Lecture 16

The Message of Starlight

(Not delivered Fall 2007)

Outline of Lecture 16

- Spectral sequence OBAFGKMLT as sequence in surface (effective) temperature or intrinsic color from blue to red and beyond (infrared).
- Hertzsprung-Russell diagram of L versus T_e, or brightness (absolute or apparent) versus color (ratios of brightness in different filters; denoted B-V for blue vs. visual [in logarithmic terms]).
- Nuclear reactions in main-sequence stars and beyond:
  – Thermonuclear fusion reactions using charged particles require high temperatures so that nuclei can overcome the Coulomb barrier to come close enough to allow *strong nuclear force* to bind them together.
  – Starting from mostly protons (because the Sun and other stars are made mostly of hydrogen), fusion reactions must convert roughly half the protons into neutrons. This transformation is accomplished by the *weak nuclear force*.
  – Competition between the short-range forces of nuclear attraction among neutrons and protons and the long-range force of electrostatic repulsion among the protons leads to the iron-group elements being the most bound of all atomic nuclei. This means that nuclear energy can be released by two means: (1) *fusion reactions* that combine light nuclei to build intermediate-mass nuclei, (2) *fission reactions* that break heavy nuclei into intermediate-mass pieces.

Deciphering Starlight

- Stars like Sirius are suns at great distances (Huygens).
- Auguste Compte (1798-1857): "There are some things of which the human race must remain forever in ignorance, for example, the chemical constitution of the heavenly bodies."
- Spectroscopic resemblance of stars to Sun (Fraunhofer) → Similar kind of chemical makeup (Kirchhoff).
- Spectroscopic classification by Williamina Fleming (1857-1911) and Annie Jump Cannon (1863-1941): linear alphabetical sequence in decreasing strength of H lines (A, B, …).
- Alphabetical sequence is not temperature sequence. Megnhad Saha (1863-1956) and Henry Norris Russell (1877-1957) showed that sequence in decreasing surface (effective) temperature is OBAFGKMLT.
- Quantitative spectral analysis by Cecilia Payne Gaposchkin (1900-1999): dominance of H and He in universe of stars.

Spectral Signatures & Effective Temperatures

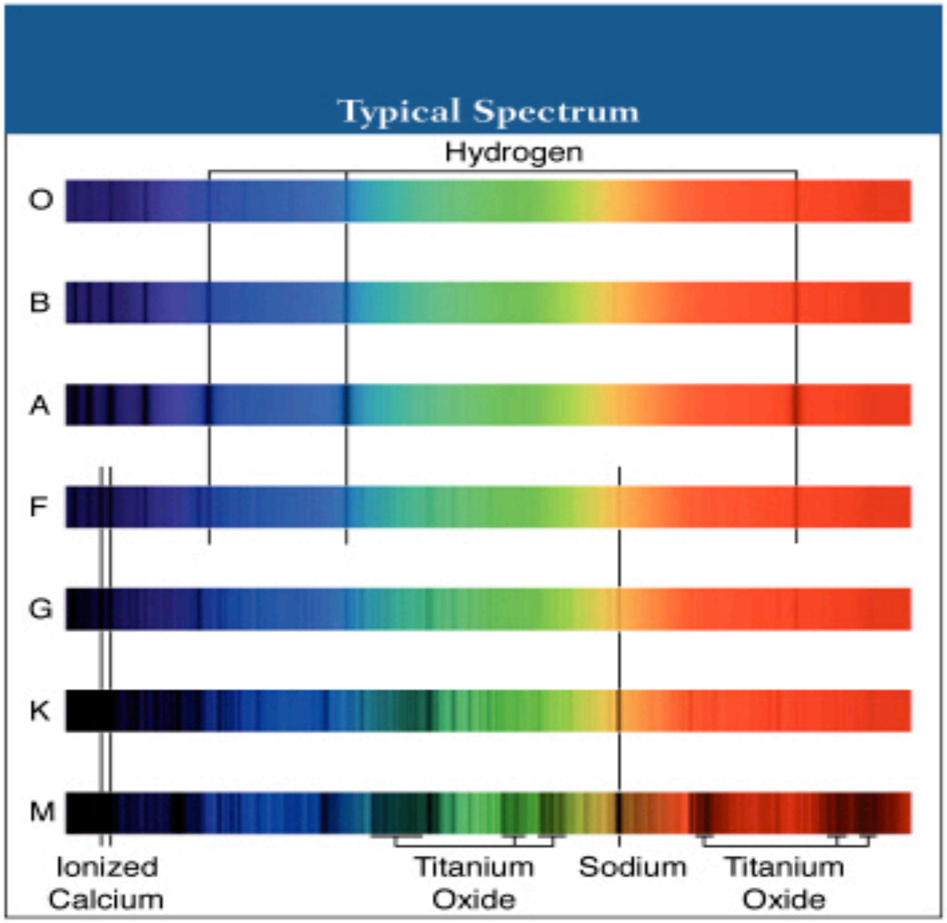
Oh
Be
A
Fine
Girl (Guy)
Kiss
Me!

Table 15.1(a) The Spectral Sequence

Spectral Type	Example(s)	Temperature Range	Key Absorption Line Features	Brightest Wavelength (color)
O	Stars of Orion's Belt	>30,000	Lines of ionized helium, weak hydrogen lines	<97 nm (ultraviolet)*
B	Rigel	30,000 K–10,000 K	Lines of neutral helium, moderate hydrogen lines	97–290 nm (ultraviolet)*
A	Sirius	10,000 K–7,500 K	Very strong hydrogen lines	290–390 nm (violet)*
F	Polaris	7,500 K–6,000 K	Moderate hydrogen lines, moderate lines of ionized calcium	390–480 nm (blue)*
G	Sun, Alpha Centauri A	6,000 K–5,000 K	Weak hydrogen lines, strong lines of ionized calcium	480–580 nm (yellow)
K	Arcturus	5,000 K–3,500 K	Lines of neutral and singly ionized metals, some molecules	580–830 nm (red)
M	Betelgeuse, Proxima Centauri	<3,500 K	Molecular lines strong	>830 nm (infrared)

* All stars above 6,000 K look more or less white to the human eye because they emit plenty of radiation at all visible wavelengths.

Appearance of Stellar Spectra



Type O Blue stars with surface temperatures of 20,000 to 35,000 K. Spectra show multiple ionized atoms, especially He II, C III, N III, O III, Si V. He I is visible, but H I is weak.

Type B Blue-white stars with surface temperatures of about 15,000 K. He II lines have disappeared, He I is strongest at B2. H I lines getting stronger. O II, Si II, and Mg II lines are visible.

Type A White stars with surface temperatures of about 9000K. The H I lines dominate the spectrum and are strongest at A0. He I no longer visible. Neutral metal lines begin to appear.

Type F Yellow-white stars with surface temperatures of about 7000 K. The H I lines are getting weaker while Ca II are getting stronger. Many other metals such as Fe I, Fe II, Cr II, and Ti II are getting stronger.

Type G Yellow stars like the Sun with surface temperatures of about 5500 K. H I lines still getting weaker while Ca II lines are strongest at G0. Metal lines are getting stronger.

Type K Yellow-orange stars with surface temperatures of about 4000 K. Spectrum is dominated by metal lines. Ca I getting stronger. TiO bands become visible at K5.

Type M Red stars with surface temperatures of about 3000 K. TiO bands are very prominent. Ca I at 423 nm is very strong. Many neutral metal lines are seen. For stars cooler than M4, absorption by TiO is so severe that it is very difficult to find the continuum.

