# *Einführung in die Astronomie II*

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Sommersemester 2007

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## *Introduction*



## Astronomie an der FAU

**NF im Vordiplom/BA:** Gebraucht werden:

- Klausuren Astronomie I und II
- Astronomisches Praktikum (Schein)

**Astronomie im Hauptstudium Physik:** hängt davon ab. . .

**PWB:** 10 SWS weiterführende Vorlesungen Astro-/Teilchenphysik, davon 2 SWS Theorie

**nichtphysikalisches Wahlfach:** wie NF im Hauptstudium, nur wenn Astronomie nicht im Vordiplom!

**Nebenfächler** (NF im Hauptstudium für Nichtphysiker):

- Astronomie I und II
- Eine weiterführende Vorlesung (2 SWS)
- Ein physikalischer Praktikumsschein (z.B. Astronomisches Praktikum)

**Frühstudium:** freiwillig,

- möglich sind Klausuren Astronomie I und II ($\Longrightarrow$ Scheine)





## Klausuren?!?

*Bologna-Prozess* ändert alles: politisch beschlossene Einführung von BA/MA Studiengängen.

*Idee:* Kumulative Abschlüsse, keine Prüfung am Ende.

An der FAU: Ab WS 2007/2008 BA , aber:

1. Wir haben (leider!!!) zu großen Andrang auf's Praktikum
2. Wir haben Frühstudierende, die BA studieren werden
3. Wir sollen Klausuren üben, bevor es Ernst wird. . .

### $\Longrightarrow$ KLAUSUR am 10. Juli 2007

Klausuren werden zu einem *benoteten* Schein führen, auf Wunsch sind bei Bestehen der Klausur auch *unbenotete* Scheine möglich.

## Praktikum

Praktikum wird an der Dr. Karl Remeis-Sternwarte, Bamberg, als Blockpraktikum durchgeführt:

- 10.09.–21.09.2007: NF im Vordiplom/BA, Lehramt
- 24.09.–05.10.2007: NF im Vordiplom/BA, Lehramt

Endgültige Voraussetzung für eine Teilnahme am Praktikum sind normalerweise zwei Scheine aus Astronomie I und II.

⟹ Wir haben zur Zeit eine Warteliste. Zulassungen zum Praktikum werden in der Astronomie I im WS07/08 stattfinden. Die Klausur aus dieser Vorlesung kann als Teil der Zulassungsvoraussetzungen benutzt werden.





## Textbooks

CARROLL & OSTLIE, 1996, *Modern Astrophysics*, Reading: Addison-Wesley, €80 (softcover), 1400 pp.
Advanced level, expects good physics background.
Recommended if you want to specialize in astronomy.

ZEILIK & GREGORY, 1998, *Introductory Astronomy & Astrophysics*, 4th ed., Thomson Learning, €64, 600 pp.
Intermediate level, self contained, but sometimes chaotic order.

KUTNER, 2003, *Astronomy: A Physical Perspective*, Cambridge: Cambridge Univ. Press, €55, 580 pp.
Modern physics based textbook, easy to read. Recommended.





## Textbooks

KARTUNNEN, KRÖGER & OJA, 2003, *Fundamental Astronomy*, Heidelberg: Springer, €64 (softcover), 500 pp.
Good general overview of astronomy.
Recommended, especially for exam preparation.

UNSÖLD & BASCHEK, 2004, *Der neue Kosmos. Einführung in die Astronomie und Astrophysik*, Berlin: Springer, €50, 577 pp.
Very good overview of stellar astronomy, weaker on extragalactic astronomy.
Good secondary reading.

DE PATER & LISSAUER, 2004, *Planetary Sciences*, Cambridge: Cambridge University Press, €93, 544 pp.
*The* textbook of planetary science.
Good secondary reading.





## Contents

| | |
|---|---|
| 17 Apr | Introduction, Reminders, Stellar evolution |
| 24 Apr | Stellar Evolution, II |
| 01 May | **no lecture** – May day |
| 8 May | End stages of stellar evolution |
| 15 May | Milky Way and Galactic Center |
| 22 May | Galaxies: Classification, properties |
| 29 May | **no lecture** – Pentecost |
| 5 Jun | Galaxies: Distances, Mass |
| 12 Jun | AGN, Galaxy clusters |
| 19 Jun | Cosmology: Expansion of the Universe |
| 26 Jun | Cosmology: Big Bang, first 3 minutes |
| 3 Jul | Evolution of the Universe |
| 10 Jul | EXAM |
| 17 Jul | Wrap up |

# *Stellar Structure and Evolution: Reminder*



## Zero Age Main Sequence

Once star has collapsed and nuclear fusion has started: zero age main sequence (ZAMS) is reached

> The Main Sequence is the result of steady state fusion ("burning") of hydrogen into helium in stellar centers.

. . . longest phase of stellar evolution (10 billion years for Sun)

Stellar structure defined by balance between pressure inwards due to gravitation and pressure outwards due to energy release ("hydrostatic equilibrium").





