# Astrophysics I: Stars and Stellar Evolution

## AST 4001

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Stars and Stellar Evolution, Fall 2008

# Agenda

1. Recap
   - Web site access
   - Basic Assumptions About Stars
   - The Sun
2. Stellar System
   - Spectra and Colors
   - Observations of Groups of Stars
   - Evolution of the Sun
3. Summary
   - Stellar System
   - Build Your Own Star

# Overview

# Contact

- **Location & Dates:**
  Physics 236A, MTWTh 10:10-11:00 AM
- **Office hours:**
  Wednesdays, 13:00-14:30, 342F Tate
- **email:**
  *I cannot guarantee that I will receive all emails due to SPAM filters. On class days I will try to reply to email within 24 h.*
- **Web site:**
  `http://stellarevolution.org/AST-4001`
  I will post notes, updates, problem sets, etc.
- **Google course calendar** (on Web site):
  `o86pe6r5paic30h4qv6acm9ej0%40group.calendar.google.com`

# Web site access

- user name: **Ast-4001**
- password: **&32y^nbY**

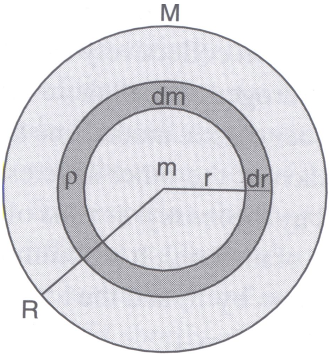
# What are Stars?

Stars

1. are bound by self-gravity
2. radiate energy supplied by an internal source

Usually stars have a nuclear energy source

# Relation between mass and radius coordinates




- integral formulation:

$$m(r) = \int_0^r 4\pi r^2 \rho(r)\,\mathrm{d}r$$

- differential formulation

$$\mathrm{d}m = 4\pi \rho r^2 \mathrm{d}r$$

(first *stellar structure equation*)

# The Sun

- Luminosity
  $L_\odot = 3.84 \times 10^{33}$ erg/s $= 3.84 \times 10^{26}$ J/s
- Mass
  $M_\odot = 1.98 \times 10^{33}$ g $= 1.98 \times 10^{30}$ kg
- Radius
  $R_\odot = 6.98 \times 10^{10}$ cm $= 6.98 \times 10^{5}$ km

# Gravitational Binding Energy

Binding energy can be approximated by

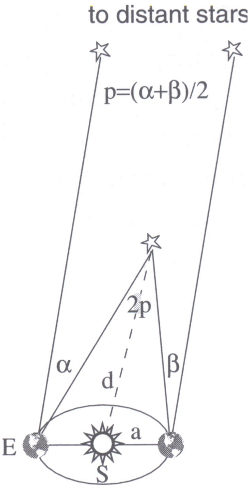
$$E = \frac{\mathrm{G}M^2}{2R} \quad , \qquad G = 6.67259 \times 10^{-8} \frac{\mathrm{cm}^3}{\mathrm{g\,s}}$$

The lifetime of the star is then defined by how long it takes to radiate away that energy, hence dividing by luminosity

$$\tau_{\mathrm{KH}} = \frac{E}{L} = \frac{\mathrm{G}M^2}{2RL}$$

This is called the *Kelvin-Helmholtz time-scale*.
It tells how long a star takes to radiate away it gravitational binding energy. This is also the time-scale for stars to get in *gravo-thermal* equilibrium.

# Parallax




- Sufficiently close objects change their position in the sky relative to an infinitely remote background as the earth moves around the sun.
- maximum "baseline" is 2 AU, about $3 \times 10^{13}$ cm
  1 AU = Earth-Sun Distance
- distance can be obtained from
  $p = (\alpha + \beta)/2$
  $\frac{a}{d} = tan(p) \approx p$, $d = p/a$
- Proxima Centauri: p=0".76, $d = 4.3$ lyr
- method works till about 500 pc

# Basic Assumptions

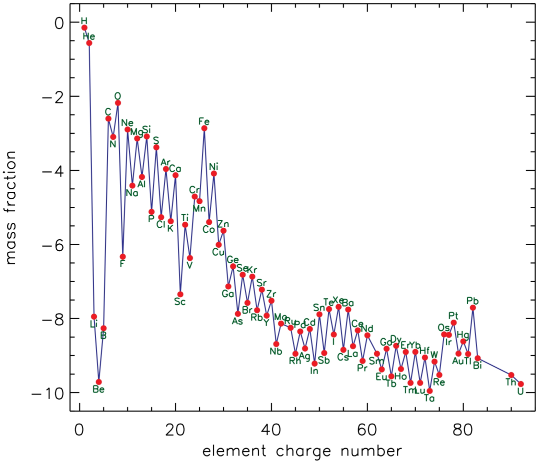
- stars evolve *in isolation*
  distances between stars are large compared to their radii
- spherical symmetry
  sun rotates once in 27 days, $\omega \approx 2.5 \times 10^{-6}\,\mathrm{s}^{-1}$

$$\frac{M\omega^2 R^2}{GM^2/R} = \frac{\omega^2 R^3}{GM} \approx 2 \times 10^{-5}$$

