Observational Astronomy - Lecture 8
Stars I - Distances, Magnitudes, Spectra, HR Diagram

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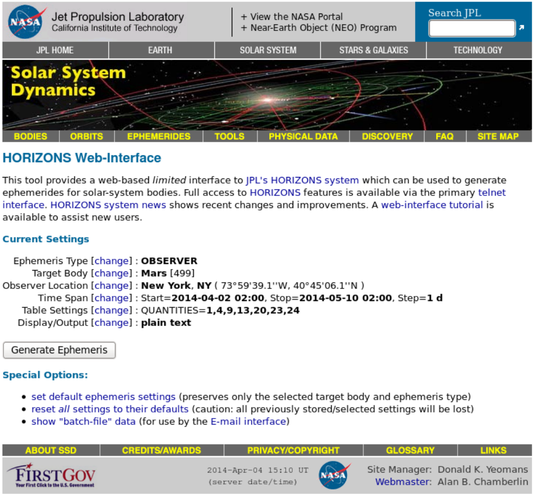
JPL Horizons Database



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HORIZONS Web-Interface

This tool provides a web-based *limited* interface to JPL's HORIZONS system which can be used to generate ephemerides for solar-system bodies. Full access to HORIZONS features is available via the primary telnet interface. HORIZONS system news shows recent changes and improvements. A web-interface tutorial is available to assist new users.

Current Settings

Ephemeris Type [change] : **OBSERVER**
Target Body [change] : **Mars** [499]
Observer Location [change] : **New York, NY** (73°59'39.1''W, 40°45'06.1''N)
Time Span [change] : Start=**2014-04-02 02:00**, Stop=**2014-05-10 02:00**, Step=**1 d**
Table Settings [change] : QUANTITIES=**1,4,9,13,20,23,24**
Display/Output [change] : **plain text**

Generate Ephemeris

Special Options:

- set default ephemeris settings (preserves only the selected target body and ephemeris type)
- reset *all* settings to their defaults (caution: all previously stored/selected settings will be lost)
- show "batch-file" data (for use by the E-mail interface)

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FIRSTGOV Your First Click to the U.S. Government

2014-Apr-04 15:10 UT
(server date/time)

Site Manager: Donald K. Yeomans
Webmaster: Alan B. Chamberlin

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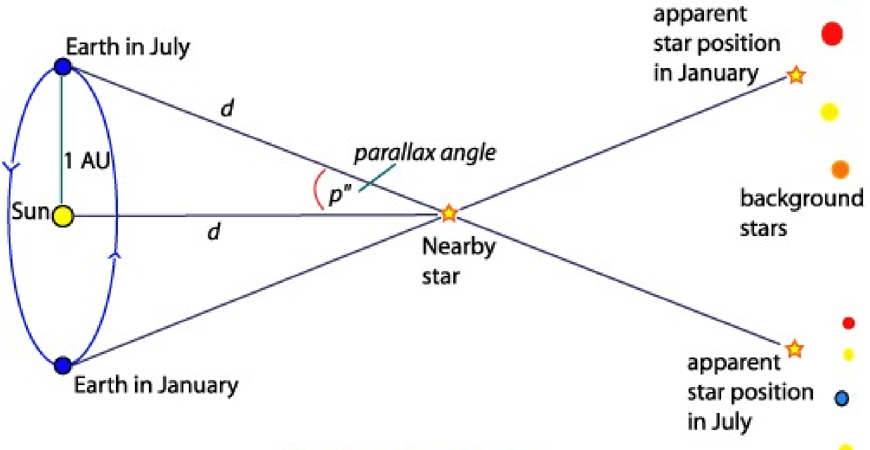
http://ssd.jpl.nasa.gov/horizons.cgi

Basic Properties of Stars

- Distance
  - We measure distance using a technique called parallax.
- Brightness
  - As we've discussed, we characterize brightness by magnitude.
- Color
  - Color can be characterized simply, but the full spectrum contains a great deal of information.
- Energy Output

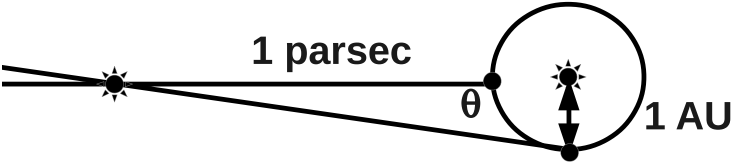
Parallax - Measuring the distance to the stars



Parallax of nearby star

You can see the same effect by looking at your extended thumb, closing one eye, and then the other.