## Stellar Structure

Stellar structure governed by four coupled differential equations:

Mass structure
(mass conservation)

$$\frac{dM}{dr} = 4\pi r^2 \rho(r)$$

Pressure structure
(hydrostatic equilibrium)

$$\frac{dP}{dr} = -\rho(r)\frac{GM(r)}{r^2}$$

Temperature structure
(energy transport)

$$\frac{dT}{dr} = -\frac{3}{4ac}\frac{\kappa\rho(r)}{T^3}\frac{L(r)}{4\pi r^2}$$

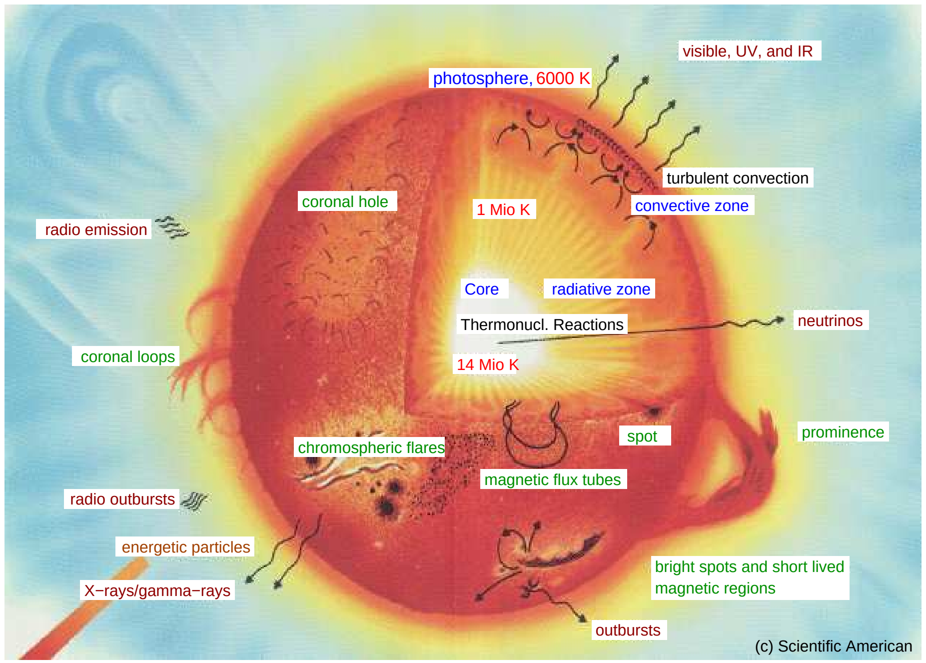
Energy conservation
(energy transport)

$$\frac{dL}{dr} = 4\pi r^2 \rho(r)\epsilon(r)$$

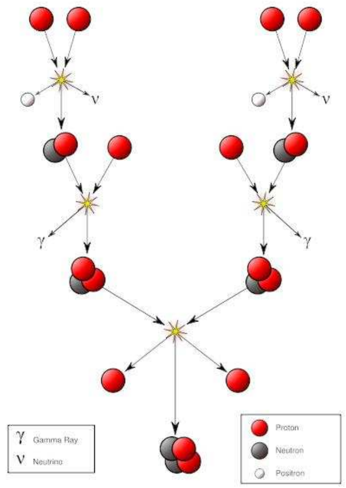
plus "equation of state" ($P = P(T, \rho)$), energy generation ($\epsilon = \epsilon(T, \rho, Z)$),. . .

> Stellar model: numerical solution of stellar structure equations.





## Energy generation: Proton-Proton chain




For moderate central temperatures, He is produced using the proton proton chain.

First, two protons create a deuteron:

$$^{1}\text{H} + {}^{1}\text{H} \longrightarrow {}^{2}\text{H} + \text{e}^{+} + \nu_{\text{e}} \qquad (2.1)$$

This process is slow (happens once for a nucleon per $10^{10}$ years)

Then an additional proton is attached:

$$^{2}\text{H} + {}^{1}\text{H} \longrightarrow {}^{3}\text{He} + \gamma \qquad (2.2)$$

and two helium nuclei can form an alpha particle:

$$^{3}\text{He} + {}^{3}\text{He} \longrightarrow {}^{4}\text{He} + 2{}^{1}\text{H} \qquad (2.3)$$

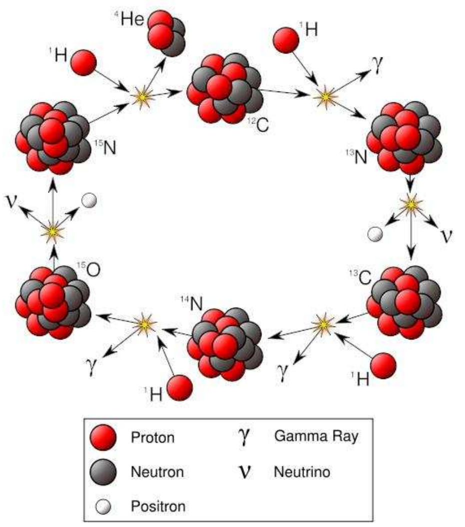
This is the so called pp I-cycle, minor variations of the theme exist (pp II, pp III cycles), but pp I dominates.

pp chain dominates for $T \lesssim 2 \times 10^{7}$ K, $\epsilon_{\text{pp}} \propto T^{5}$; Sun: 98.4%.





## Energy generation: CNO cycle




The CNO cycle (Bethe-Weizsäcker-cycle) requires the presence of C, N, and O isotopes as catalysts.

CNO cycle has slightly smaller energy release than pp-cycle because of higher neutrino losses.

Reaction $^{14}\text{N} + p \longrightarrow {}^{15}\text{O} + \gamma$ is th slowest reaction (one million years).

CNO cycle dominates above $2 \times 10^{7}$ K, $\epsilon_{\text{CNO}} \propto T^{17}$; Sun: 1.6%.