- only small variation in (initial) composition of stars
  sun: $X = 0.70$, $Y = 0.28$, $Z = 0.02$, $X + Y + Z = 1$
- small magnetic fields - even for $B \sim 1000\,\mathrm{G}$:

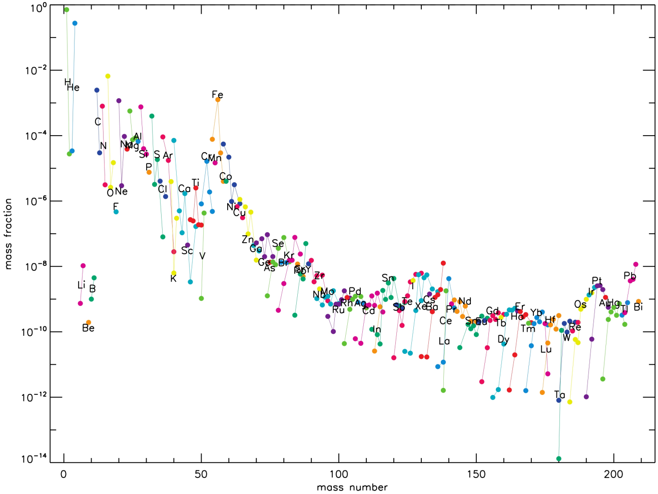
$$\frac{B^2}{GM^2/R^4} = \frac{B^2 R^4}{GM^2} \sim 10^{-11}$$

# The Solar Abundance Pattern (Elements)



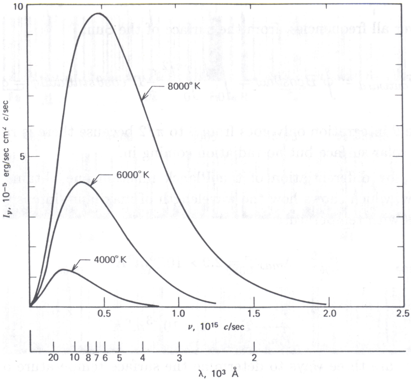

The solar abundance pattern, by mass fraction of elements.

# The Solar Abundance Pattern (Isotopes)



# Overview

# The Planck "Spectrum"




**Black Body Radiation:**

number of photons:

$$n(\nu)\mathrm{d}\nu = \frac{8\pi\nu^3}{c^3}\frac{\mathrm{d}\nu}{e^{\frac{h\nu}{kT}} - 1}$$

energy:

$$E(\nu)\mathrm{d}\nu = h\nu\ n(\nu)\mathrm{d}\nu\ .$$

# Solar Lines

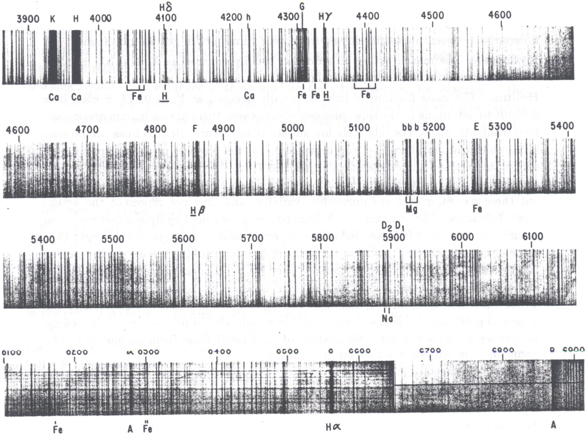



Figure 4. Absorption line spectrum of the Sun. Wavelengths are given in angstroms ($10^{-10}$ m).