Definition of the parsec



- A distance of one parsec is defined as the distance at which an object has a parallax of one arc second. This is an angle of:

$$\theta(\text{radians}) = \frac{1.0\,\text{AU}}{1.0\,\text{parsec}}$$

- Converting to arc seconds:

$$\theta(\text{arcseconds}) = \frac{1.0\,\text{AU}}{1.0\,\text{parsec}} \times \frac{360}{2\pi} \times 60 \times 60 = \frac{1.0\,\text{AU}}{1.0\,\text{parsec}} \times 206265$$

- So 1 parsec $=$ 206,265 AU. It is also about 3.26 light-years.

Typical distances in parsecs

- Nearest star (Alpha Centauri) - 1.3 pc
- Sirius (brightest star) - 2.6 pc
- Polaris - 130 pc
- Pleiades cluster - 130 pc
- Betelgeuse - 200 pc
- Orion Nebula - 410 pc
- Center of our galaxy - 7.9 kpc
- Andromeda Galaxy - 780 kpc
- Brightest Quasar (3C273) - 750 Mpc
- Approximate size of observable universe - 15 Gpc

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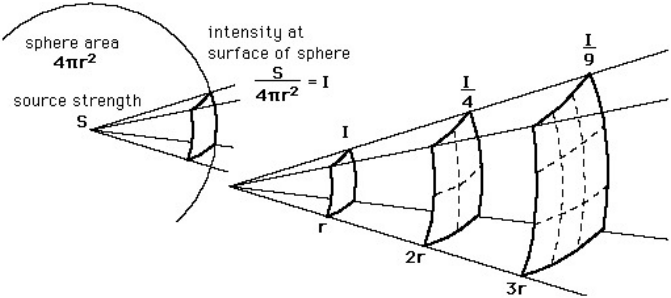
Historically, only the nearest stars had a measurable parallax, but recent satellites (Hipparcos, Gaia) are able to measure the parallax of large numbers of stars.

The Inverse Square Law



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As objects get further away, they get fainter according to the inverse square law. This is because the same amount of radiated light energy gets spread over larger and larger areas.

Magnitude Review - 1

- Hipparchus defined the original magnitude scale:
  - Brightest stars - Magnitude 1
  - Dimmest stars - Magnitude 6
- Much later, measurements revealed $\approx 100\mathrm{X}$ difference between these two.
- Our senses respond logarithmically.
- Accordingly, magnitude is defined as follows (here I is the *intensity* of the object):

$$\boxed{\mathrm{m_{object}} - \mathrm{m_{reference}} = -2.5 \ \ \log_{10}\left(\frac{\mathrm{I_{object}}}{\mathrm{I_{reference}}}\right)}$$

- This means that each smaller magnitude is $10^{0.4} = 2.512$ times brighter than the one before.

Magnitude Review - 2

Remember - brighter objects have smaller magnitudes!

- Sun ≈ -27
- Full Moon ≈ -13
- Venus ≈ -4
- Jupiter ≈ -2.5
- Sirius (brightest star) ≈ -1.5
- Vega (historical standard) ≈ 0
- Faintest star visible with naked eye (Manhattan) ≈ 3.5
- Faintest star visible with naked eye (dark skies) ≈ 6.0
- Faintest star visible with binoculars (dark skies) ≈ 9.5
- Faintest star visible with Hubble space telescope ≈ 31.5

Magnitude Review - 3

- Apparent magnitudes tell how bright an object appears.
- Absolute magnitudes tell how intrinsically bright an object is.
  - An object can appear bright because it is intrinsically bright, or simply because it is close.
  - Absolute magnitude is defined as the apparent magnitude when viewed at a distance of 10 parsecs.
  - The sun has an apparent magnitude of 4.83.
  - Astronomers usually use m for apparent magnitudes, M for absolute magnitudes.

Magnitude Review - 4

- Recall:

$$m_{obj} - m_{ref} = -2.5 \ \ \log_{10}(\frac{I_{obj}}{I_{ref}}) = 2.5(\log_{10}(I_{ref}) - \log_{10}(I_{obj}))$$

- As objects get further away, they get fainter according to the inverse square law.
- Here I is the *intensity* of the light received, L is the *luminosity* of the object, and D is the distance in parsecs.