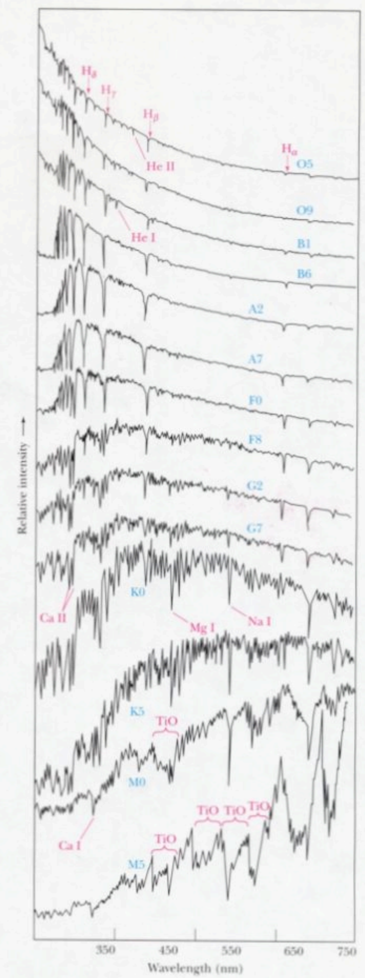


Figure 19-11

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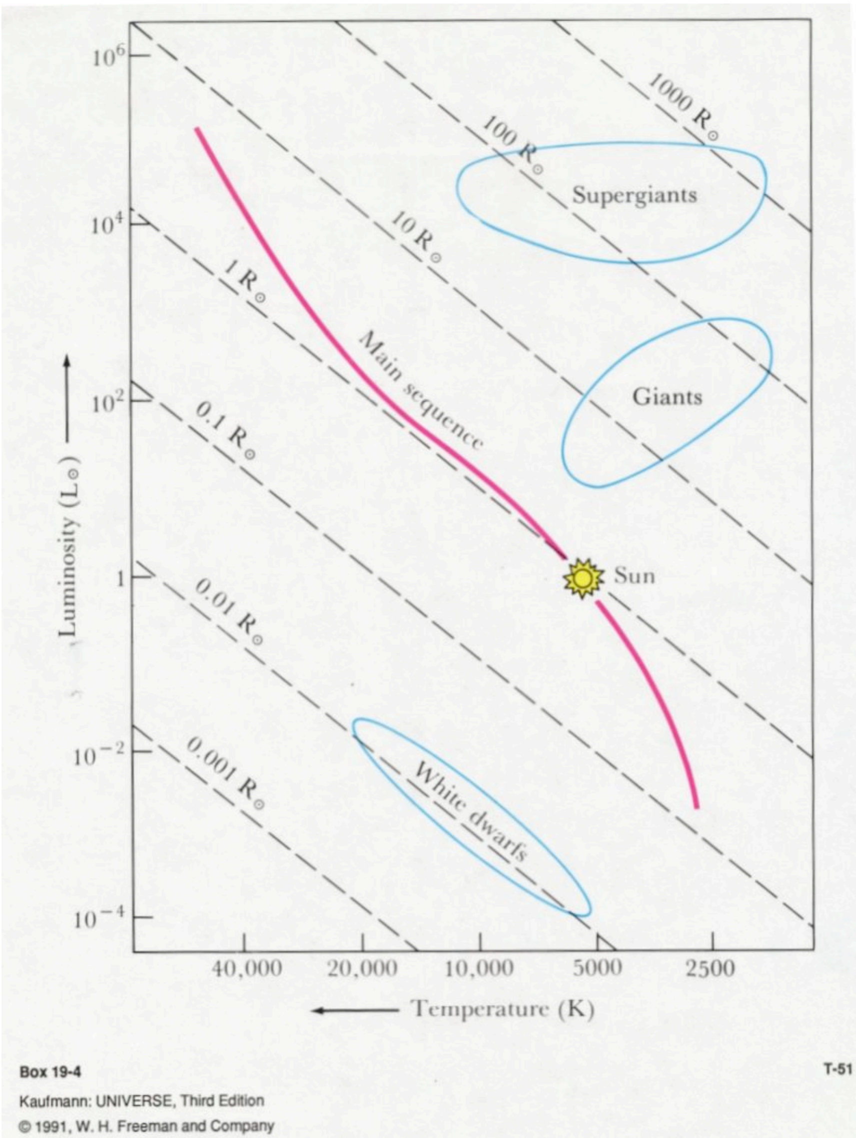
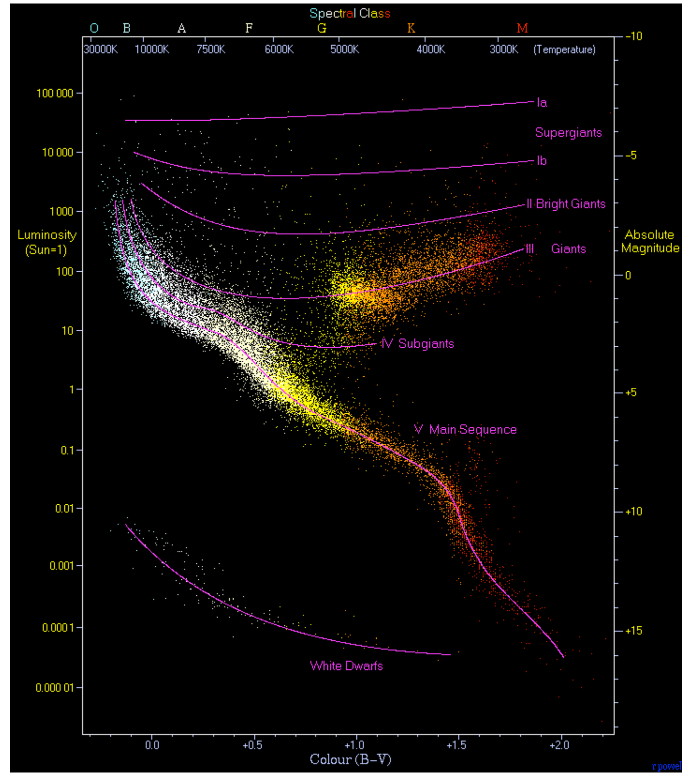
Kaufmann: UNIVERSE, Third Edition

Hertzsprung-Russell Diagram





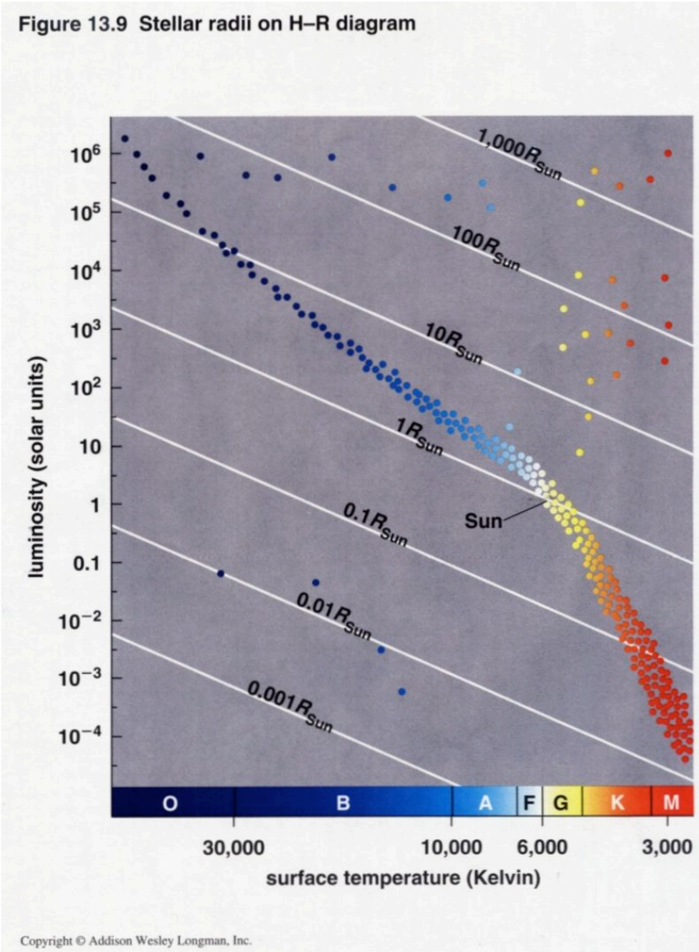
Modern H-R diagram for 22,000 nearby stars with a mixture of ages and initial elemental abundances whose distances were obtained by the Hipparchos astrometric satellite, supplemented by 1,000 cool red dwarfs from Gliese's catalog of nearby stars. (Powell/Wikipedia)