Wikipedia





## Solar Structure

Based on observations of

- Solar Mass: $1\,M_{\odot} = 1.997 \times 10^{30}$ kg $= 1.997 \times 10^{33}$ g
- Solar Luminosity: $1\,L_{\odot} = 3.127 \times 10^{26}$ W $= 3.127 \times 10^{33}$ erg s$^{-1}$
- Solar chemical composition (=elemental abundances): 75% H, 24% He, 1% metals (by mass)

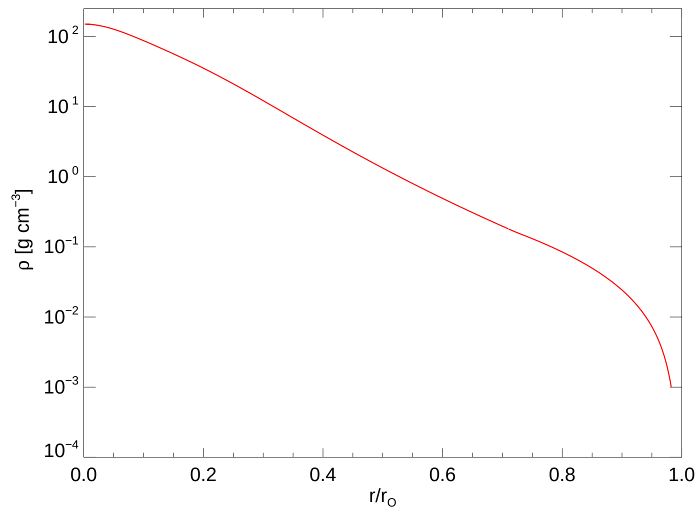
it is possible to use the equations of stellar structure to determine a model for the structure of the Sun, i.e., $M_r$, $L_r$, $\rho(r)$, $T(r)$, abundances$(r)$.

The best models available are called "standard models".



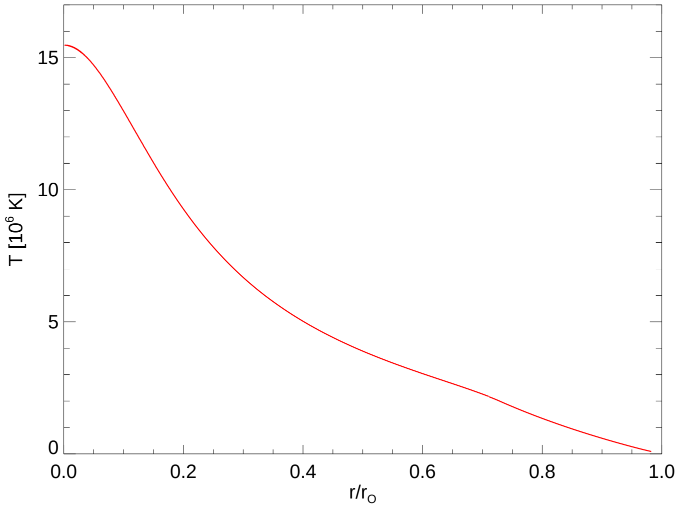


## Standard Solar Model, I




Standard solar model of Bahcall & Serenelli (2005, ApJ 626, 530)

## Standard Solar Model, II

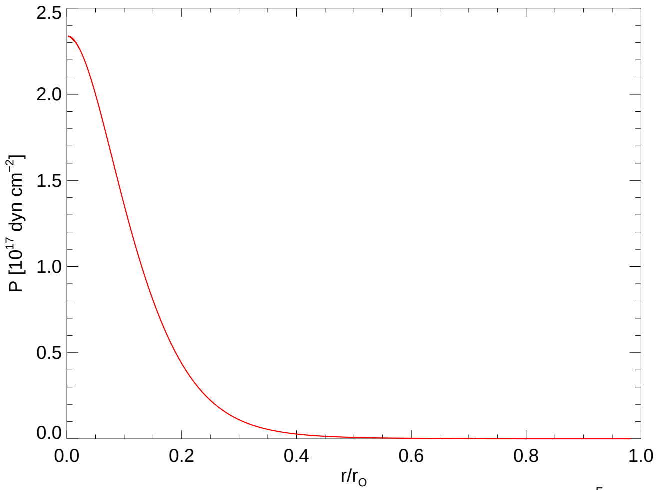



Standard solar model of Bahcall & Serenelli (2005, ApJ 626, 530)





## Standard Solar Model, III

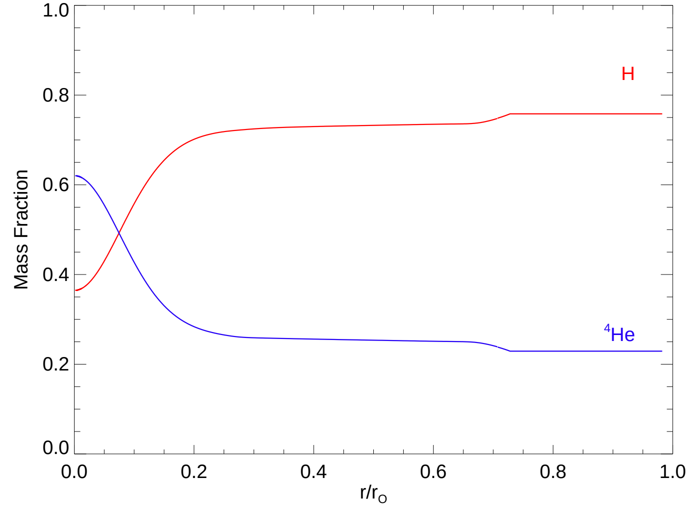



Standard solar model of Bahcall & Serenelli (2005, ApJ 626, 530; 1 dyn $= 10^{-5}$ N, 1 dyn cm$^{-2}$ $= 0.1$ Pa)