$$I(D) = \frac{L}{4\pi D^2}$$

- Taking logs of both sides:

$$\log_{10}(I(D)) = \log_{10}(L) - 2\log_{10}(D) - \log_{10}(4\pi)$$

Magnitude Review - 5

- So:

$$\mathrm{m(D)} - \mathrm{m(10)} = 2.5(\log_{10}(\mathrm{L}) - 2\log_{10}(10) - \log_{10}(4\pi) \\ - (\log_{10}(L) - 2\log_{10}(D) - \log_{10}(4\pi))$$

$$\mathrm{m(D)} - \mathrm{M} = 2.5(-2 + 2\log_{10}(\mathrm{D}))$$

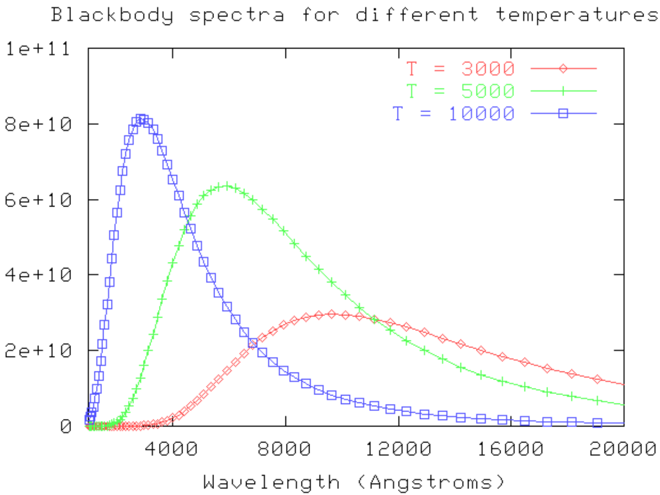
$$\boxed{\mathrm{m(D)} = \mathrm{M} - 5 + 5\log_{10}(\mathrm{D})}$$

- We can also write:

$$\mathrm{M_{obj}} - \mathrm{M_{ref}} = -2.5 \ \ \log_{10}(\frac{\mathrm{I_{obj}}}{\mathrm{I_{ref}}}) = -2.5 \ \ \log_{10}(\frac{\mathrm{L_{obj}}}{\mathrm{L_{ref}}})$$

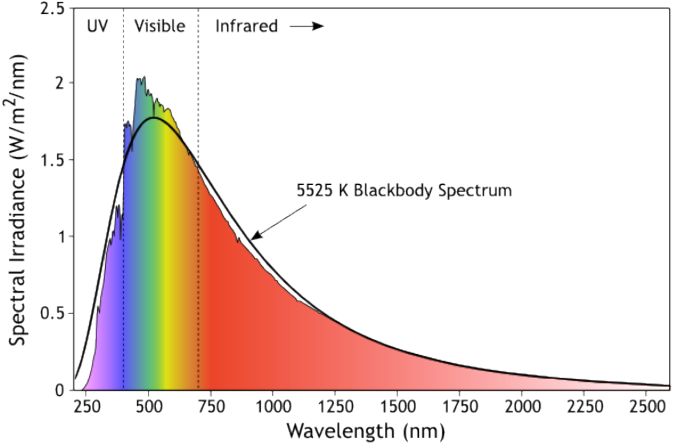
$$\frac{\mathrm{L_{obj}}}{\mathrm{L_{ref}}} = 10^{0.4(\mathrm{M_{ref}} - \mathrm{M_{obj}})}$$

Blackbody Spectra



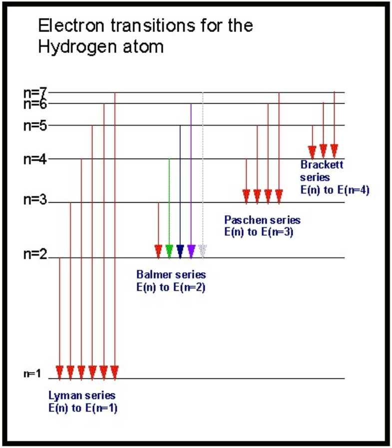
Cooler bodies are redder, hotter bodies bluer

The Spectrum of the Sun



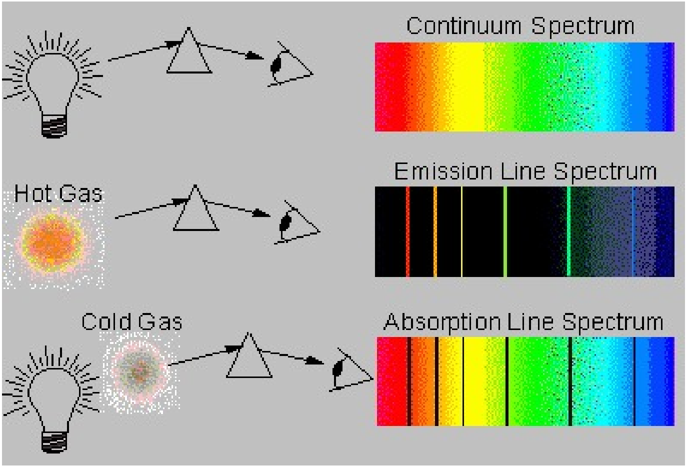
The sun is a close approximation to a blackbody, but it includes absorption lines due to absorption by atoms in the sun.