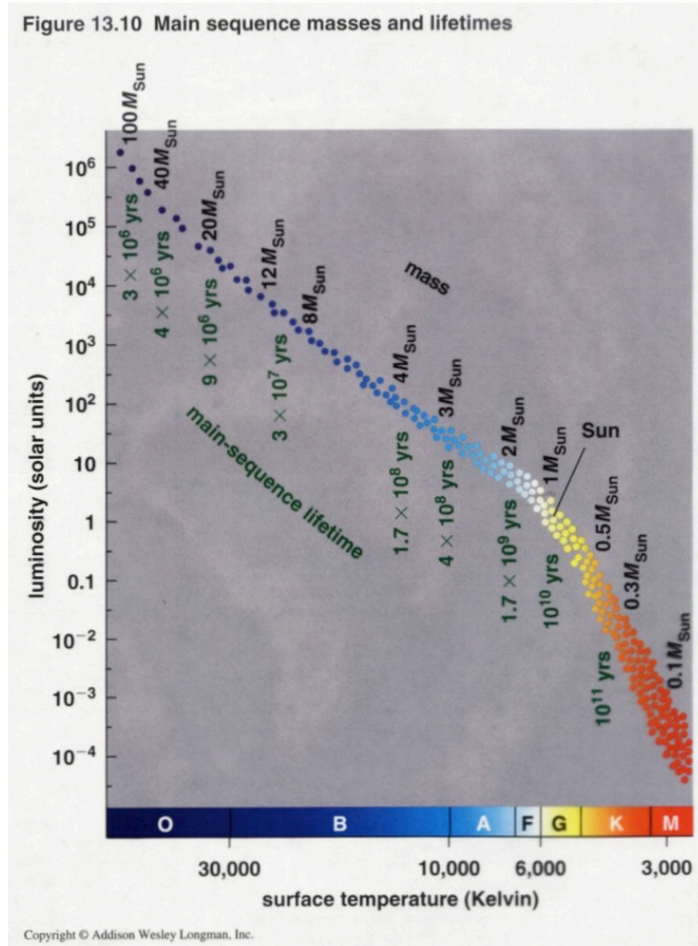
Main-Sequence Stars and Brown Dwarfs

- 90% of visible stars are found on diagonal band in H-R diagram called the "main-sequence."
- On the main-sequence, stars are steadily fusing H into He in their cores at a rate that offsets the radiative loss of energy from their surfaces (photospheres).
- The balance between energy generation and energy loss is achieved by adjusting the radius (and, thereby, the central temperature) of the star.
- At "zero age," main-sequence stars have a uniform chemical composition (deduced to be their present surface compositions).
- In *Population I* stars, this initial chemical composition is about 70% H (by mass), 28% He, and 2% heavier elements. *Population II* stars typically have 10-100 times less heavy elements.
- On main-sequence, low-mass stars have small *L* and low T_e (lower-right); high-mass stars have large *L* and high T_e (upper-left).

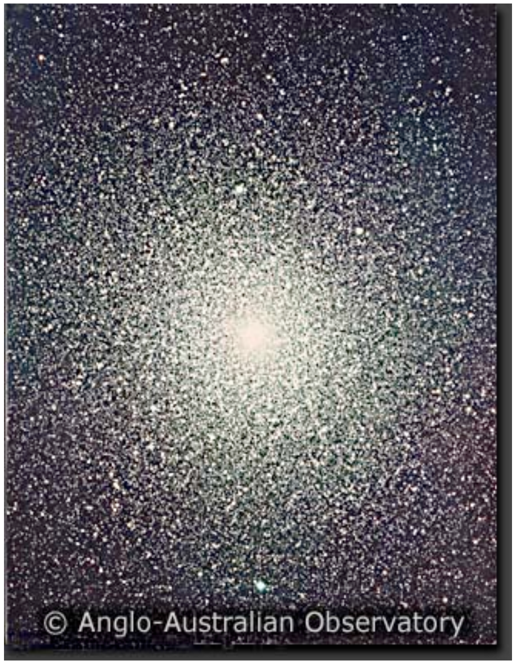
- More than fifty years ago, theorists hypothesized objects *between stars* (capable of thermonuclear fusion) *and planets* (incapable of thermonuclear fusion).
- Later they were given the name brown dwarfs by Jill Tarter (now a prominent SETI researcher – model for role of Jodie Foster in movie *Contact*).
- Brown dwarfs have masses between 0.08 $M_\odot$ and 0.013$M_\odot$, too low to fuse H but high enough to fuse D (deuterium = "heavy hydrogen"). Because they are extremely faint, brown dwarfs were discovered observationally only during the last decade.
- The surface temperatures of brown dwarfs are very low, often below 2000 K. Two new spectral types have been invented to characterize their atmospheres (photospheres):
  - L → TiO bands weak or absent (condensed and dropped out of atmosphere).
  - T → Methane bands begin to appear (atmosphere cool enough to have relatively fragile molecule).
  - Oh, Be A Fine Girl (Guy), Kiss Me, Like That!

Radii, Masses, and Lifetimes on the Main Sequence





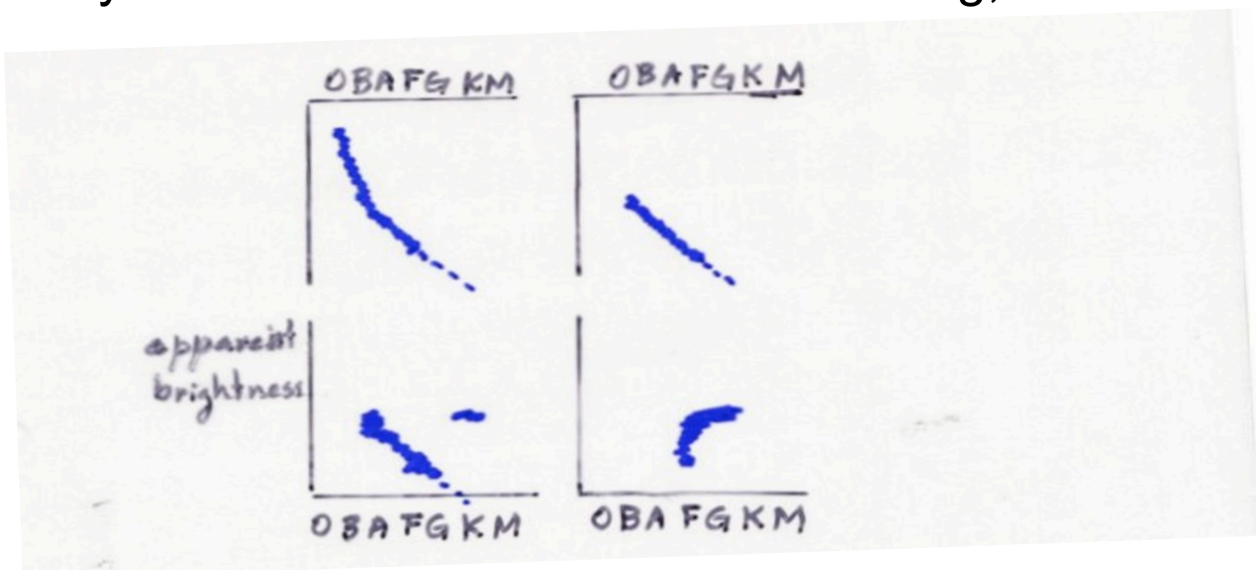
Two Kinds of Star Clusters



- Stars in a given cluster have same age and same initial elemental composition.
- Different clusters have different ages and different initial compositions for elements heavier than H and He.
- Extremes are found for two kinds of star clusters:
  - Open (left): found in disk of galaxy, younger ages, higher abundances of heavy elements -- Population I
  - Globular (right): found in halo of galaxy, oldest ages, lower abundances (but not zero!) of heavy elements -- Population II