## Standard Solar Model, IV

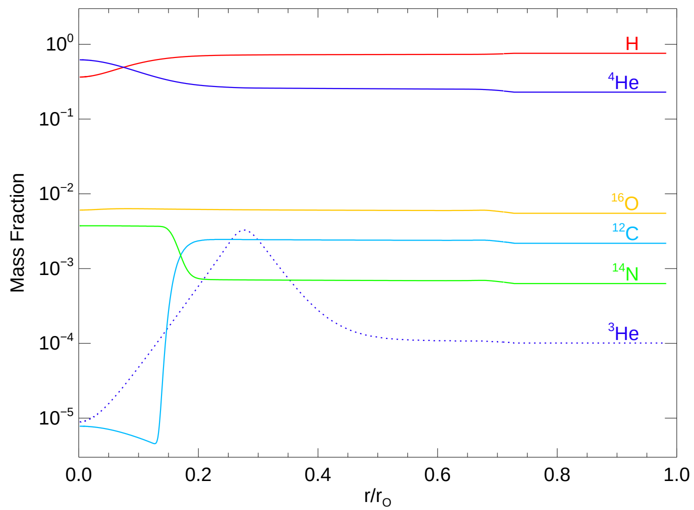



Standard solar model of Bahcall & Serenelli (2005, ApJ 626, 530)



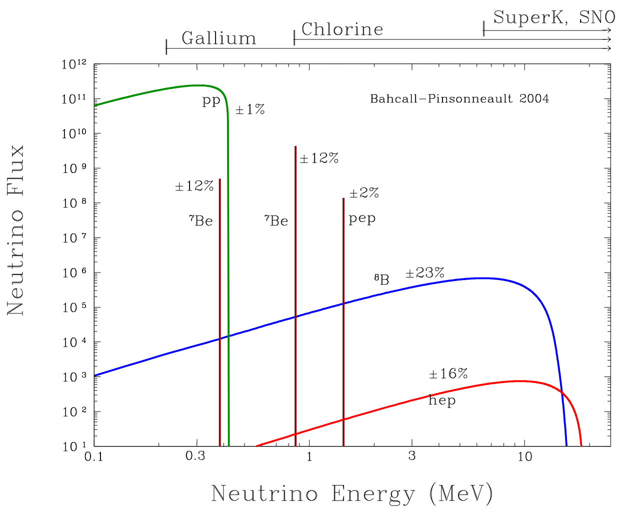


## Standard Solar Model, V




Standard solar model of Bahcall & Serenelli (2005, ApJ 626, 530)

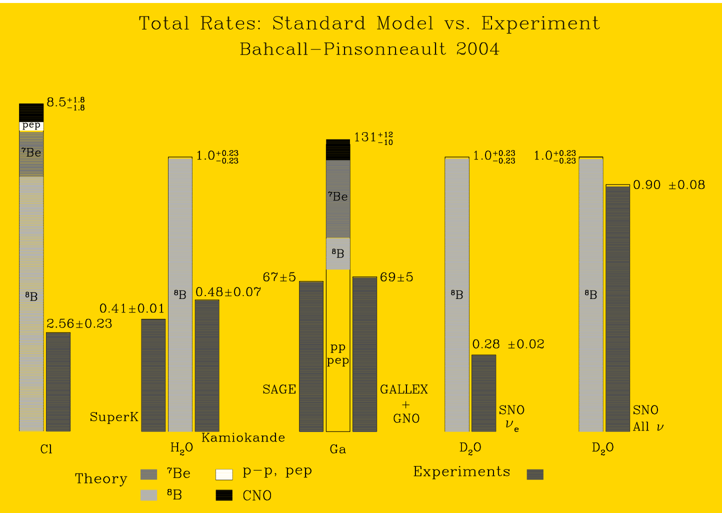
## Solar Neutrinos




The solar model predicts a solar neutrino spectrum that can be compared with Earth based measurements. This is the most direct test of theory of stellar structure known.

after Bahcall






Bahcall

SNO (2001): When taking *all* neutrino flavors into account, i.e., take into account that solar neutrinos change their flavor on the way from the Sun to us, the measured and predicted neutrino fluxes agree.



## *Stars: Evolution*



## Stellar Evolution

Now that we believe that the solar model is correct: stellar evolution

*Principle:*

1. Construct stellar model by solving equations of stellar structure for given radial abundances.
2. Evaluate change in elemental abundances as a function of radius based on the local fusion processes.
3. Change abundances appropriately for a time step $\Delta t$.
4. goto step 1

## Characteristic Timescales

Main sequence: Hydrogen burning at the center.

Evolution timescale dominated by the nuclear timescale = timescale needed to use the fuel in the center of the star.

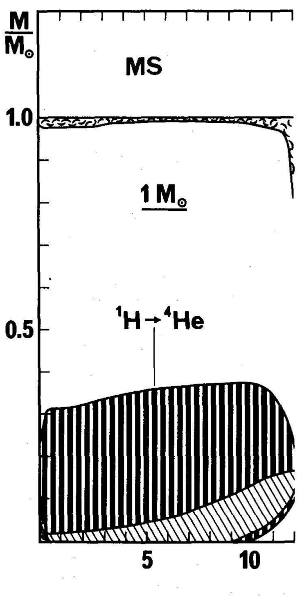
According to simulations, this is ∼10% of the available Hydrogen.
Since 0.7% of $M_{\text{core}}c^2$ converted into He, the nuclear timescale is

$$t_{\text{n}} = \frac{0.007 \cdot 0.1 M c^2}{L} = \frac{M/M_\odot}{L/L_\odot} \cdot 10^{10}\,\text{years} \tag{3.1}$$