Atomic Energy Levels



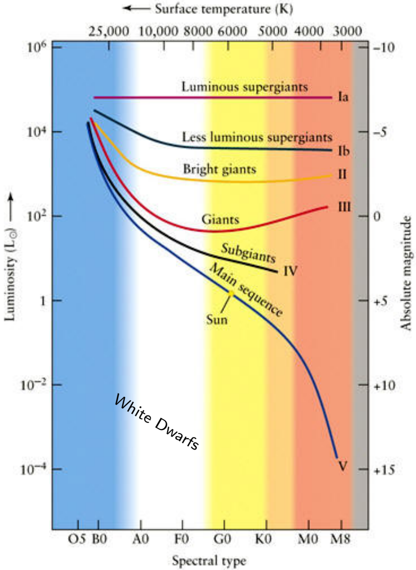
Atoms can only exist in discrete energy levels. As the atom transitions from one level to another, it absorbs or emits light at specific wavelengths. Each atom has characteristic wavelengths of emission and absorption.

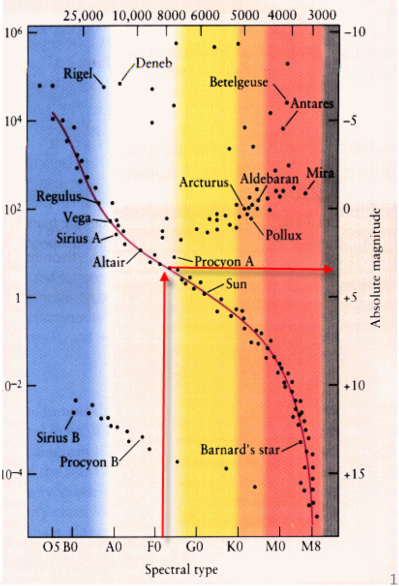
Emission and Absorption Lines



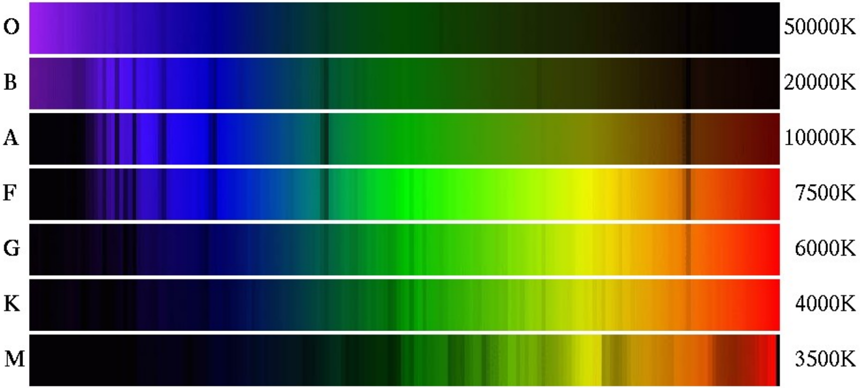
Each atom emits and/or absorbs at specific wavelengths. We can use this information to identify what elements a star contains.

The Color-Magnitude or Hertzsprung-Russell (H-R) diagram.





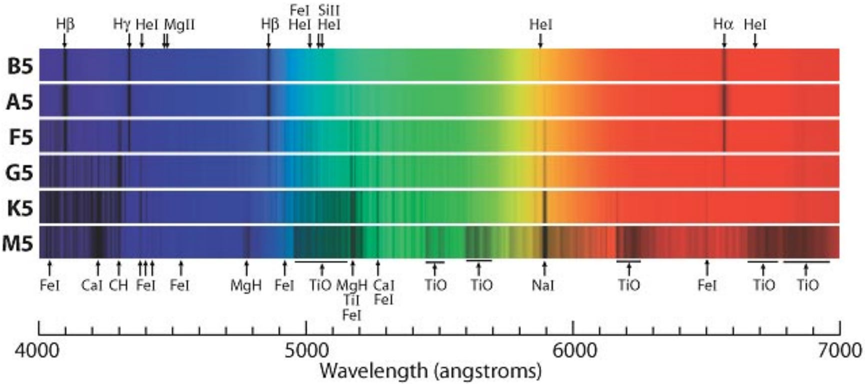
Stellar Spectra - OBAFGKM



The sun is a G-type star.