H-R Diagram of Open Clusters

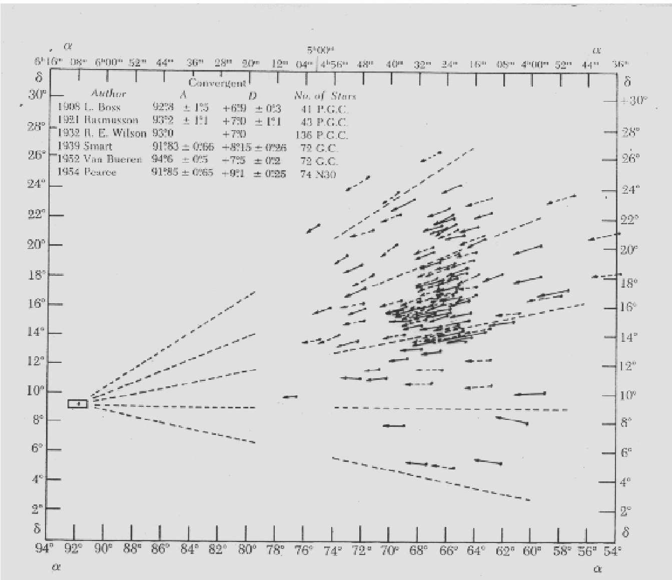
- Investigation by Trumpler of H-R diagram of open star clusters (discovery of interstellar extinction & reddening; Lecture 18).



- Recognition that main-sequence turnoff represents core-hydrogen exhaustion.
- Nature of stellar nuclear reactions explained by Bethe; Burbidge, Burbidge, Fowler, & Hoyle; Salpeter; Cameron; and their collaborators.
- Modern computation of stellar structure and evolution by computers.

Distances to Open Clusters and Absolute Magnitudes

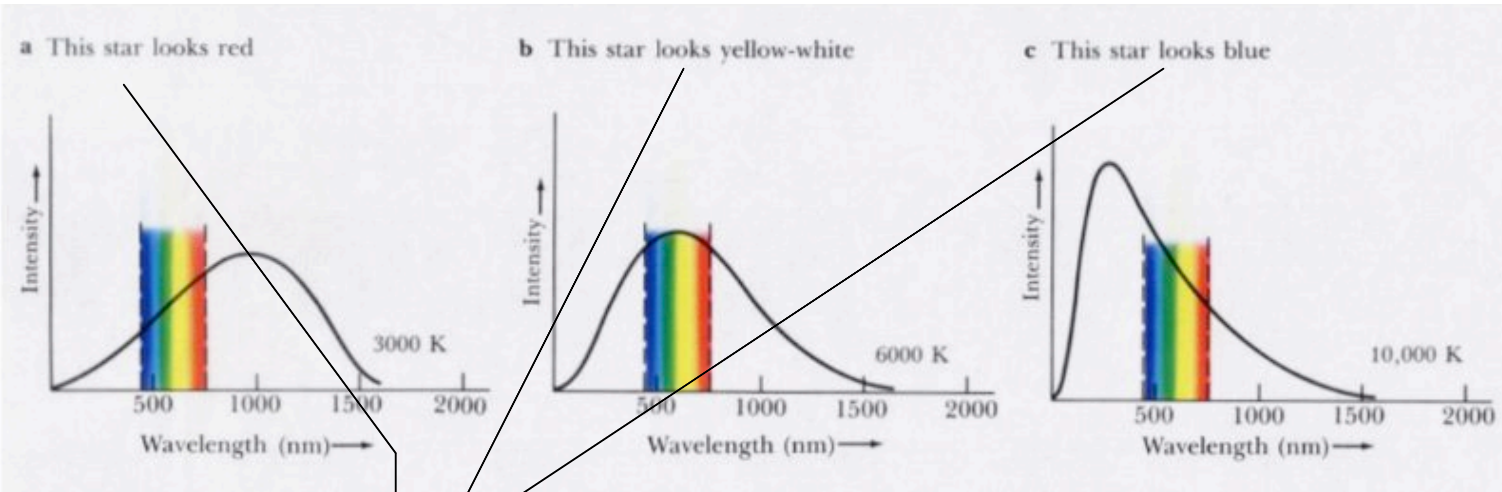
- Below the turnoff in the H-R diagram, stars are still on the main-sequence and therefore, for the same mass, should have the same absolute brightness (luminosity *L* or absolute magnitude *M*) for a given effective temperature.
- Main sequence of different open clusters have different apparent brightness (received flux *f* or apparent brightness *m*) only because they lie at different distances *r*: $f = L / 4\pi r^2$.
- Thus, how far one has to slide a cluster's main-sequence up or down an observational H-R diagram relative to a fiducial standard (the Hyades cluster) indicates how far that open cluster is relative to the standard.
- The Hyades cluster is close enough to us that its distance (430 lt-yr) can be determined by the "moving cluster method."



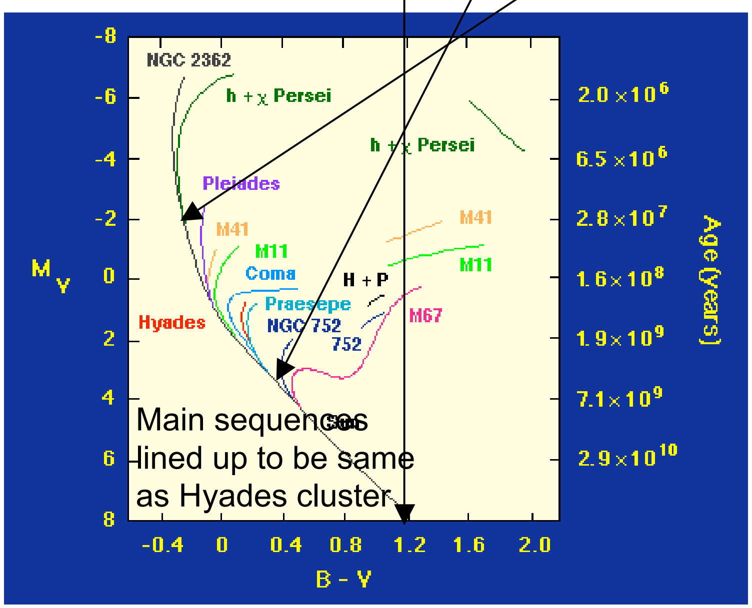
From Struve, Lynds, & Pilans, *Elementary Astronomy* (1959)

