
- EC 13471-1258:
  - WD: T_{eff} = 14085 ± 100 K, log g = 8.25 ± 0.05, M = 0.77 ± 0.04 $M_\odot$,
  - RD: T_{eff} ~ 3000 K, M = 0.55 ± 0.11 $M_\odot$, R ~ 0.44 $R_\odot$.
  - Inclination = 74 ± 2°.

Cataclysmic Variable Stars



- Classical Novae – thermonuclear runaways of the hydrogen rich matter accretes onto the white dwarf surface.
- Dwarf novae – release of gravitational energy, caused by a temporary large increase in rate of mass transfer through the disk.
- Nova-like variables – the so called "non-eruptive" CVs.

Cataclysmic Variable Stars

- Magnetic CVs are separated into:
  - Polars (AM Hers) – strong magnetic fields.
    - $B \sim 10^7$-10^8 G,
    - Magnetically phase locked to the companion star ($P_{spin} = P_{orb}$),
    - Do not have an accretion disk,
    - Are strongly polarized.
  - Intermediate polars (DQ Her stars) – weaker magnetic fields.
    - $B < 10^7$ G,
    - WD rotates more rapidly than the orbital rate ($P_{spin} \sim \frac{1}{10} P_{orb}$),
    - An accretion disk is present.

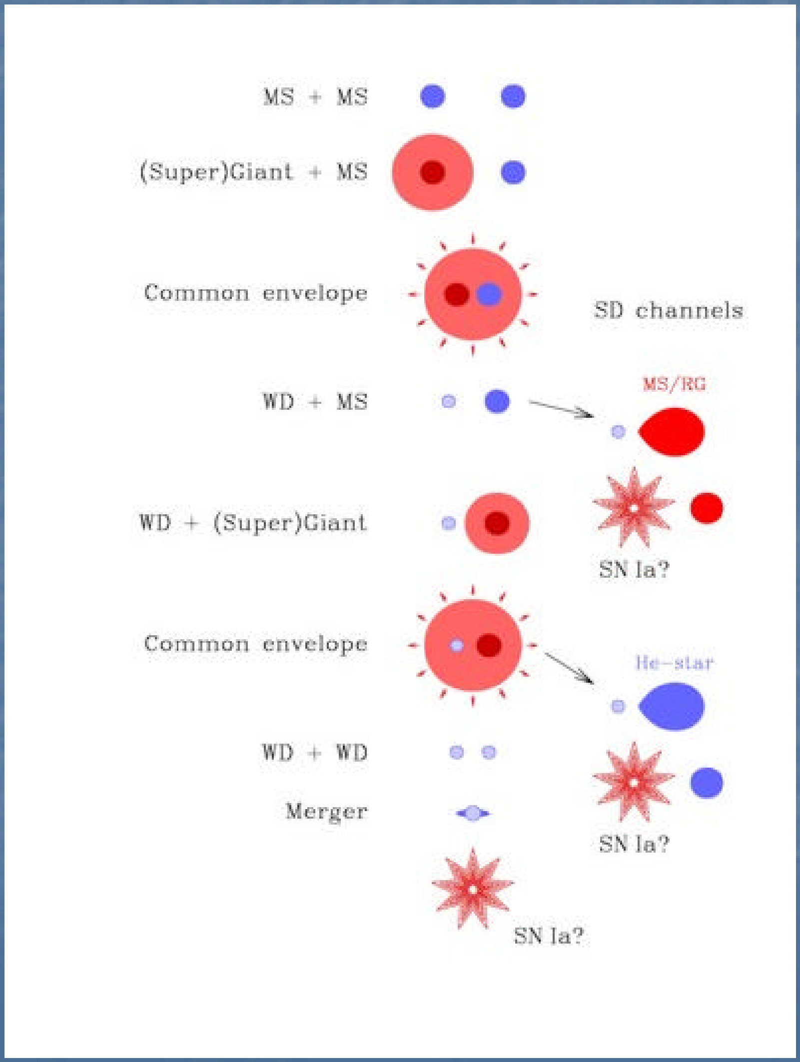
Type Ia Supernovae

- Supernovae (SNe) can be classified into 2 major groups:
  - Type I: H-deficient,
  - Type II: spectra exhibit H.
  - Ia: show SiII, Ib: show HeI, Ic do not show either strong SiII or HeI.
- SNe Ia are believed to result from the thermonuclear disruption of C/O white dwarfs.
- While SNe II are the result of core collapse of massive stars (and probably SNe Ib/Ic)

SN 1994d in NGC 4526

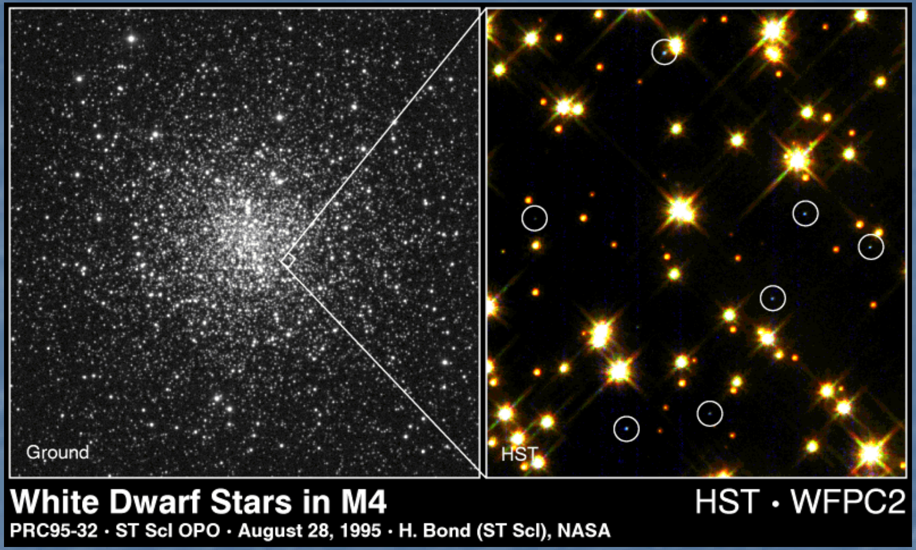
- SNe Ia have been used as distance indicators.
  - They are luminous,