The mnemonic is "Oh, Be a Fine (Girl/Guy), Kiss Me"

Spectral Lines in Stellar Spectra



This identifies some of the lines seen in stellar spectra due to absorption by various elements.

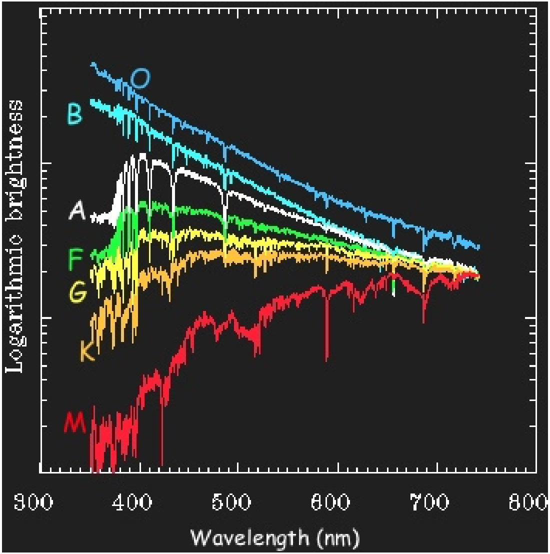
Stellar Spectra Determine the Composition of Stars

On the subject of stars, all investigations which are not ultimately reducible to simple visual observations are ... necessarily denied to us. While we can conceive of the possibility of determining their shapes, their sizes, and their motions, we shall never be able by any means to study their chemical composition or their mineralogical structure ... Our knowledge concerning their gaseous envelopes is necessarily limited to their existence, size ... and refractive power, we shall not at all be able to determine their chemical composition or even their density... I regard any notion concerning the true mean temperature of the various stars as forever denied to us.

Auguste Comte, Cours de la Philosophie Positive, 1835.

Fourteen years later Kirchhoff discovered the chemical composition of a gas could be deduced from its electromagnetic spectrum.

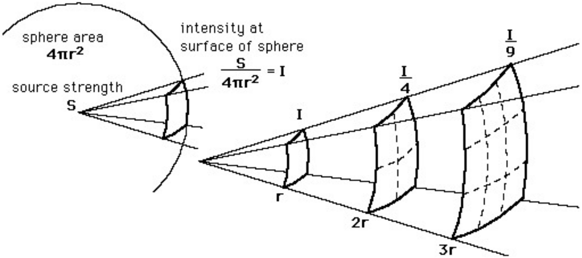
Another Look at Stellar Spectra



Energy and Power

- Energy is a measure of work expended, usually measured in Joules. Examples:
  - Lifting a 1 pound object a distance of 1 foot $\approx$ 1 Joule.
  - Climbing a flight of stairs $\approx$ 4000 Joule.
  - Energy content of a Snickers bar $\approx$ 1,200,000 Joule.
  - Burning a gallon of gasoline $\approx$ 140,000,000 Joule.
- Power is energy per unit time. It is measured in Watts. One Watt is one Joule per second. Examples:
  - A typical light bulb - 20 - 100 watts.
  - A toaster $\approx$ 1000 watts.
  - Baseline energy consumption of human body $\approx$ 100 watts.
  - Leisurely cycling pace $\approx$ 50-100 watts.
  - Tour de France cycling pace $\approx$ 400-600 watts.
  - A car engine $\approx$ 40,000 watts. (1 horsepower = 746 watts)
  - Power used by all of humanity $\approx 10^{13}$ watts.
  - Power emitted by the sun (its *Luminosity*) $= 4 \times 10^{26}$ watts.

Power received from the Sun at Earth orbit



- The power received per unit area is called *Flux* or radiation *Intensity*:

$$F = \frac{L}{4\pi R^2}$$

- The distance from the Earth to the sun is 1.0 AU $= 1.5 \times 10^{11}$ m, so

$$F = \frac{L}{4\pi R^2} = \frac{4 \times 10^{26}\,\text{Watts}}{4\pi \times (1.5 \times 10^{11}\,\text{m})^2} = 1400\frac{\text{Watts}}{\text{m}^2}$$

What powers the stars? - 1

- In the 19th century, as the concepts of energy and power became clear and the power output of the sun became known, people began to ask what source powered the sun.
- Idea number one - chemical burning - What if the sun were burning gasoline? How long could it burn?
    - Gasoline produces about 40 MJoules/liter.
    - Gasoline weighs about 1 kg/liter.
    - The mass of the sun is about 2.0×10^{30} kg, so:

$$\mathrm{T} = \frac{2.0 \times 10^{30}\,\mathrm{kg} \times 4.0 \times 10^{7}\,\frac{\mathrm{Joules}}{\mathrm{liter}}}{1.0\,\frac{\mathrm{kg}}{\mathrm{liter}} \times 4.0 \times 10^{26}\,\frac{\mathrm{Joules}}{\mathrm{sec}}} = 2.0 \times 10^{11}\mathrm{sec} = 60,000\,\mathrm{years}$$

- Not nearly long enough!