# The Solar Spectrum

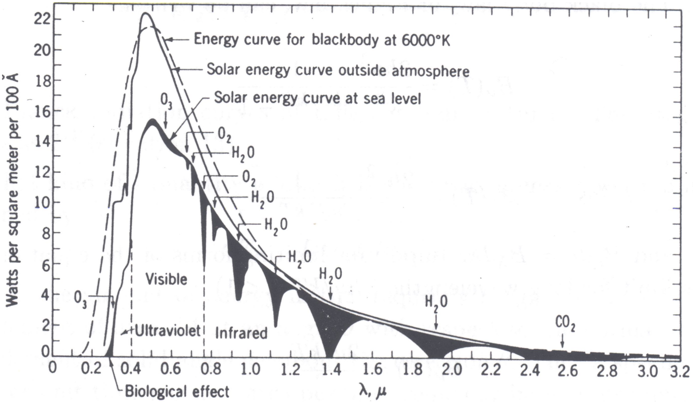
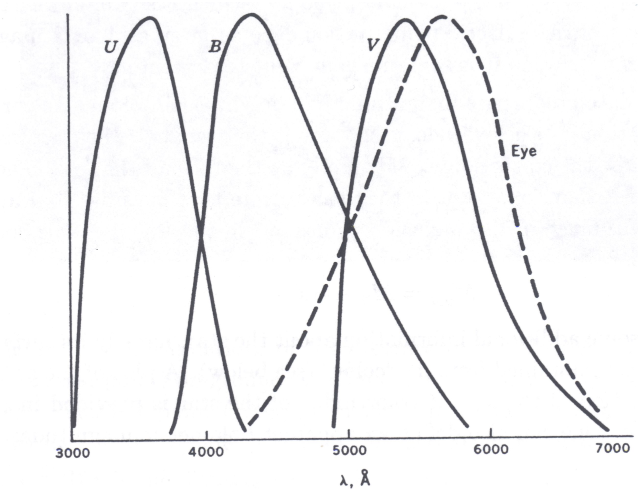
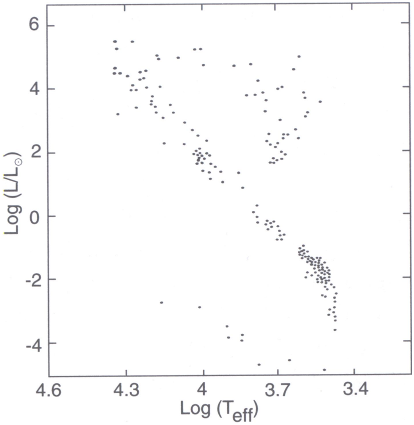



**FIGURE 2.1** The spectral energy curve of the Sun at sea level and extrapolated outside the atmosphere, as given by E. Pettit. *From Astrophysics by J. A. Hynek (ed.). Copyright, 1951. McGraw-Hill Book Company.*

# Colors - Filters



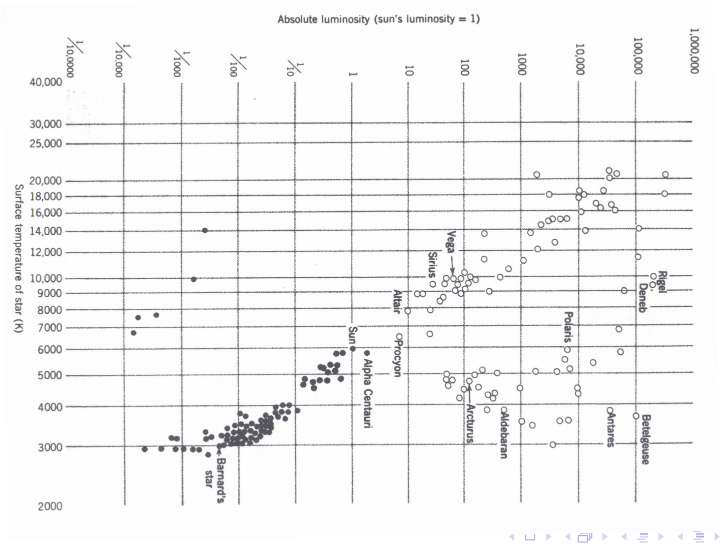
# The Hertzsprung-Russell Diagram (H-R diagram, HRD)




HRD in the neighborhood of the sun.

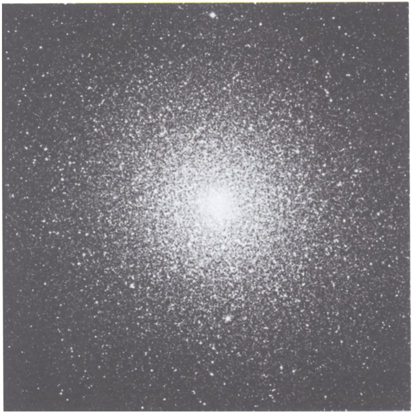
- $\log_{10}(T_{\rm eff}/{\rm K})$ on *x*-axises *decreasing*
- $\log_{10}(L/{\rm L}_\odot)$ on *y*-axis