A second important timescale is the timescale the star would need to radiate its stored thermal energy: thermal timescale.
Roughly given as

$$t_{\text{t}} = \frac{0.5 G M^2/R}{L} = \frac{(M/M_\odot)^2}{(R/R_\odot)(L/L_\odot)} \cdot 2 \times 10^{7}\,\text{years} \tag{3.2}$$



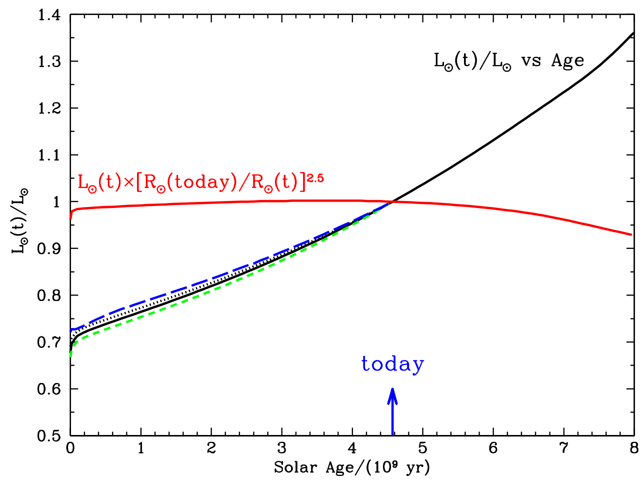



$t(10^9\,\text{years}) \longrightarrow$

Evolution of the structure of a 1 $M_\odot$ star on the main sequence (after Maeder & Meynet, 1989).



## MS Evolution: Luminosity

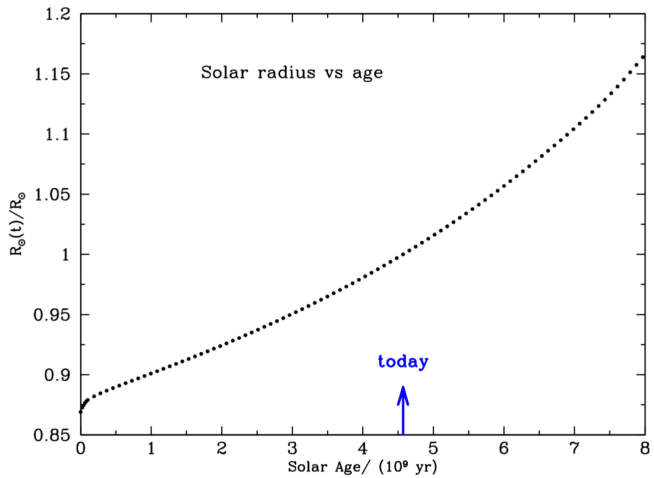



Bahcall, Pinsonneault & Basu (2001, ApJ 555, 990)



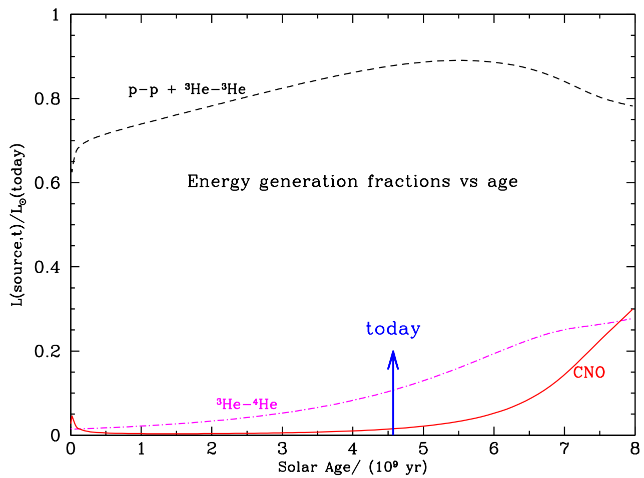


## MS Evolution: Radius




Bahcall, Pinsonneault & Basu (2001, ApJ 555, 990)

## MS Evolution: Energy Generation

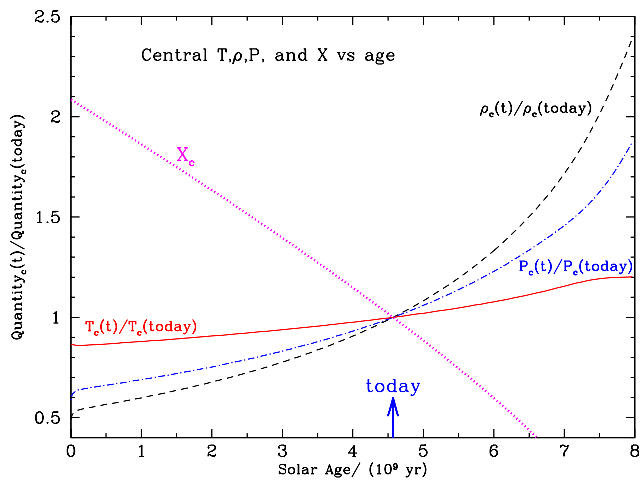



Bahcall, Pinsonneault & Basu (2001, ApJ 555, 990)





## MS Evolution: Center

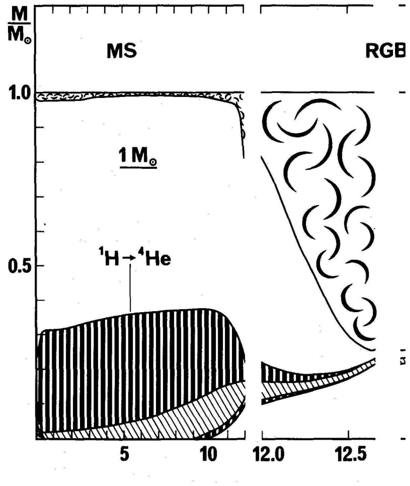



Bahcall, Pinsonneault & Basu (2001, ApJ 555, 990; $X_c$ is the central H fraction)