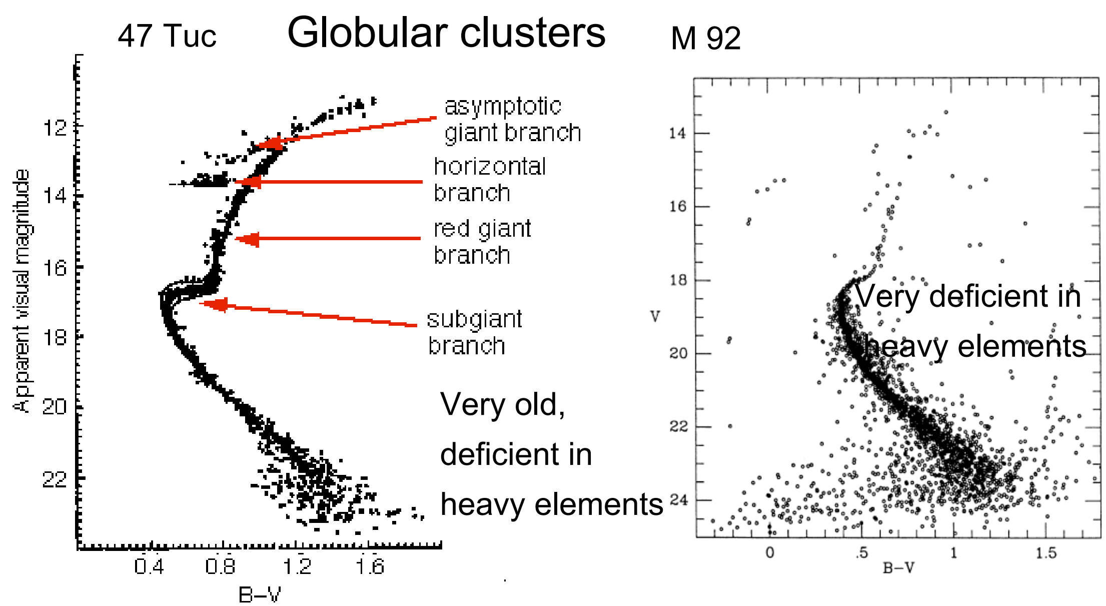
Convergence of proper motion of stars in Hyades toward a distant point indicates that the cluster has a component of motion directed away from us. Measurement of the component of velocity along the line of sight (by the Doppler shift of spectral lines), plus the rate at which the angular size of the cluster decreases, yields the distance *r* of the Hyades cluster.

Observational H-R Diagrams of Open and Globular Clusters

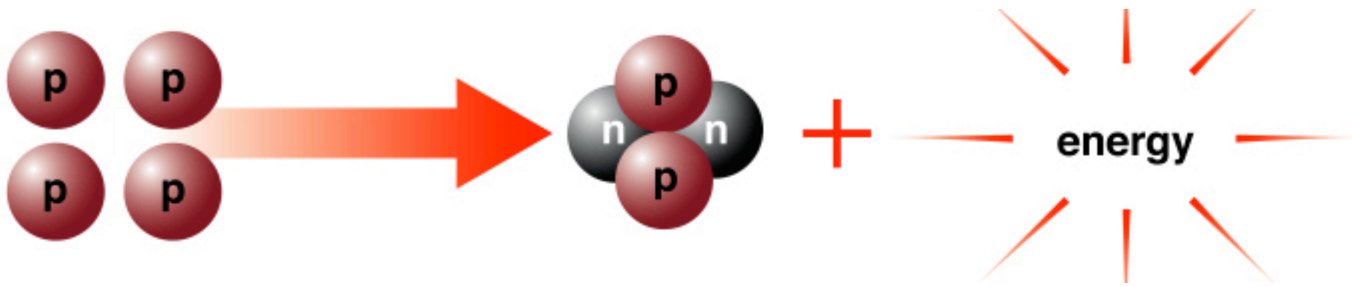


Ratio of apparent brightness in, say, blue to visual (difference *B-V* in magnitudes) is a measure of the intrinsic color or effective temperature of a star (but need to correct for interstellar reddening, more in Lecture 18).





Intuitive Idea for Energy Source of Sun and Other Main-Sequence Stars



Basic Questions: How do 2 protons become 2 neutrons?

How can repulsive electric force between protons in nucleus be overcome by greater attractive binding?

Answers: Existence of weak and strong nuclear forces.

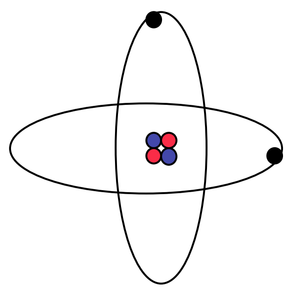
Nuclear Forces

- Matter is made of a *triad* of particles:

electrons	+	protons & neutrons
in shells of atoms		in nuclei of atoms

- Example: He atom

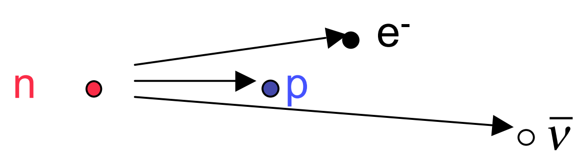
$^{4}_{2}\mathrm{He}$



Electrons are pointlike particles that form fuzzy atomic shells that are 10^5 times larger than nuclei, which themselves are about 10^{-15} m in size.

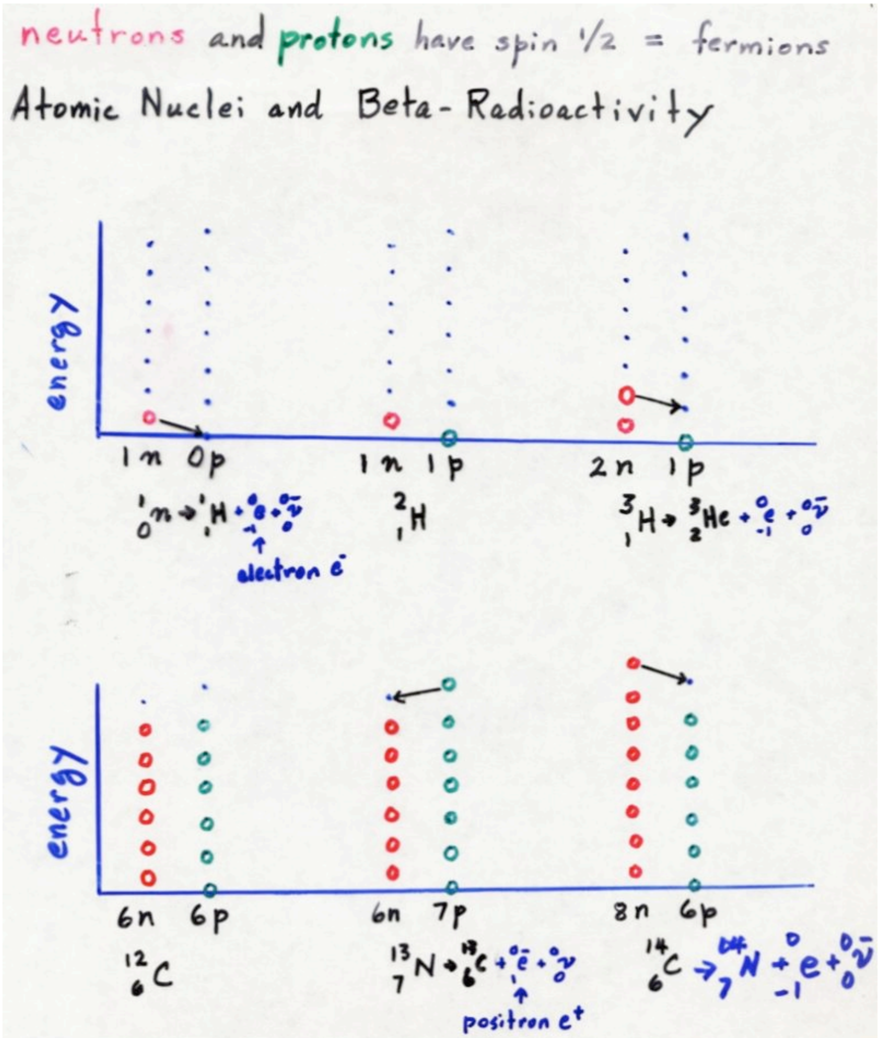
- Strong nuclear force: attractive part binds protons and neutrons together in nucleus – repulsive part keeps atomic nuclei at almost constant density → "liquid drop" model of atomic nucleus.
- Weak nuclear force: allows neutron to change to proton and vice-versa.