What powers the stars? - 2

- Idea number two - Kelvin, Helmhotz. Gravitational contraction.
  - As material falls, it gains energy due to gravity.
  - If the sun were slowly contracting, this could be its source of energy.
  - Suppose the sun contracted by 10%. How long could it shine?

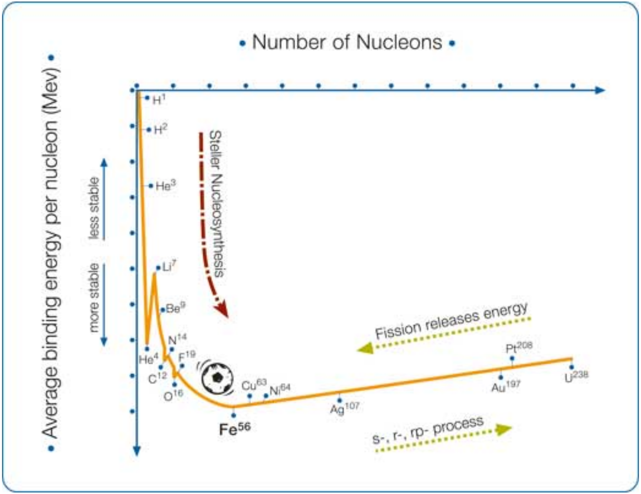
$$\mathrm{T} = \frac{\mathrm{GM}^2}{\mathrm{R}}\frac{\Delta \mathrm{R}}{\mathrm{R}} = \frac{6.67 \times 10^{-11}\,\frac{\mathrm{m}^3}{\mathrm{kgs}^2}(2.0 \times 10^{30}\,\mathrm{m})^2 \times 0.1}{7.0 \times 10^{8}\,\mathrm{m} \times 4.0 \times 10^{26}\,\frac{\mathrm{Joules}}{\mathrm{sec}} \times 3.1 \times 10^{7}\,\frac{\mathrm{sec}}{\mathrm{yr}}}$$

$$\mathrm{T} = 3,000,000\,\mathrm{years}$$

- For a time, this was thought to be a possible explanation, but fossil and geologic evidence made it clear that the Earth is billions of years old.

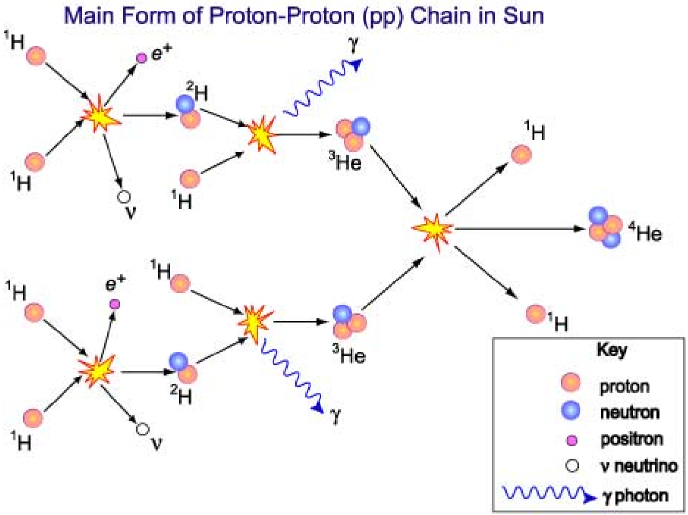
- Today, we know that the sun and stars are powered by *nuclear fusion* This was discovered by Hans Bethe in the early 20th century.