## Solar Mass Stars: Post Main Sequence, I




(Maeder & Meynet, 1989)

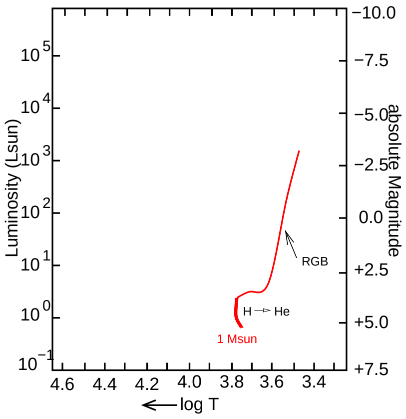
Once H is used up in center:
H continues to burn in a shell around the He core ("shell burning").

For stars with $M \lesssim 1\,M_\odot$): Star reacts by expanding convective hull until it is almost fully convective.





## Solar Mass Stars: Post Main Sequence, II




(after Iben, 1991)

Once H is used up in center:
H continues to burn in a shell around the He core ("shell burning").

For stars with $M \lesssim 1\,M_\odot$): Star reacts by expanding convective hull until it is almost fully convective.

$\Longrightarrow$ luminosity increases, temperature decreases

$\Longrightarrow$ motion in HRD horizontally towards the right, then upwards to higher $L$: red giant stage.

## Solar Mass Stars: Post Main Sequence, III

Reminder: stars are in hydrostatic equilibrium: inwards gravitational pressure balanced by outwards gas pressure

Since the gas pressure is $P = nkT$: energy source needed to heat gas (=fusion).

This is a problem for the core during the red giant stage, as virtually no fusion ongoing

$\Longrightarrow$ Core gets compressed

$\Longrightarrow$ $\rho$ and $T$ increase

BUT:

collapse cannot continue indefinitely!

$\Longrightarrow$ once $\rho$ has increased appreciably, there must be a point where quantum mechanical effects become important.





## QM interlude, I

Quantum mechanics: One of the stranger phenomena in QM is the Pauli exclusion principle:

> For particles such as electrons ("Fermions"), at least one of their quantum numbers must be different.

Quantum numbers are, e.g.,

- position $(x, y, z)$,
- momentum $(mv_x, mv_y, mv_z)$,
- angular momentum,
- spin $(s)$

All of these numbers are "quantized", i.e., can only have discrete values (e.g., spin: $+1/2$, $-1/2$).

In a typical gas, this is not a problem ("phase space is (almost) empty") once it becomes dense $\Longrightarrow$ exclusion principle kicks in.





### Different ways to write the equation of state of an ideal gas

Among the more confusing subjects of thermodynamics are the many different ways in which the ideal gas equation can be written.

The one I prefer for astronomy is

$$P = nkT$$

where

- $P$: Pressure (measured in $N\,\mathrm{m}^{-2}$)
- $n$: particle density (i.e., number of particles per cubic meter, unit: $\mathrm{m}^{-3}$)
- $k = 1.38066 \times 10^{-23}\,\mathrm{J\,K^{-1}}$: Boltzmann constant
- $T$: Temperature (measured in Kelvins)

This equation has the advantage that it counts all particles individually (thus using $n$). If you know the mass of the gas particles, $m_{\text{gas}}$ then another way of writing the ideal gas equation is

$$P = \frac{n m_{\text{gas}}}{m_{\text{gas}}} kT = \rho kT \frac{1}{m_{\text{gas}}}$$

illustrating that for an ideal gas, $P \propto \rho$, where $\rho$ is the mass density.

Another way to write the ideal gas equation is in terms of the total number of gas molecules, $N = nV$, where $V$ is the volume. The ideal gas equation then is

$$P = \frac{N}{V} kT \quad \Longleftrightarrow PV = NkT \quad \Longleftrightarrow \frac{PV}{T} = Nk$$

This version has the problem, however, that the number of gar molecules is typically rather large (there are $6 \times 10^{23}$ molecules in a volume of 22.4 liters of gas, this number of particles is called one *mole*). Because working with smaller numbers is generally thought a good idea, chemists prefer to work with moles. Per definition, the unit of particle number here is the Avogadro number $N_{\mathrm{A}} = 6.0221 \times 10^{23}$. So, if you want to work with moles, then the above equation becomes

$$PV = \frac{N}{N_{\mathrm{A}}} AkT = N_{\text{mol}} RT$$

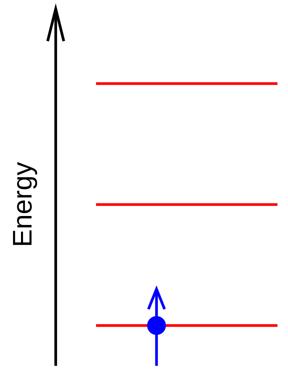
where

- $N_{\text{mol}}$: the number of moles of the gas in the volume $V$,
- $R = N_{\mathrm{A}} k 8.3145\,\mathrm{J\,mol^{-1}\,K^{-1}}$: the universal gas constant

To summarise, each of these equations has its own uses, and which one you want to use, really depends on the circumstances of the problem you are solving. For your future life as physicists, try to remember one of them, and then understand how you get from this one to the others, instead of memorising all four ones. This approach will need less memory and lead to a better understanding of what is really going on behind the scenes.