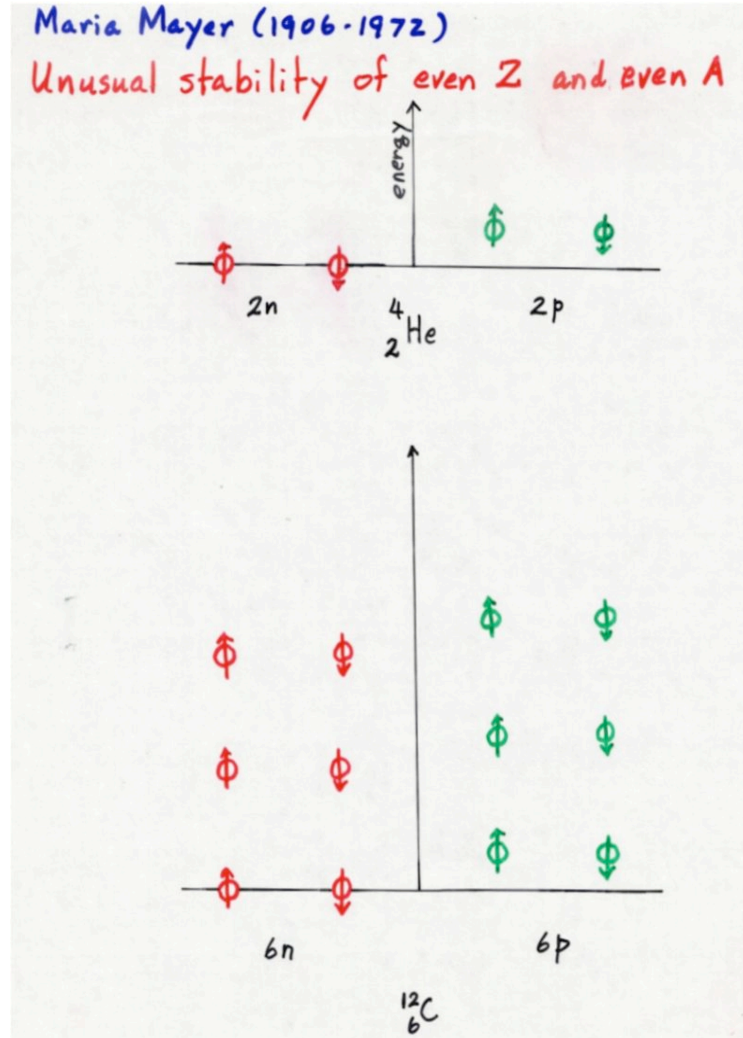
$n \rightarrow p + e^- + \bar{\nu}$ (antineutrino)



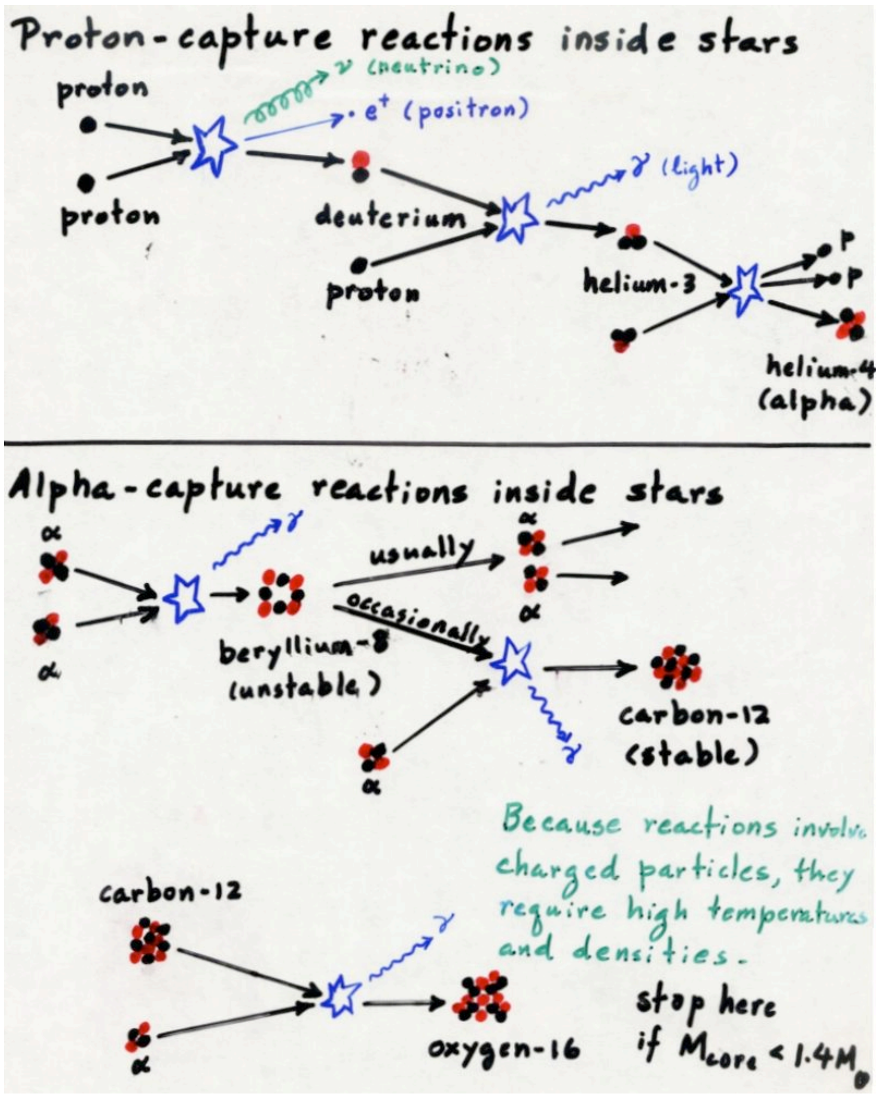
- To conserve both energy and linear momentum in above decay process, Wolfgang Pauli (1901-1976) postulated the existence of neutrino (and antineutrino).

Stacking of Proton & Neutron Energy Levels





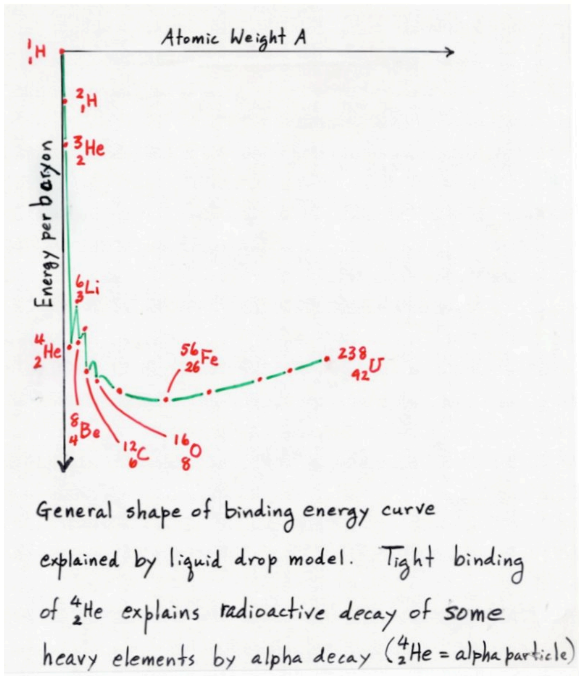
Proton & Alpha Capture Reactions

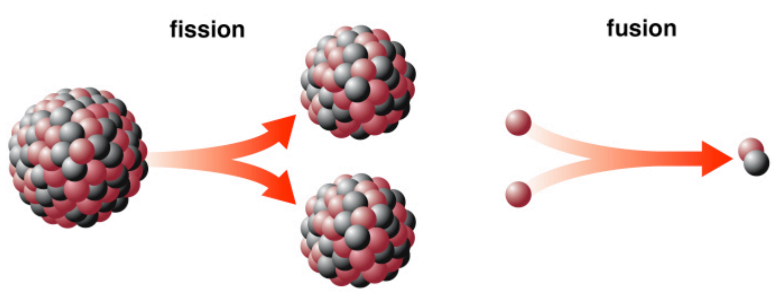


Important on main-sequence

Important at tip of red giant branch and horizontal branch. More complex reactions come into play for advanced stages of stellar evolution of high-mass stars.