Basics of Nuclear Energy



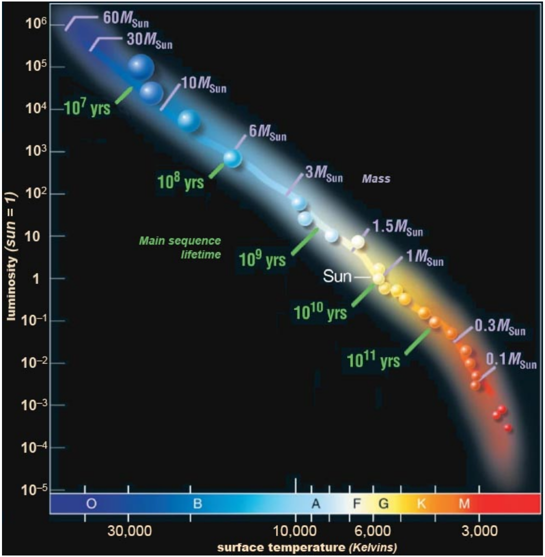
We can gain energy by either splitting heavy nuclei (*nuclear fission*, which powers nuclear reactors), or by putting together light nuclei (*nuclear fusion*, which powers the stars). Iron is the most stable nucleus.

The Solar Proton-Proton Cycle



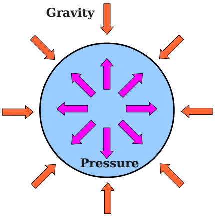
This chain is responsible for most of the energy production in the sun.

The Main Sequence

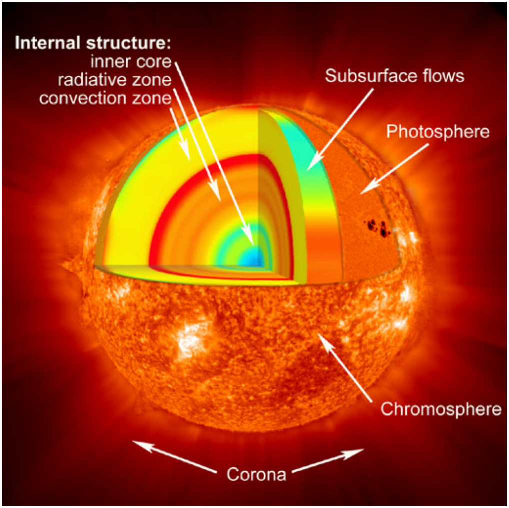


- The main sequence is where a star resides when it is initially formed.
- It stays on the main sequence while it is fusing hydrogen.
- Mass determines where a star is on the main sequence.
- More massive stars burn their fuel more quickly, and so live shorter lives.
- Low mass stars are much more common than high mass stars.

Basic Structure of Stars

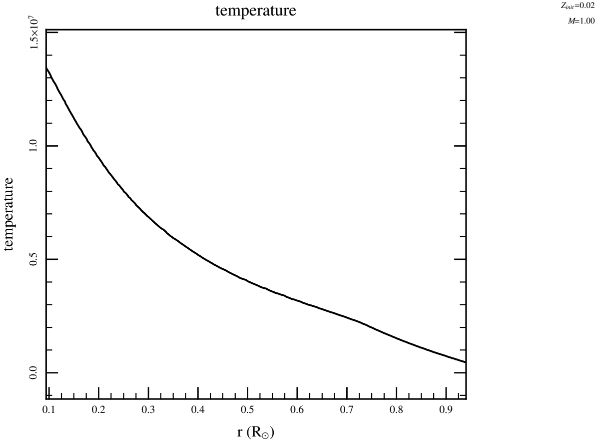


Stars are in *Hydrostatic Equilibrium*, with the outward pressure balancing the inward pull of gravity.



The interior of the sun.

Temperature Profile of the Sun



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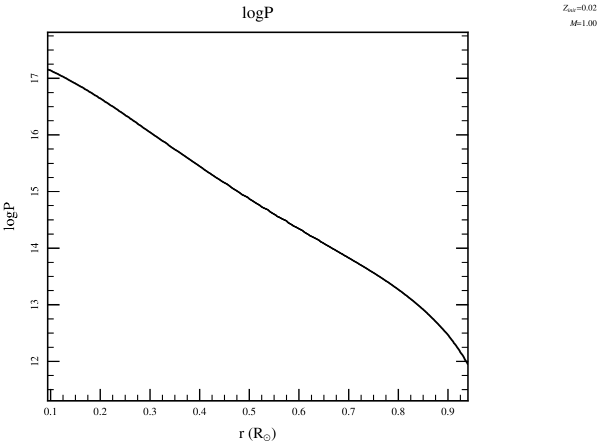
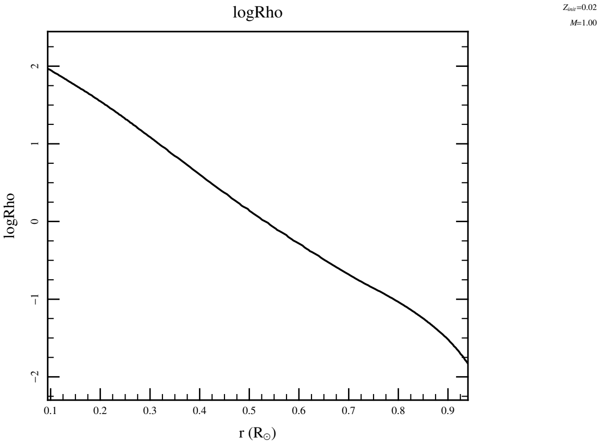
The sun is about 5000K at the surface, 15,000,000 K in the center.