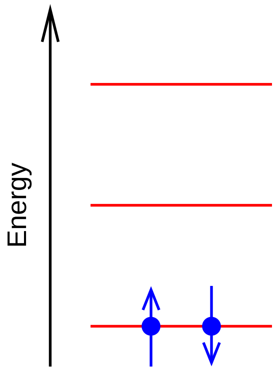
## QM interlude, II




Effect of high density on electron energy

Energy of electrons at the same position in space

## QM interlude, III



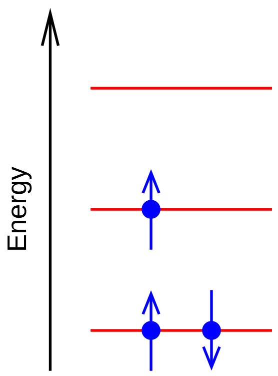

Effect of high density on electron energy

Energy of electrons at the same position in space





## QM interlude, IV



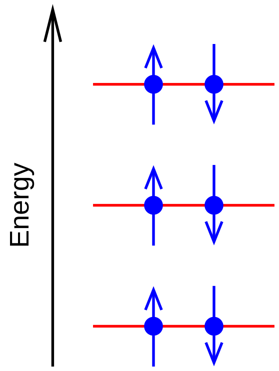

Effect of high density on electron energy

Energy of electrons at the same position in space





## QM interlude, VIII




Energy of electrons at the same position in space

Effect of high density on electron energy:

In degenerate electron gases, electrons have much higher energies than in thermal gas.

Interaction of electrons results in degeneracy pressure:

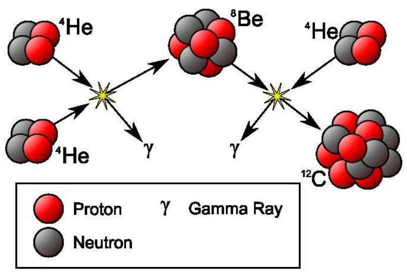
$$P = \frac{\hbar^2}{m_\mathrm{e}} n_\mathrm{e}^{5/3} \propto \rho^{5/3}$$

*Note:* The degeneracy pressure is independent of the temperature!





## Solar Mass Stars: Post Main Sequence, I




In the degenerate core, once $T_\mathrm{core}$ ~100 × $10^6$ K: Fusion stars the Triple alpha process:

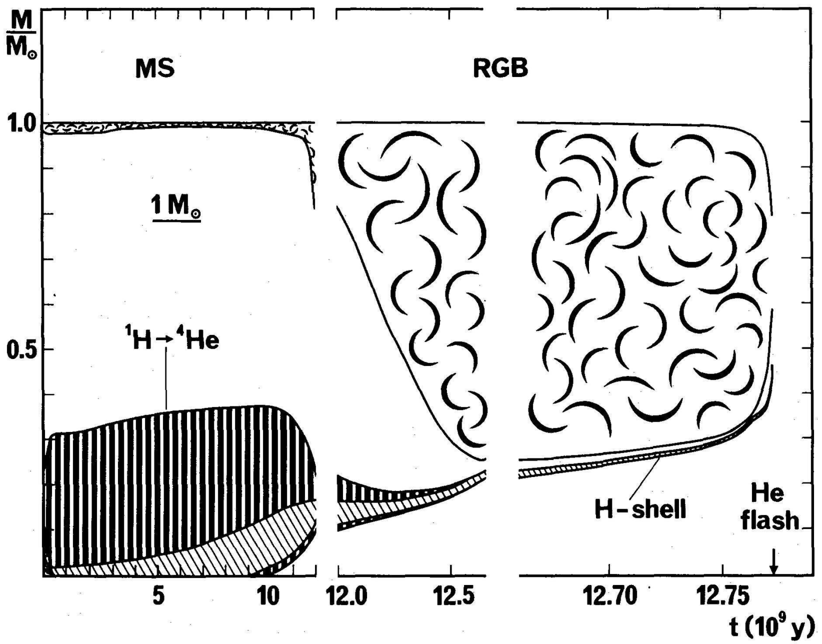
$$^4\mathrm{He} + {}^4\mathrm{He} \leftrightarrow {}^8\mathrm{Be}$$
$$^8\mathrm{Be} + {}^4\mathrm{He} \longrightarrow {}^{12}\mathrm{C}$$

Since $^8$Be has a half life of only $2.6 \times 10^{-16}$ s: effectively this can only work if 3 $\alpha$-particles collide.

But core is degenerate:

$\Longrightarrow$ High thermal conductivity of electrons
$\Longrightarrow$ core has uniform temperature
$\Longrightarrow$ $3\alpha$ onset is rapid
$\Longrightarrow$ He flash

Not seen on surface ("buffered" by convective envelope).



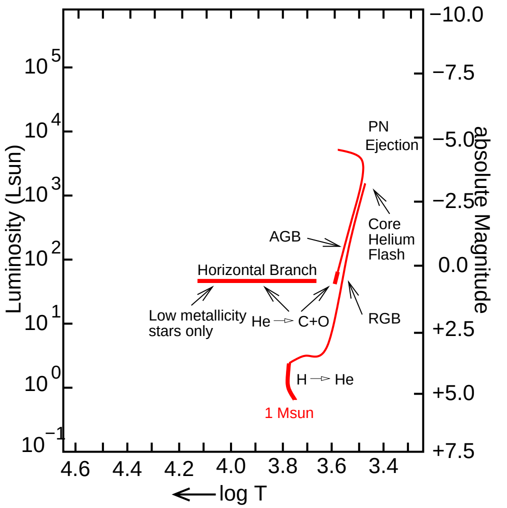

Evolution of the structure of a 1 $M_\odot$ star to the Helium flash (Maeder & Meynet, 1989).