# HRD in the neighborhood of the sun



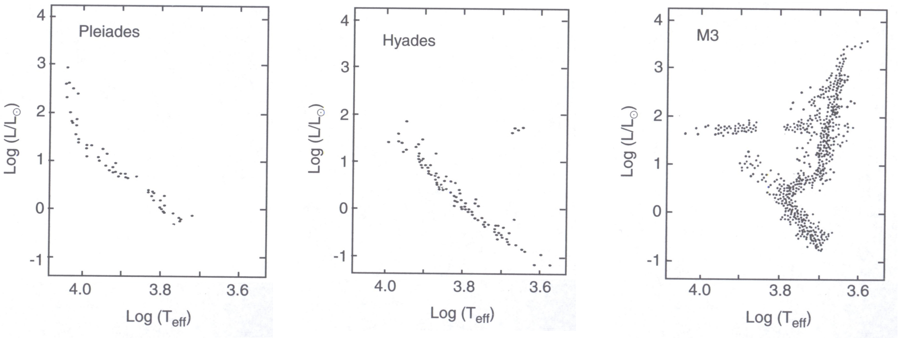
# Clusters of Stars

Pleiades cluster
open cluster

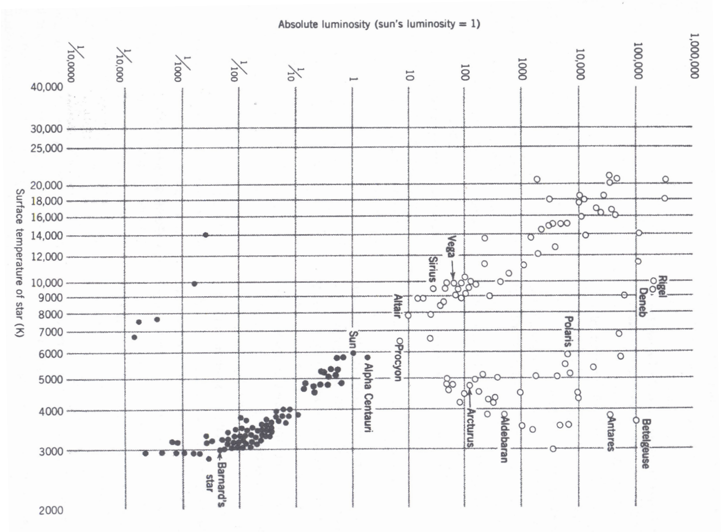


47 Tucanae cluster
globular cluster

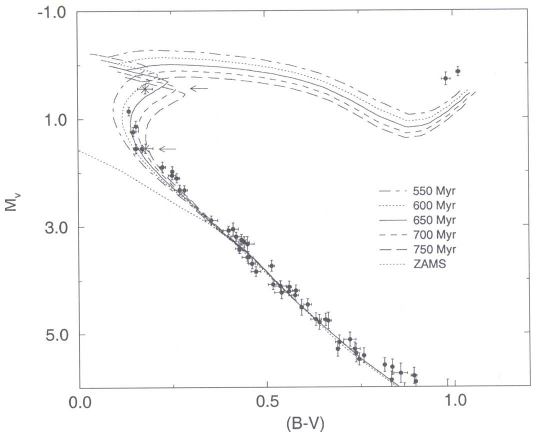
# HRD and Stellar Age



# HRD and Stellar Age

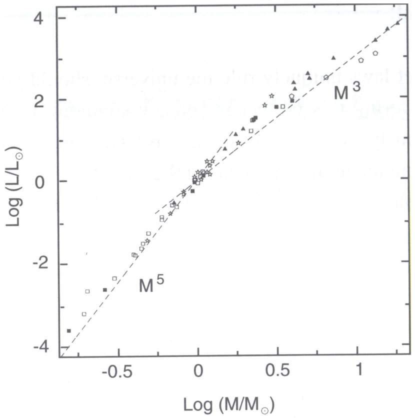


# Cluster Ages




Hyades cluster and stellar tracks

# Mass-Luminosity Relation




Mass-Luminosity relation for (zero-age) main-sequence (ZAMS) stars

$$L \propto M^{\nu}$$

with $\nu = 3 \ldots 5$.
Can be calibrated piecewise to

$$\frac{L}{\mathrm{L}_\odot} = \left(\frac{M}{\mathrm{M}_\odot}\right)^{\nu}$$

# Quiz

Determine the mass-luminosity relation for the most massive stars, stars with more than 100 $\mathrm{M}_\odot$.
Their luminosity is limited by the *Eddington luminosity*.
Assume that