Binding Energy Curve of Nuclei





Two ways to extract nuclear energy

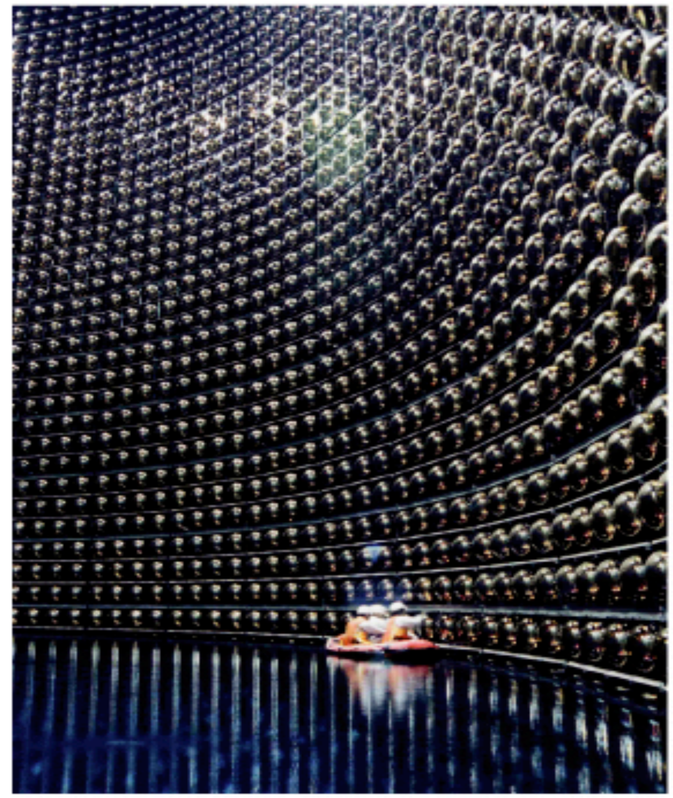
Keeping the nuclear density approximately constant, it is energetically favorable for small nuclei to gain baryons (protons or neutrons) because the added attractive strong nuclear force more than compensates for the extra repulsive Coulomb force (since roughly half of the added baryons have to be protons for nuclear stability). However, because the strong nuclear attraction is short-range (effective only over ~ 10^{-15} m) whereas the electrostatic repulsion is long-range (declining only as $1/r^2$), the binding of the former outweighs the disruption of the latter only up to ^{56}Fe. Nuclei heavier than iron-56 actually have less binding energy per baryon than iron-56. Thus, very heavy nuclei, such as all the isotopes of uranium are unstable to spitting out small particles (alpha, beta, gamma) in an attempt to get lighter (radioactive decay). A few, such as ^{235}U (even number of protons, odd number of neutrons) are unstable to fissioning into two approximately equal pieces when a neutron is added to them. Since the fission products contain, proportionally, too many neutrons for their atomic weight, the process releases on average more (between 2 and 3) than the one neutron that it took to split the original U-235 nucleus, making a chain reaction (runaway = bomb; controlled = reactor) possible if a pile of uranium contains enough U-235 compared to more ordinary U-238. The last usually requires a process of *uranium enrichment.*

Check on Fusion as Energy Source of Sun: Solar Neutrinos (extra material)

- Conversion of protons into neutrons (to turn 4H into 1 He) releases neutrinos ν. Only ν can come to us directly from center of Sun. Only problem: How to detect ν?
- Two basic techniques:
  - Nucleus + $\nu \rightarrow$ radionuclide $\rightarrow$ radioactive decay (detectable).
  - Electron in water + $\nu \rightarrow$ fast electron in water traveling faster than the light it emits in water $\rightarrow$ Cerenkov radiation (detectable).
- Extremely difficult measurements because cross sectional area of neutrinos in interactions with matter is very small ("weak interaction").
- Experiments:
  - Chlorine radiochemical experiment (Raymond Davis).
  - Super Kamiokande (large Japanese group) outgrowth of Kamiokande experiment searching for proton decay.
- Results: solar ν seen only at about 1/3 of expected theoretical level computed by John Bahcall (1934-2005) and others on basis of "standard solar model."

Solar Neutrino Experiments (extra material)