Abell 39 (WIYN, AURA, NOAO, NSF)

planetary nebulae: material ejected during AGB phase, photoionized once remaining core of former star has shed enough mass to emit UV photons.



## Solar Mass Stars: Post Main Sequence, III




After the He flash star has He burning in core and H shell burning

$\Longrightarrow$ starts to expand again

$\Longrightarrow$ "asymptotic giant branch"

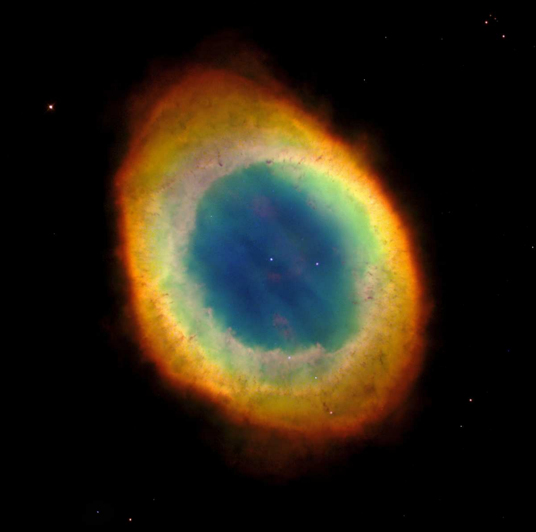
Instable He fusion processes ("thermal pulses") lead to ejection of outer layers ($\sim$50% of total mass!)

Effect of He core being unable to transport energy away quickly enough.

$\Longrightarrow$ inner (hotter) parts of star become visible.

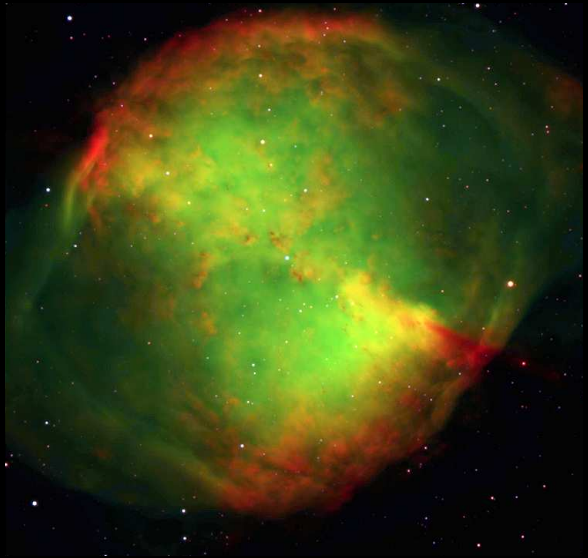
after Iben, 1991





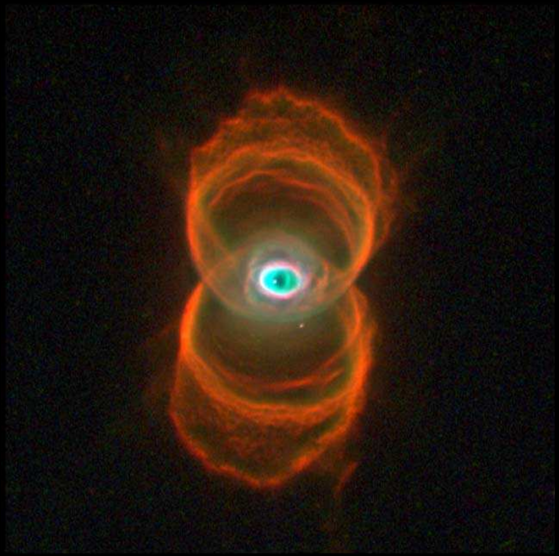
Ring Nebula (HST/STScI/NASA)

planetary nebulae: material ejected during AGB phase, photoionized once remaining core of former star has shed enough mass to emit UV photons.



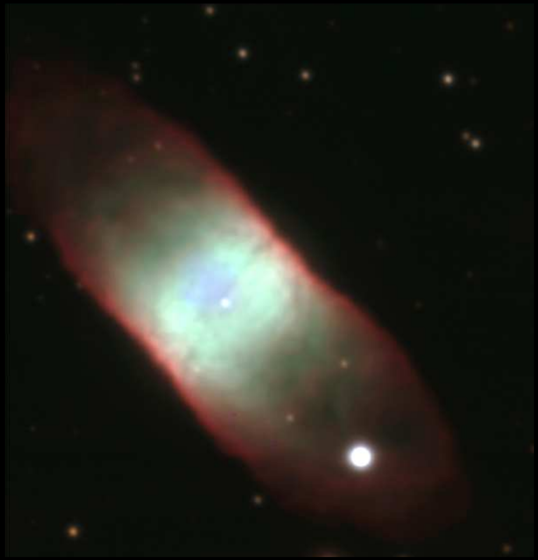
NGC 6853/M27 ("Dumbbell Nebula"; ESO VLT/FORS)

planetary nebulae: material ejected during AGB phase, photoionized once remaining core of former star has shed enough mass to emit UV photons.



Hourglass Nebula (HST/Sahai/Trauger)

planetary nebulae: material ejected during AGB phase, photoionized once remaining core of former star has shed enough mass to emit UV photons.



IC4406 (ESO VLT)

planetary nebulae: material ejected during AGB phase, photoionized once remaining core of former star has shed enough mass to emit UV photons.