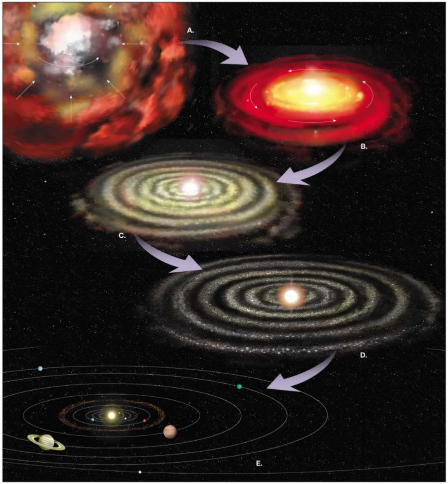
- these stars have a lifetime independent of mass
- they use all their nuclear fuel
- they all have the same composition and therefore the same amount of total nuclear energy release per unit mass.

What is the index $\nu$ in

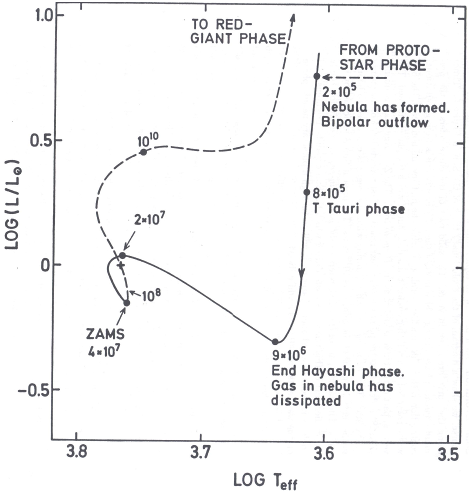
$$\frac{L}{\mathrm{L}_\odot} = \left(\frac{M}{\mathrm{M}_\odot}\right)^{\nu}$$

for these stars? Discuss with your neighbor(s).

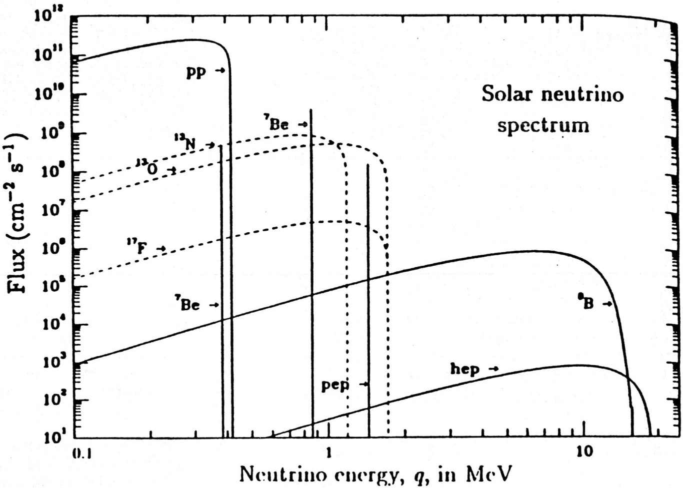
# Formation of the Solar System



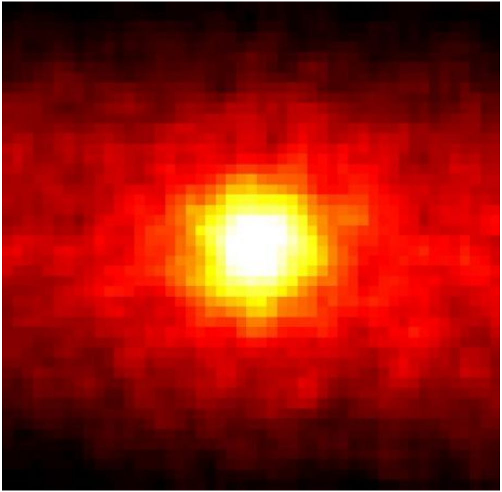
# Evolution of the Sun in the HRD



# The Solar Neutrino Spectrum



# The Sun as Seen in Neutrinos



# Overview

# Summary

- The lifetime of a star depends on its (initial) mass
- More massive stars live shorter
- Ages of clusters of stars, with all stars formed at about the same time, can be determined form the most massive star that is still on the "*main sequence*" (central hydrogen burning)

# Stellar Evolution Project

- Bill Paxton's **EZ Stellar Evolution** code
  `http://www.kitp.ucsb.edu/~paxton/EZ-intro.html`
- Uses Linux `gfortran`
- g95 FORTRAN compiler can be downloaded for most platforms.
  `http://www.g95.org`