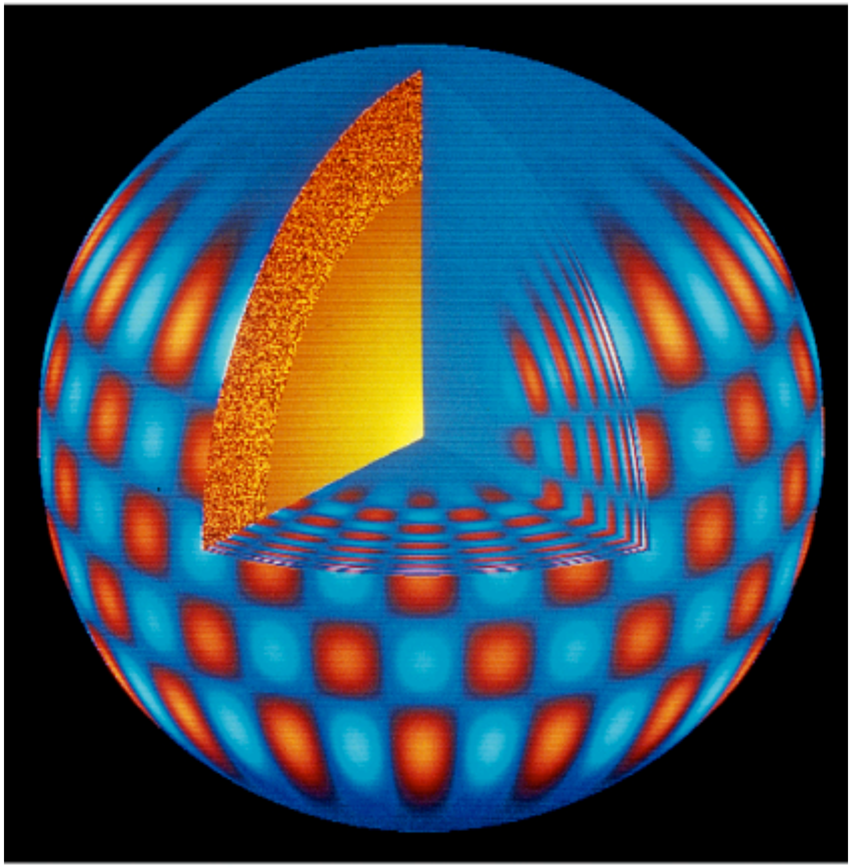
Chlorine experiment



Super Kamiokande

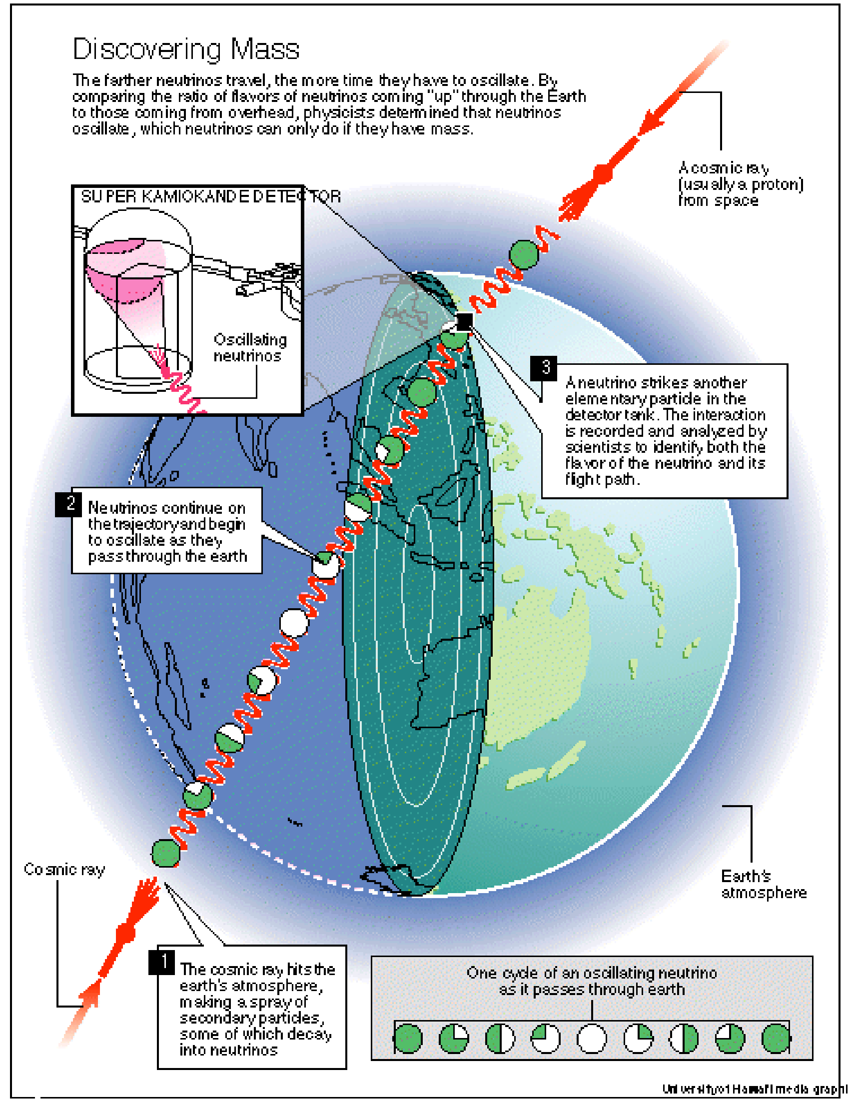
Check on the Standard Solar Model (extra material)

- At first, most physicists thought the problem must be that the astronomers have made a mistake.
- This attitude changed when precise helioseismology (solar oscillations) experiments, tracing sound waves as they traverse through the interior of the Sun, verified the temperature calculations of the "standard solar model" to the 1 part in a 1000 level.
- Recent revisions of solar abundances, however, have worsened the agreement somewhat.



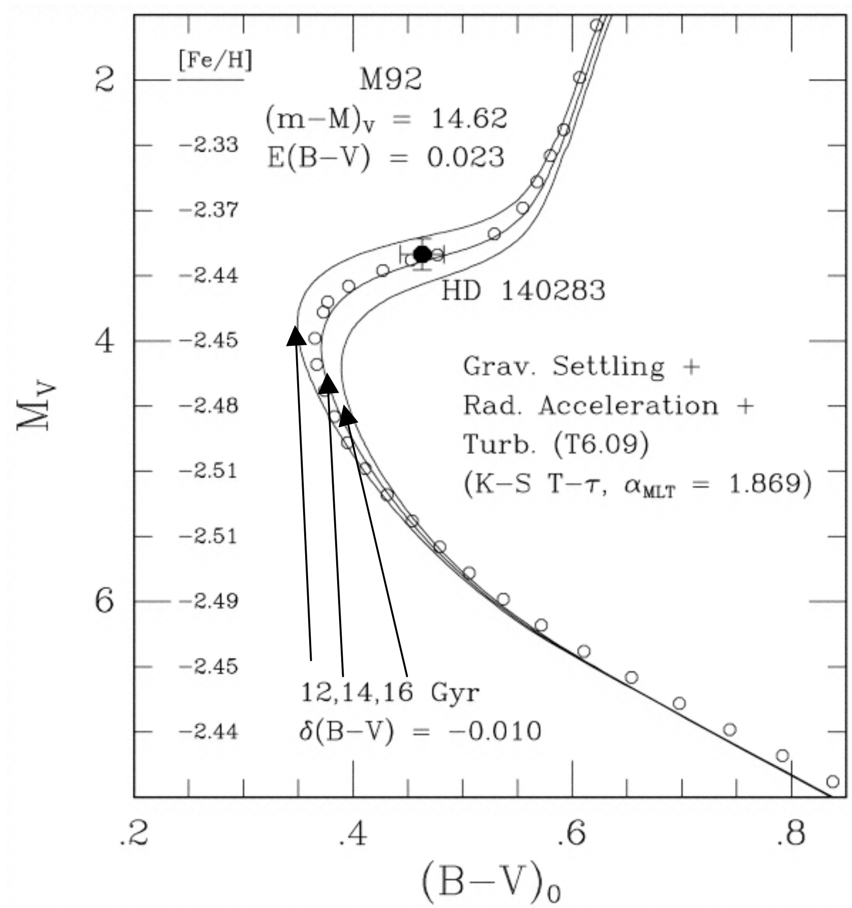
Resolution of Solar Neutrino Problem (extra material)

- Today, scientists believe that the electron neutrinos generated in solar fusion reactions are able to “oscillate” among three different forms (electron, “mu,” and “tau” neutrinos) as they travel from the Sun to Earth. Since ordinary laboratory apparatuses contain only electrons and no muons or tauons (heavy analogs of the electron produced in accelerators), such experiments detect, on average, only about 1/3 of the actual neutrinos that were released at the source.
- Half of the 2002 Nobel Prize in Physics went to the two leaders of the chlorine radiochemical and water cerenkov experiments that found and confirmed the discrepancy with original theoretical expectations (as well as discovered conclusive evidence for neutrino oscillations and neutrino mass for neutrinos created in the Earth’s atmosphere by cosmic-ray interactions). The other half went to Riccardo Giacconi, who pioneered satellite X-ray astronomy that led to the discovery of black holes discussed in Lecture 15.



Age of Oldest Stars in the Galaxy

- At the turnoff, stars have just exhausted H in their cores by fusing 4H into He.
- The time it takes to exhaust core H starting with a given uniform composition is well understood for stars of a given mass because the rate of nuclear burning is known through its luminosity *L*.
- On the other hand, the mass of a star at the turnoff can be found knowing its color (or effective temperature T_e).
- For a globular cluster like M92, the mass at the turnoff is close to 0.8 $M_\odot$ which corresponds to a main-sequence lifetime somewhat greater than that of the Sun, 10 billion years.
- The best-fit for M92 gives it an age of about 13 billion years.



Vandenberg, Michaud, & Richer

(2002, ApJ, 571, 478)

Practical Lessons (extra material)

- The Sun and other main-sequence stars are controlled thermonuclear furnaces.
- Total amount of sunlight captured by the Earth, with practical efficiencies folded in, is adequate, but not by much, to provide a viable standard of living for every man, woman, and child presently on Earth.
- Wind and geothermal energy sources are much less viable.
- Middle East oil will last only for a few more decades; entire coal supply of Earth, for only a few more centuries. Burning them also gives rise to a terrible greenhouse effect.
- Given these facts, we cannot afford as a civilization to overlook nuclear energy as (part of) the solution. After all, the basic lesson of the Sun and other stars as an energy source is that nuclear energy is roughly one million times more powerful per kg than chemical energy sources. This factor of a million should not be thrown away lightly.

- Problems with terrestrial fission reactors:
  - Radioactive waste (low-level and high-level) disposal and nuclear proliferation – difficult, but more easily faced than global warming.
  - Bad public image – better education.
  - Temporary solution to get us through this century: Advanced fuel cycle initiative involving thorium cycle.
- Problems with fusion reactors:
  - Much smaller difficulty with nuclear waste.
  - Very difficult to achieve controlled thermonuclear fusion in laboratory – confinement of hot plasmas by magnetic fields rather than by huge gravitational field of Sun.
  - Another technical approach – inertial “confinement” by lasers focused on fusion pellets.
- Fundamental advantage of fusion: enough deuterium in sea water to make every liter of the ocean more powerful than 100 liters of gasoline. (After we extract the small amount of D, the rest can be put back into the ocean with no harmful effects.) A clean and almost inexhaustible source of energy if we can tap it.
- Byproduct of troubles in the Middle East: Renewal of interest in fission and fusion research in US, Asia, and Europe.