  - Have small dispersion ($\sigma < 0.3$ mag) among their peak magnitute,
  - Believed to be standard candles.

Type Ia Supernovae



- Two possible explanations have been proposed:
  - MS+WD, where the WD is very near the Chandrasekhar limit where the MS accretes onto the WD, when the WD exceeds its Chandrasekhar limit it becomes a supernova.
  - WD+WD, where the total mass of the 2 white dwarfs exceed the Chandrasekhar limit, if they are close enough, gravitational wave loss will cause them merge.

White Dwarfs in Clusters



- White dwarfs can be used as standard candles for determining the distance to the cluster.
  - The colors and luminosities of white dwarfs are insensitive to metallicity.
- Can be used to determine the age of the cluster.
  - A lower limit on the age of a cluster by measuring determining the properties of the faintest white dwarfs.
  - Or if a population of white dwarfs can be observed, use the luminosity function to determine the age of the cluster.

Summary

- Most stars ($M < 8M_\odot$) will end their life as a white dwarf star.
- They are very compact objects and therefore very faint.
- Have a maximum mass – Chandrasekhar limit – 1.4 $M_\odot$.
- Most have a H-rich atmosphere (~75%).
- Luminosity of a white dwarf is the result of the release of thermal energy through the thin atmosphere.
- Several instability strips in the white dwarf cooling sequence, the most notable one is the ZZ Ceti instability strip which is due to the partial ionization of hydrogen.
- Play an important part in binary star evolution.
- White dwarfs are very useful in determining the age of the disk and clusters.