Pressure Profile of the Sun



The pressure in the sun's core is about 100 billion times the atmospheric pressure on the Earth.

Density Profile of the Sun



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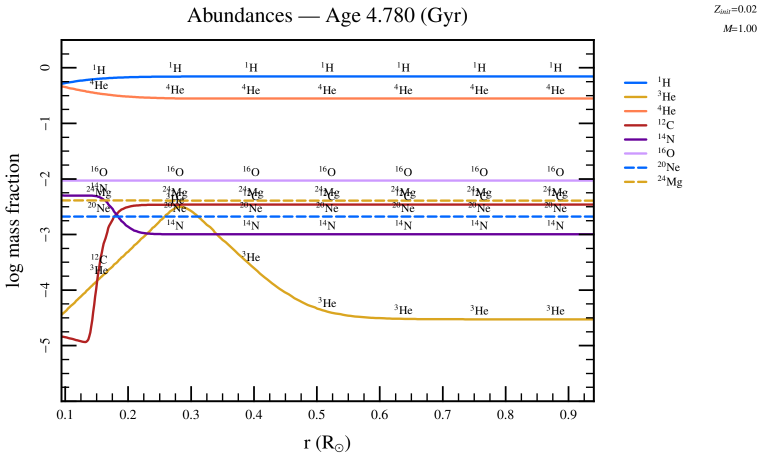
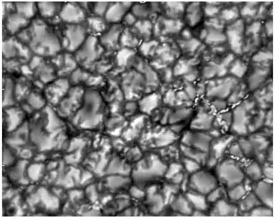
The density of the sun is about 100 times the density of water in the center.

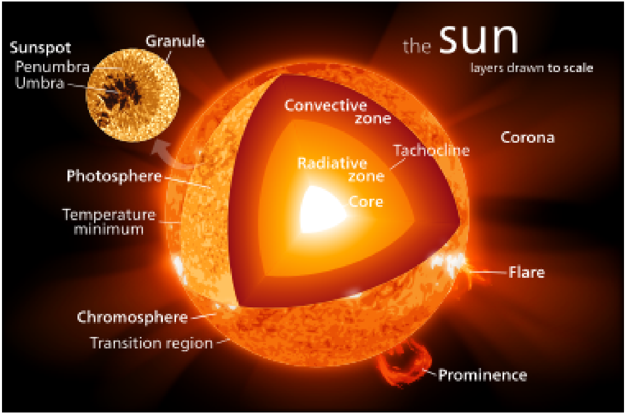
Abundance Profile of the Sun



The sun has already burned about 50% of its hydrogen in the center. These are all generated with the Mesa stellar modeling program, which runs on your laptop.

Movie of the Solar Photosphere





These convective cells are about the size of the United States.

Summary - 1

1. We measure star distances using parallax.
   - A star at a distance of 1 parsec has a parallax of 1 arc second.
   - One parsec is 206,265 AU or 3.26 light-years.
   - The stars we see in the sky range from a few parsecs to a few thousand parsecs away.
2. We characterize star brightness using magnitudes, which is a logarithmic scale.
3. The spectra of stars tell us a great deal about them:
   - The overall color of the star tells us how hot it is.
   - The spectral lines tell us what elements the star contains and how much of each element.

Summary - 2

1. When plotted on a Color-Magnitude diagram (also called a Hertzsprung-Russell or H-R diagram), the stars split into distinct bands.
   - The stars on the Main Sequence are still fusing hydrogen in their cores.
   - Others stars have evolved off of the Main Sequence.
   - A star's characteristics are determined mainly by its mass. More massive stars are hotter, bluer, and more luminous, and have shorter lifetimes.
2. Stars are powered by nuclear fusion.
   - The Sun is mainly powered by fusing hydrogen into helium.
3. We have detailed numerical models of the Sun and other stars.
   - The center of the sun is about 15 million K, about 100 billion atmospheres, and about 100 times the density of water.